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REAL TIME MONITORING OF HYDROLOGICAL VARIABLES FOR OPERATIVE LANDFILL STABILITY AND PERCOLATION FLUX CONTROL

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Abstract

Leachate production and management are recognized as one of the greatest problems associated with environmentally operations for landfills. Variations in leachate quality and quantity are related to rainfall depth and its infiltration processes into landfill.
This work examines important hydrological problems of the Scarpino site (Genoa, northern Italy), a garbage dump which covers the valley of a first order flash creek with a surface of 100 hectares, located in one of the rainiest area of Italy. The landfill is one of the largest in Europe and it operates since the Sixties collecting waste at a rate of about 1000 tons per day. Its present structure shows several horizontal layers of waste deposit separated by covers of compacted soil for a depth ranging from 40 to 70 meters. The landfill surface is subdivided in zones delimited by artificial slopes.
The hydrology of the landfill is analyzed with a real time monitoring system which has been set up in order to manage and control leachate fluxes and landfill slope stability acquiring: (i) meteorological variables, (ii) soil moisture profiles, (iii) leachate levels inside the landfill body, (iv) discharge measurements of surface runoff basin and drained leachate at the landfill outlet, and (v) leachate levels inside the storage tanks. Although it was a preliminary development state, this monitoring system was able to provide the necessary information in order to evaluate the overall landfill hydrological response, particularly focused on the leachate volume production.

Key words: landfill hydrology, leachate, real-time monitoring

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1. Introduction

In most European countries, municipal solid wastes (MSW) are commonly eliminated in landfill disposals (EEA, 2013). In spite of many advantages (e.g. waste-derived power production), the generation of heavily polluted leachates, which present significant variations in both volume and chemical composition, constitutes a major drawback. Variation in leachate composition and quantity is often attributed to water volume, which infiltrates through the waste, and directly related to the natural processes occurring inside the landfill (Kulikowska and Klimiuk, 2008; Rusu et al., 2017).

Landfill leachate is a high polluting liquid with great concentration of organic and inorganic compounds (Vaverková and Adamcová, 2015; Yao, 2017), and its uncontrolled outflow is considered as an environmental crime punishable by the Italian law. Unless returned to the environment in a carefully

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controlled manner, this leachate may cause harmful effects on groundwater and surface water surrounding a landfill site, due to its significant concentrations of ammoniacal nitrogen which is toxic to many organisms (Salem et al., 2008). Therefore, a proper understanding of leachate generation is highly recommended for a better management and risk mitigation (Aharoni et al., 2017).

For these reasons leachate dynamic is a key problem in the management of urban wastes in landfills, and in the triggering role of hydrologic processes that can enhance leachate volume production and, mainly, its temporal distribution, have to be carefully considered (Di Bella et al., 2011; Fellner and Brunner, 2010; Reddy et al., 2013). For instance, as rainwater infiltrates and flows through the waste, it is expected to extract, dissolve, and finally wash out a wide range of organic and inorganic constituents (Tatsi and Zouboulis, 2002). In addition to the environmental problem, excess level of percolation fluid in the landfill body may affect landfill slopes stability. Monitoring activities allow to understand this complex system and design the right hydraulic works able to reduce the interaction with meteorological conditions. Usually, landfill monitoring deals with problems related to chemical hazards (Clark and Piskin, 1977) that is still a key issue in scientific literature (Vaverkova and Adamcova, 2015), but in some cases, as the one of the Scarpino landfill, monitoring hydro-meteorological processes is also related to percolation production as well as landfill slope stability (Coduto and Huitric, 1990). In this analysis, monitoring activities are carried out in order to provide assurance that landfill operations do not cause harm to human health neither to the surrounding environment. The study case is the Scarpino landfill, built on the main creek of the upper part of a mountain basin (the Cassinelle River, which flows into the Ligurian Sea), that merges leachate production from municipal solid wastes and hydrological processes typically of a river basin. Hence, this high interaction between leachate production with rainfall infiltration and hill slope drainage leads to design a real-time monitoring system of main hydrological fluxes and leachate level control in the landfill.

In this paper, we describe the structure of the landfill monitoring system, which was settled up between September 2013 and July 2014 as a smart network of a wider operative system (later developed) with the objective to test and verify instrument operations in a such complex area as the Genoa garbage dump.

The first section of the paper deals with the system layout, also discussing the underlying assumptions of the monitoring system, variables to be measured, their spatial representativeness, measurement methods and the installed sensors. The second part presents an early application of the monitoring system at its initial development status, evaluating the hydrological water balance for the Scarpino landfill (distinguishing Scarpino 1 and Scarpino 2 landfill areas), based on the available dataset, discussing the general landfill behaviour and the considered hypothesis too.

2. Study area

Established in 1968, the landfill for municipal solid waste of Scarpino (province of Genoa) is one of the largest landfills in Europe. Currently, the disposed waste in landfill feeds a biogas extraction system, through probes and channel network, which transforms the gas naturally produced by waste into electricity (an average of 54 million kWh per year). In 2006, the landfill has obtained the ISO (International Organization for Standardization) 14001 environmental certification, which highlights the AMIU (an Italian acronym that stands for Multiservice Company and Urban Hygiene) commitment for the implementation of a management system aimed at protecting the environment through the use of best available technologies and the use of transparent business processes.

The landfill covers the bottom valley of the Cassinelle creek with a surface of 0.52 km^2, while the entire catchment area is 1.21 km^2 (Fig. 1). The landfill is located in the mountains upstream of Genoa (Italy). It spans from a height of 350 to 600 meters above the sea level with an average slope of about 30%. This site is considered as one of the rainiest areas of Italy with an annual rainfall of about 1400 mm; A few kilometres from this place, the maximum 24-hour precipitation of about 950 mm was recorded in year 1970: this is still the heaviest storm in Italy of any time.

This location was chosen in the Sixties mainly due to its distance from Genoa city centre, presenting the advantage to be far away from urban settlements. On the other hand, the location on the upper stream of the Casinelle creek enhances the strong interaction with hydrological processes and its connection with slope stability problems. Slope stability, in fact, is mainly affected by the level of leachate inside the landfill that, in this case, it is also strongly correlated with the hydrology of the catchment and, in particular, with rainfall infiltration fluxes. The leachate is drained through a drainage system installed inside the landfill body into two reinforced concrete reservoirs of 14000 m^3 as total volume situated at the landfill outlet. These reservoirs are used to regulate the leachate outflow toward the treatment plant, located at the bottom of valley in the western area of Genoa city, that cannot exceed a given threshold value of about 125 m^3 h^{-1}. During January 2014 the leachate reservoirs were completely filled due to the extended severe rainfall occurred on December 2013. After the analysed period 2013-2014, here described, the landfill is now under enlarging works with new caps both in the upper and bottom areas. The landfill is nowadays divided in two zones (Fig. 2): the oldest part, called Scarpino 1 (0.26 km^2), located in the upper area of the catchment, and the recent part, called Scarpino 2 (0.26 km^2, divided into Lot I and Lot II), and composed by a central part (0.20 km^2) and a bottom one (0.06 km^2).

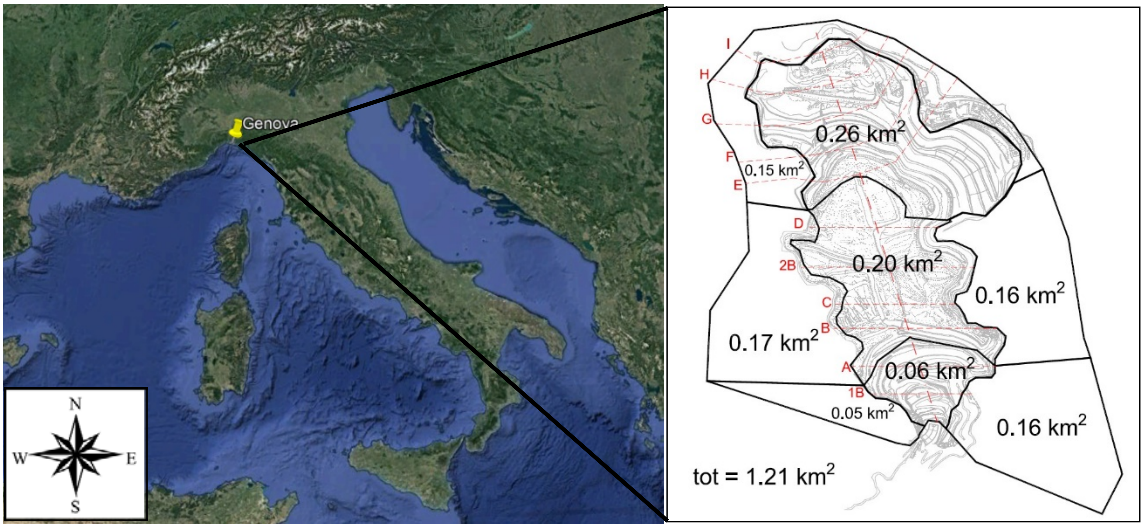

Fig. 1. Geographical area of Scarpino landfill, near Genoa city, North-West of Italy (left). The catchment area of the upper stream of the Cassinelle basin (right) closed at the landfill outlet with the calculation cross sections. The figure shows also the entire hydrological catchment (1.21 km^2), the occupied area by the landfill (0.26 + 0.20 + 0.06 = 0.52 km^2) and the external hill slope areas (0.15 + 0.17 + 0.16 + 0.05 + 0.16 = 0.69 km^2) that partially drains into the landfill

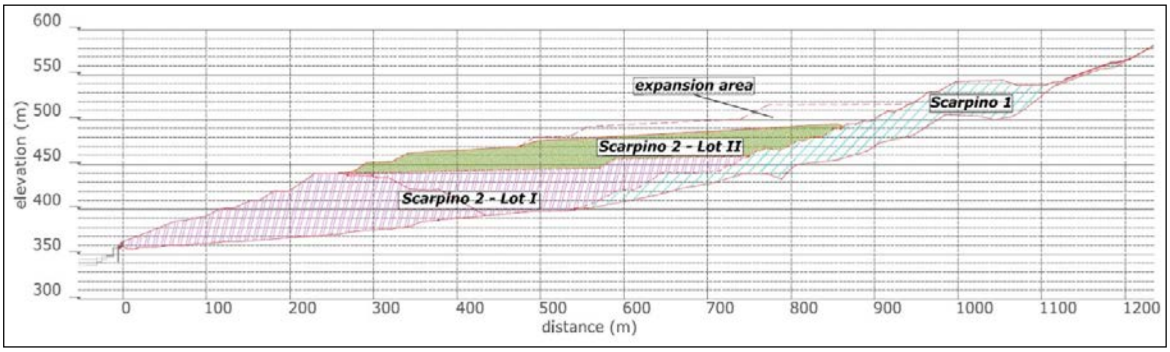

Fig. 2: Longitudinal section of the Scarpino valley with the main layers of the landfill

The Scarpino 1 and the Scarpino 2 bottom sectors present a definitive surface cap to avoid rainfall infiltration according to Italian regulations. The central area of Scarpino 2 shows a surface temporary cap made by silty compacted soil liner with mean saturated hydraulic conductivity of 10^{-7} m s^{-1}. The definitive cap of this part is now under construction, in order to dispose the area for the realization of a planned expansion of the landfill (Scarpino 3).

3. Hydrological monitoring system setup

The current hydrological monitoring system of Scarpino landfill has been designed in 2012, as an update of the previous one, following the recommendations given by the Province of Genoa after the approval of the expansion project of Scarpino 2 in August 2011.

Acquired data instruments are sent to a main server via a specific communication wireless network. This new monitoring system has been planned as a real time system characterized by a continuous and automatically data reading and recording to the monitoring mother stations located at central offices in the upper part of Scarpino landfill. This is the most important difference and upgrade in comparison with the previous monitoring system, which was only constituted by manual and periodical data reading. In fact, from the central station is now possible to: (i) do a remote check of all installed measuring instruments showing any possible instruments failure, (ii) plot all data in real time (Fig. 3), (iii) and display alarms due to threshold value exceeding.

The instrument installation of the current monitoring system took place at different steps. In 2013, an experimental monitoring system (called MO.SE.M.V., an Italian acronym which stands for Experimental Module of Monitoring and Visualization) has been realized to verify the operating working of instruments and their reliability. At the beginning, it was composed by 7 piezometers, 2 soil moisture probes, 1 flowmeter and 1 level sensor. Later in March 2014, following a very intense rainy period, an extension of the MO.SE.M.V. project has been carried out. During this second installation step, 6 piezometers, 2 level sensors and 1 soil moisture probe have been added.

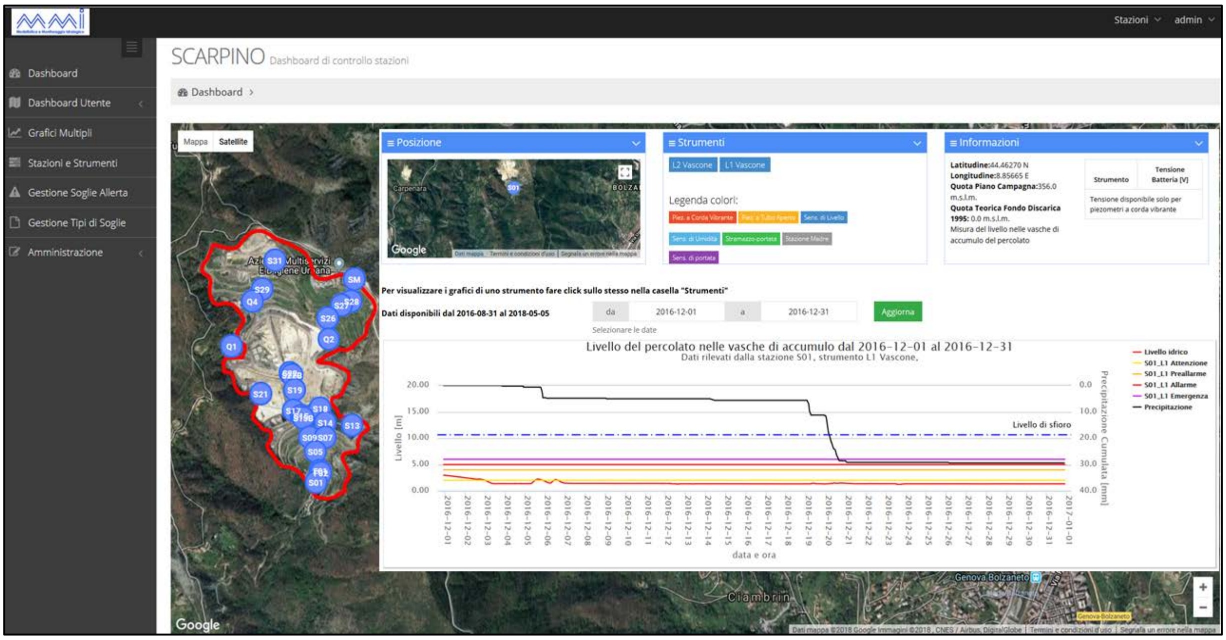

Fig. 3. Dashboard visualization of the monitoring system (left). A zoom, when you click on a station (in this example, S01), of the leachate level data (right) measured by a water level sensor

In total, the hydrological monitoring system, here reported, is composed by nineteen measuring points and two control rooms where data are acquired, as shown in Fig. 4. In particular:

- two weather stations (by Davis in purple rhombus, and by Lastem in pink circle) at the top of the landfill;
- four soil moisture monitoring units by Sentek (U03, U07, U16, U20, respectively located from the bottom part of the landfill to the upper one), equipped with probes for soil water content profile;
- sixteen open pipe piezo-resistive cell (by Adcon Telemetry) for leachate level and pressure measures;
- four vibrating wire piezometers (by Sisgeo) at different depths from the surface (from 25 to 60 m) for leachate pressure measures;
- one flow meter station, the 2150 Area Velocity Flow Module by ISCO (azure dot);
- two piezometers placed in the central area of the landfill along the its perimeter;

two level sensors placed in one of the leachate reservoirs for measuring the storage volume.

A detailed description of the characteristics for each sensor of the MO.SE.M.V. monitoring network of Scarpino landfill is presented in Appendix A at the end of the paper.

4. Landfill hydrological water balance

Leachate flow rate is closely linked to precipitation, surface run-off, and infiltration or intrusion of groundwater percolating through the landfill. The climate has also a great influence on leachate production because it affects the input of precipitation and losses through evaporation. In addition, leachates production depends on the nature of the waste itself, namely its water content and its degree of compaction into the tip. The production is generally greater whenever the waste is less compacted since compaction reduces the filtration rate.

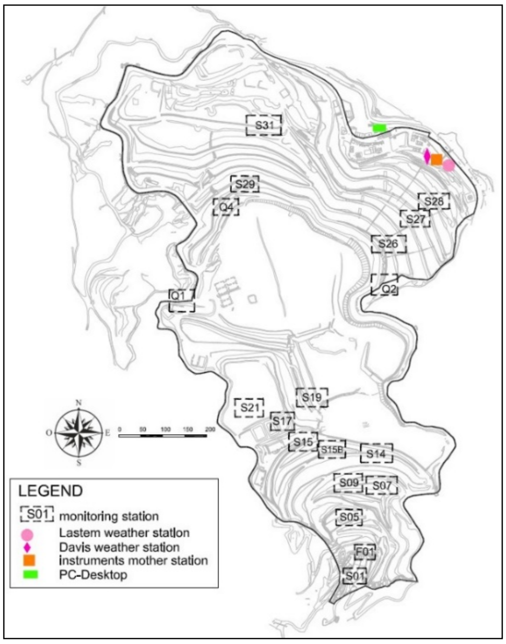

Fig. 4. Map of the installed instruments in the Scarpino landfill

In this section, we show the hydrological water balance of Scarpino 1 and 2 areas, comparing the leachate volume variation obtained by the balance equation and the section discretizing method. The monitoring system plays an important role in the leachate volume evaluation, providing measurements for the estimation of each balance equation terms and for the section discretizing method. In particular, the balance is assessed on a monthly scale in order to take into consideration the complex effects of this peculiar basin on its hydrological response. The reference period considers the time window between September 2013 and June 2014, which is a first test bed period to analyze the landfill monitoring system data and its possible applications even at its early stages of development. A first balance is determined considering the landfill of Scarpino 1 and the surrounding area (hereafter referred to as the "Scarpino 1 hydrological balance"), while a second balance is calculated considering the Scarpino 2 sector (named as "Scarpino 2 hydrological balance").

4.1. The Scarpino 1 area

The oldest area of the Scarpino landfill (called Scarpino 1), which started out as an uncontrolled accumulation zone since the 1960s, does not appear to be hydrologically separated from the external catchment area that surrounds it, and where it forms part of its river basin. Otherwise, Scarpino 1 is separated by a clayey impermeable layer of about 1 m thickness from the more recent area of the landfill (Scarpino 2). These observations, together with the available piezometric measurements, support the hypothesis of the presence of a separate leachate layer in Scarpino 1 as regards Scarpino 2.

4.1.1. The Scarpino 1 hydrological balance

Scarpino 1 is not hydrologically disconnected from its external catchment area; hence, this peculiarity has been evaluated in the balance considering the total contributing area composed by the landfill area and its external part. The hydrological balance is calculated on monthly basis, from September 2013 to June 2014, in order to consider the overall effect of the basin on the hydrological response. Finally, the leachate volume variation, obtained by equations, is compared with the leachate volume variation calculated by the available piezometric measurements.

The Scarpino 1 hydrological balance is modelled according to the Eq. (1):

$$P_T - D - ET - Q_f = \frac{dW_{S_1}}{dt} \qquad (1)$$

where: P_T is the total precipitation; D is the surface runoff; ET is the evapotranspiration; Q_f is the outlet filtration flow; $\frac{dW_{S_1}}{dt}$ is the liquid volume variation in Scarpino 1.

These input to calculate the hydrological balance take into account the entire contributing area, (i.e. inside and outside the boundaries of Scarpino 1, since they have different infiltration characteristics), both for the total precipitation (P_T), the surface runoff (D), the evapotranspiration (ET), and the filtration flow (Q_f) overall collected by the drainage cross line at Scarpino 1 downstream, that conveys the leachate in the covered channel located over the landfill bottom. This culvert runs downstream under the Scarpino 2 accumulation area and it delivers the intercepted leachate towards the two accumulation reservoirs situated at the landfill outlet. The evapotranspiration is calculated based on the Hargreaves equation. The contribution of Scarpino 1 area to the evapotranspiration fluxes is separated from the external catchment area, in order to consider the different land use which characterizes these two zones (discontinuous turf in Scarpino 1, broad-leaved woods and pine forests in the external area of Scarpino 1 catchment); hence an overall weighted parameter of evapotranspiration was estimated.

The filtration flow (Q_f) is evaluated with the Darcy equation, considering an appropriate filtration section into Scarpino 1, deduced from the reconstruction of cross-sections of the landfill volume and piezometric measurements. The interaction between input and output produces a liquid volume variation $\frac{dW_{S_1}}{dt}$ within the domain obtained as a result from the balance equation.

Expliciting each terms, the equation balance (Eq. 1) becomes Eq. (2):

$$\begin{aligned} & P \cdot A_C - (P \cdot A_{S_1} \cdot \varphi_{S_1} + P \cdot A_{S_{1E}} \cdot \varphi_{S_{1E}}) + \\ & -ET \cdot A_C - k \cdot A_f \cdot i = \frac{dW_{S_1}}{dt} \end{aligned} \qquad (2)$$

where: P is the total precipitation per month; A_C is the catchment area given by the surface of Scarpino 1 (A_{S_1}) equal to 0.28 km^2, and the external landfill area ($A_{S_{1E}}$) equal to 0.16 km^2; ϕ_{S_1} is the Scarpino 1 surface runoff coefficient assumed equal to 0.6; $\phi_{S_{1E}}$ is the surface runoff coefficient of its external area, assumed equal to 0.3; k is the saturated permeability of Scarpino 1, estimated equal to $1 \cdot 10^{-5}$ m s^{-1}; A_f is the filtration section area, obtained as an average of the wet areas of sections G and H (Fig. 5) where the calculation domain is subdivided; i is the hydraulic grade line, evaluated as the slope of the reconstructed piezometric surface based on the available measurements.

Particularly in this equation, the term of surface runoff is explicited considering the two contributions of Scarpino 1 area and the external part.

The liquid volume variation, evaluated on a monthly basis, is then compared with the one obtained from the leachate levels observed in Scarpino 1 with a total liquid volume (Eq. 3) valued as:

$$\overline{W_{S_1}} = n \cdot W_{sat} \qquad (3)$$

where: n is the waste porosity, assumed equal to 0.3 (Min et al., 2010), and W_{sat} is the total saturated waste volume.

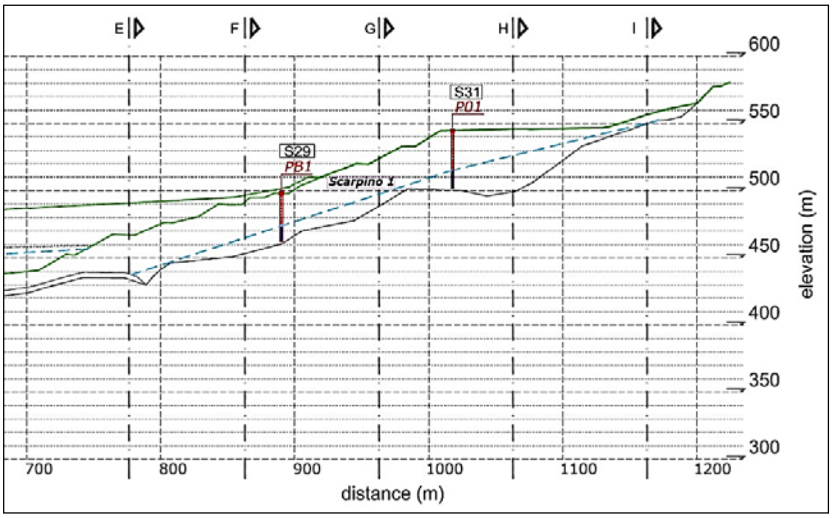

Fig. 5. Longitudinal section with the calculation scheme adopted to evaluate the liquid volume W_{S1} inside Scarpino 1. The landfill surface is shown in green line, the piezometric surface in dashed light blue, while the landfill bottom in black

The saturated waste volume within Scarpino 1 is calculated using the section discretizing method, i.e. dividing the domain into 5 sections (E, F, G, H, I) with around 100 m distance and considering the volume portions across each section. The piezometric surface is reconstructed using the piezometers measurements, in particular the leachate levels measured by the piezometers installed in P01 well of S31 station and in PB1 well of S29 station, assuming that, along the longitudinal development of the landfill, the piezometric line is equal to the one which joins the levels of the two considered piezometers. Therefore, by extending this line upstream and downstream it is possible to obtain the leachate level in the sub-sections.

For each considered day in the hydrological balance analysis, the piezometric level line equation (Eq. 4) is evaluated as:

$$h(x) = ax + b \tag{4}$$

with $a = \frac{h_{P01} - h_{PB1}}{\Delta x}$, where h_{P01} and h_{PB1} are the leachate levels measured, respectively, in P01 and PB1 wells, Δx is equal to the distance between the two wells; b is determined imposing the line crossing P01 or PB1 level.

According to this equation, leachate levels are obtained in sections E, F, G, H and I where the calculation domain is discretized. Finally, in order to calculate the wet area A for each section, relations as $A=f(h)$, which best fit the data, are obtained (Table 1).

The term $\frac{d\overline{W_{S_1}}}{dt}$ is monthly calculated as an algebraic sum of individual daily terms (Eq. 5), which are assumed to be equal to:

$$\frac{d\overline{W_{S_1}}}{dt} = \frac{\overline{W_{S_{1(t+1)}}} - \overline{W_{S_{1t}}}}{\Delta t} \tag{5}$$

Table 1. Relation between leachate level and wet area obtained for the Scarpino 1 discretization sections

SECTION	***A(h) = a*h²+b*h***
E	set to 0 as hypothesis
F	$2.75*h^2 - 0.021*h$
G	$4.51*h^2 - 0.009*h$
H	$5.55*h^2 - 0.017*h$
I	set to 0 as hypothesis

for the generic t day. The monthly overall values obtained by the hydrological balance equation and by the section discretizing method are reported in Table 2.

In order to compare monthly variations in leachate volume within Scarpino 1 obtained by the hydrological balance equation and by the section discretizing method, the Nash index E_{S_1} is calculated according to the Eq. (6):

$$E_{S_1} = 1 - \frac{\sum_i \left(\frac{dW_{S_1}}{dt}_i - \frac{d\overline{W_{S_1}}}{dt}_i \right)^2}{\sum_i \left(\frac{d\overline{W_{S_1}}}{dt}_i - M\left(\frac{d\overline{W_{S_1}}}{dt} \right) \right)^2} \tag{6}$$

where: each term considers the i-month; $M\left(\frac{d\overline{W_{S_1}}}{dt}\right)$ is the average monthly variation in leachate volume obtained by the section discretizing method.

The Nash index, E_{S_1} equal to 0.67 in Scarpino 1 shows a good correlation between the two methods applied to determine monthly variations in leachate volume.

Results in Fig. 6 also show a good match between rainfall and leachate volume variation trends of the two methods; this means a reasonable direct response of Scarpino 1 to precipitation. Indeed, this area, from its origins as an uncontrolled waste accumulation zone, is not hydrologically separated from the one outside the landfill which form part of the water basin it belongs to; moreover, on the landfill surface affected by Scarpino 1, the definitive coverage provided by future development projects has not been realized yet.

In order to better evaluate this relation, the correlation coefficient ρ is calculated for the two methods according to the Eqs. (7-8):

$$\rho_{P\frac{dW_{S_1}}{dt}} = \frac{\sigma_{P\frac{dW_{S_1}}{dt}}}{\sigma_P \sigma_{\frac{dW_{S_1}}{dt}}} \quad (7)$$

$$\rho_{P\frac{d\overline{W_{S_1}}}{dt}} = \frac{\sigma_{P\frac{d\overline{W_{S_1}}}{dt}}}{\sigma_P \sigma_{\frac{d\overline{W_{S_1}}}{dt}}} \quad (8)$$

where: $\sigma_{P\frac{dW_{S_1}}{dt}}$ is the covariance between P and $\frac{dW_{S_1}}{dt}$

σ_P is the standard deviation of P;

$\sigma_{\frac{dW_{S_1}}{dt}}$ is the standard deviation of $\frac{dW_{S_1}}{dt}$

$\sigma_{P\frac{d\overline{W_{S_1}}}{dt}}$ is the covariance between P and $\frac{d\overline{W_{S_1}}}{dt}$

$\sigma_{\frac{d\overline{W_{S_1}}}{dt}}$ is the standard deviation of $\frac{d\overline{W_{S_1}}}{dt}$.

Results show a correlation coefficient equal to 0.88 and 0.73 for the hydrological balance method and for the section discretizing method, respectively, demonstrating the direct correlation between precipitation and leachate volume variation.

Table 2. Monthly values of the Scarpino 1 hydrological balance in cubic meters, and of the liquid volume variation obtained from the hydrological balance and the section discretizing method.

	P_T	$P \cdot A_{S_1} \cdot \phi_{S_1}$	$P \cdot A_{S_{1E}} \cdot \phi_{S_{1E}}$	ET	Q_f	$\frac{dW_{S_1}}{dt}$	$\frac{d\overline{W_{S_1}}}{dt}$
	(m³/month)						
Sep 2013	60626	6463	11725	414	22409	7891	375
Oct 2013	62162	6627	12022	537	25243	5712	19457
Nov 2013	44076	4699	8524	0	26345	-4016	1939
Dec 2013	94341	10057	18245	433	25527	21834	-6389
Jan 2014	148470	15828	28713	1383	30086	43746	53386
Feb 2014	127969	13642	24748	2291	31774	30765	18640
Mar 2014	37622	4011	7276	2079	33955	-16975	-29239
Apr 2014	31476	3356	6087	1488	26864	-12406	-32374
May 2014	26472	2822	5119	1395	24763	-12748	-14233
June 2014	15848	1689	3065	892	22652	-15515	-10014

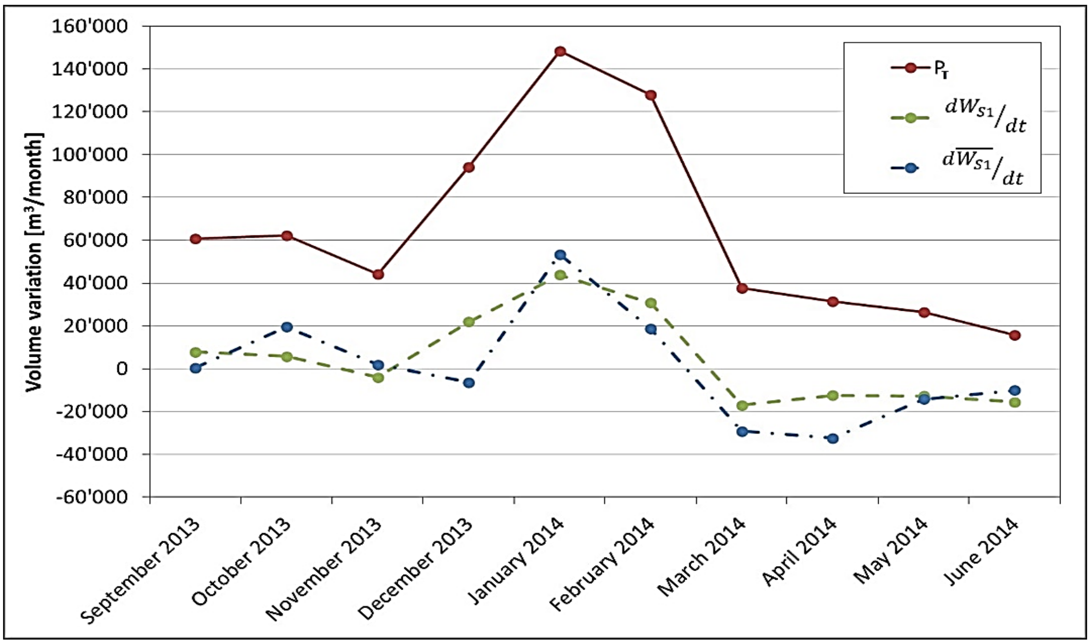

Fig. 6. Trends of the monthly variations in leachate volume within Scarpino 1 obtained by the hydrological balance Equation (green line) and by the section discretizing method (blue line) in comparison with the total precipitation volume (red line)

4.2. The Scarpino 2 area

The most recent area of Scarpino 2 lies above a waterproofing clay layer of about 1 m thickness and impermeable sheets; moreover, it is hydraulically separated from Scarpino 1 through a clay layer of about 1 m thick. Inside Scarpino 2, a further separation, is constituted by a clay layer placed between the Lot I and Lot II. Differently from Scarpino 1, the external catchment of Scarpino 2 does not contribute as input into the control volume. However, a portion of the surface runoff generated in Scarpino 1 and in its external catchment area which is able to infiltrate at the boundary area from Scarpino 1 to Scarpino 2, is considered and calculated in the Scarpino 2 hydrological balance. The drainage system inside the landfill produces an output flow whose flux directly goes into the two leachate accumulation tanks at the downstream end of the landfill.

4.2.1. Scarpino 2 hydrological balance

The Scarpino 2 hydrological balance is evaluated on Lot I, a site of leachate stratum controlled by the piezometric measurements scattered over this area. According to this, in order to estimate the incoming flow, the effect of the Lot II zone reservoir can be considered negligible on the monthly scale balance calculation; therefore, the input into the control volume are represented by the rainfall on the total surface of Lot II (waste accumulation area) of Scarpino 2, the surface runoff portion coming from Scarpino 1, and related external catchment area which infiltrates at the boundary area between Scarpino 1 and Scarpino 2. Considering the different infiltration characteristics between the waste accumulation area (Lot II) compared with the landfill downstream slope (Lot I), the surface runoff is assessed with a different flow coefficient for each of these areas. The two runoff coefficients values are evaluated considering the different compaction grade of the oldest waste stored in the landfill downstream slope (more impermeable) compared to the more recent ones in the accumulation operative area (more permeable). A further input is represented by the surface runoff portion coming from the upstream area of landfill, in particular from Scarpino 1 and its external catchment, which overall infiltrates near the slope discontinuity between Scarpino 1 and Scarpino 2. The infiltration of the surface runoff is separately computed in order to take into account the different contributions of corresponding areas, considering 20% of the surface runoff from Scarpino 1 and a 10% of the surface runoff of the external catchment area obtained by calibration.

As regards the output from the system, evapotranspiration and drained flow inside Scarpino 2 landfill are considered. The evapotranspiration is evaluated taking into account the different land use for the accumulation operative area (bare soil), and the downstream slope (mainly grassy). The output flow from the system is represented by the measurements carried out with an area-velocity sensor installed on the drainage pipe, which discharges into the leachate accumulation tanks. The interaction between input and output generates a liquid volume variation obtained as a result from the balance equation.

The Scarpino 2 hydrological balance is modelled according to the Eq. (9):

$$P_T + Q_D - D - ET - Q_{out} = \frac{dW_{S_2}}{dt} \qquad (9)$$

where: Q_D is the contribution deriving from the infiltration of the Scarpino 1 and its external catchment area surface runoff; D is the surface runoff; Q_{out} is the Scarpino 2 drained flow; $\frac{dW_{S_2}}{dt}$ is the Scarpino 2 liquid volume variation.

Expliciting each term, the Eq. (9) becomes Eq. (10):

$$P \cdot A_{S_2} + (\alpha_{S_1} \cdot P \cdot A_{S_1} \cdot \Phi_{S_1} + \alpha_{S_{1E}} \cdot P \cdot A_{S_{1E}} \cdot \Phi_{S_{1E}}) + -(P \cdot A_{S_{2M}} \cdot \Phi_{S_{2M}} + P \cdot A_{S_{2V}} \cdot \Phi_{S_{2V}}) - ET \cdot A_{S_2} - Q_{out} = \frac{dW_{S_2}}{dt} \qquad (10)$$

where: A_{S_2} is the Scarpino 2 surface equal to 0.30 km^2, α_{S_1} is the contribution coefficient of the Scarpino 1 surface runoff assumed equal to 0.2, $\alpha_{S_{1E}}$ is the contribution coefficient of the Scarpino 1 external catchment area of surface runoff assumed equal to 0.1, $A_{S_{2M}}$ is the Scarpino 2 accumulation area surface equal to 0.21 km^2, $\Phi_{S_{2M}}$ is the surface runoff coefficient of Scarpino 2 accumulation area assumed equal to 0.8, $A_{S_{2V}}$ is the Scarpino 2 downstream slope surface, equal to 0.09 km^2, $\Phi_{S_{2V}}$ is the surface runoff coefficient of Scarpino 2 downstream slope, assumed equal to 0.6, Q_{out} is the output flow measured by the area-velocity sensor installed at the end of the Scarpino 2 drainage system.

Similarly, to the previous Scarpino 1 balance evaluation, from the balance equation it is possible to evaluate the liquid volume variation by discretizing the time on a monthly basis. This variation is compared with the one calculated on the leachate levels measurements available in Scarpino 2.

In particular, the leachate volume $\overline{W_{S_2}}$ of Scarpino 2 is calculated using the same procedure, previously described for Scarpino 1, considering a porosity equal to 0.5. For each section where the domain is discretized (Fig. 7), the leachate level is obtained as a function of the measured levels by the piezometers installed in P13E well of S15 station and in P24A well of S05 station. The reference piezometric surface along the landfill longitudinal section is obtained with two linked lines: the first one joining the piezometers levels in P24A and P13E wells, while the second one joining measured levels in P13E well with the first line of drainage located at the border between Scarpino 1 and Scarpino 2. This piezometric surface is also verified according to the first experimental measurements in P10A-bis, P08C and P06A-bis wells. The leachate levels in the sub-sections are obtained from the intersection of the reconstructed piezometric line with each cross-section.

The equations of the two lines (Eq. 11-12) which the piezometric surface is divided to, are below reported:

$$h_1(x) = a_1 x + b_1 \tag{11}$$

between P24A and P13E

$$h_2(x) = a_2 x + b_2 \tag{12}$$

between P13E and drainage line located at the borders of Scarpino 1 and Scarpino 2

with: $a_1 = \frac{h_{P13E} - h_{P24A}}{\Delta x_1}$, where h_{P13E} and h_{P24A} are the measured leachate levels in P13E and P24A wells respectively, Δx_1 is equal to the distance between the two wells; $a_2 = \frac{h_D - h_{P13E}}{\Delta x_2}$ where h_D is the height of the drainage line located at the border between Scarpino 1 and Scarpino 2, Δx_2 is equal to the distance between P13E well and the drainage line; b_1 and b_2 are obtained imposing the passage of lines in P13E measured levels.

According to these equations, the leachate levels in 1B, A, B, C, 2B, D sections are obtained. Finally, relations as $A=f(h)$ that best fit the data are evaluated in order to determine the wet area for each discretizing section (Table 3).

Similarly, to Scarpino 1 domain, the $\frac{d\overline{W_{S_2}}}{dt}$ term is monthly calculated as the algebraic sum of the daily terms (Table 4). The monthly overall values obtained by the hydrological balance equation and by the section discretizing method are reported in Table 4.

The comparison shows good results between the trend of leachate volume variations determined by the hydrological balance compared to those calculated through the section discretizing method (Fig. 8). In order to evaluate this, the Nash index E_{S_2} is calculated according to the Eq. (13):

$$E_{S_2} = 1 - \frac{\sum_i \left(\frac{dW_{S_2}}{dt}_i - \frac{d\overline{W_{S_2}}}{dt}_i \right)^2}{\sum_i \left(\frac{d\overline{W_{S_2}}}{dt}_i - M\left(\frac{d\overline{W_{S_2}}}{dt} \right) \right)^2} \tag{13}$$

where: each term considers the i-month; $M\left(\frac{d\overline{W_{S_2}}}{dt}\right)$ is the average monthly variation in leachate volume obtained by the section discretizing method.

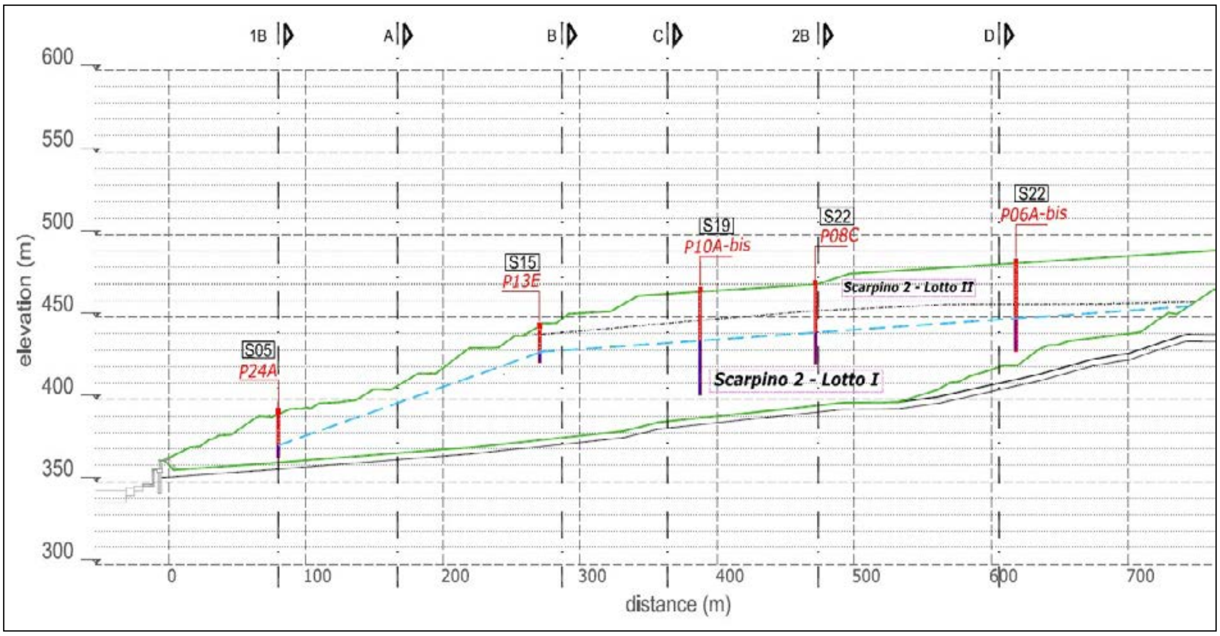

Fig. 7. Longitudinal section with the calculation scheme adopted to evaluate the liquid volume W_{S2} inside Scarpino 2. The landfill surface is shown in green line, the piezometric surface in dashed light blue, while the landfill bottom in black.

Table 3. Relation between leachate level and wet area obtained for the Scarpino 2 discretization sections

SECTION	***A(h) = a*h+b***
1B	set to 0 as hypothesis
A	210*h-2985.0
B	235.53*h-5826.2
C	268.41*h-4467.5
2B	243.27*h-3868.7
D	219.32*h-2284.0

Table 4. Monthly values of the Scarpino 2 hydrological balance terms and of the liquid volume variation obtained from the hydrological balance and from the section discretizing method

	P_T	$P \times A_{S_{2M}} \times \Phi_{S_{2M}}$	$P \cdot A_{S_{2V}} \cdot \Phi_{S_{2V}}$	***ET***	Q_{out}	$\alpha_{S_1} \cdot P \cdot A_{S_1} \cdot \Phi_{S_1}$	$\alpha_{S_{1E}} \cdot P \cdot A_{S_{1E}} \cdot \Phi_{S_{1E}}$	$\frac{dW_{S_2}}{dt}$	$\frac{d\overline{W_{S_2}}}{dt}$
	(m^3/month)								
Sep 2013	41154	23422	7126	9	5361	4690	2171	12097	10320
Oct 2013	42197	24015	7307	7	7001	4809	2226	10901	30372
Nov 2013	29919	17028	5181	0	5148	3410	1578	7551	-7724
Dec 2013	64040	36447	11089	0	10094	7298	3378	17086	10490
Jan 2014	100784	57359	17451	0	19551	11485	5317	23225	23368
Feb 2014	86867	49438	15041	60	29128	9899	4582	7680	4063
Mar 2014	25539	14535	4422	183	34281	2910	1347	-23624	-51399
Apr 2014	21367	12160	3700	93	12909	2435	1127	-3933	9313
May 2014	17969	10227	3111	111	60000*	2048	948	-52485	-75136
June 2014	10758	6123	1863	69	4091	1226	567	406	-40400

** Due to an obstruction problem that compromised the area-velocity sensor measures, the May 2014 Q_{out} value is obtained from calibration.*

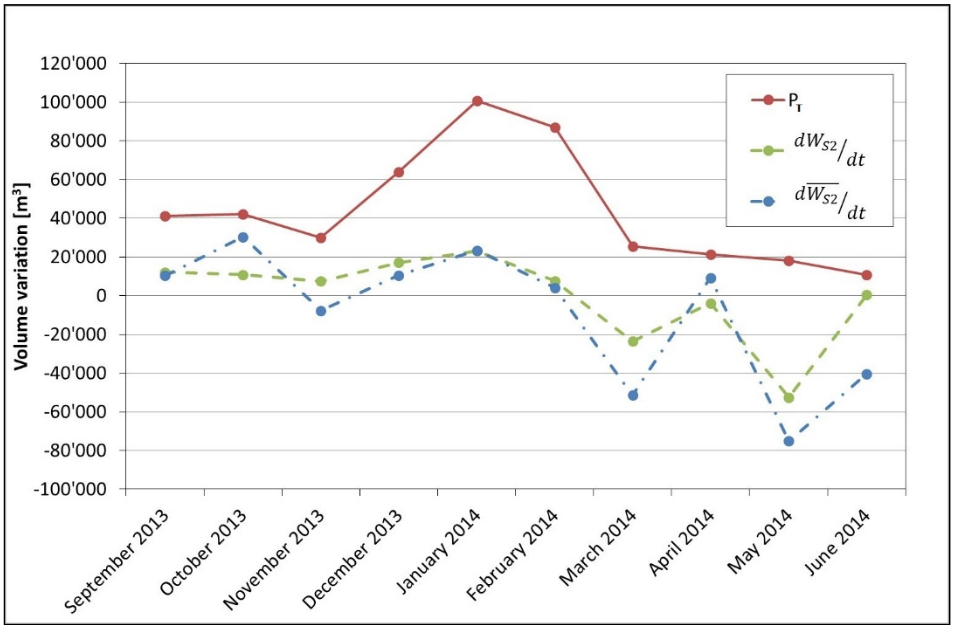

Fig. 8. Trends of the monthly variations in leachate volume within Scarpino 2 obtained by the hydrological balance equation (green line) and by the sections discretizing method (blue line) in comparison with the total rainfall volume (red line)

Also in Scaprino 2, the Nash index E_{S_2} equal to 0.66, shows a good match between the two methods applied to determine monthly variations in leachate volume.

Comparing with Scarpino 1, the Scarpino 2 landfill does not show a significant direct rainy response and it is more affected by the drainage system. The different influence of the precipitation in the leachate production of Scarpino 1 in comparison with Scarpino 2 is also observable in the different level excursion measured in the piezometers of the two landfill areas: more significant in the Scarpino 1 piezometers than in the Scarpino 2 ones.

In order to support this observation, the correlation coefficient ρ is calculated for the two methods according to the Eqs. (14-15):

$$\rho_{P\frac{dW_{S_2}}{dt}} = \frac{\sigma_{P\frac{dW_{S_2}}{dt}}}{\sigma_P \sigma_{\frac{dW_{S_2}}{dt}}} \quad (14)$$

$$\rho_{P\frac{d\overline{W_{S_2}}}{dt}} = \frac{\sigma_{P\frac{d\overline{W_{S_2}}}{dt}}}{\sigma_P \sigma_{\frac{d\overline{W_{S_2}}}{dt}}} \quad (15)$$

where: $\sigma_{P\frac{dW_{S_2}}{dt}}$ is the covariance between P and $\frac{dW_{S_2}}{dt}$

σ_P is the standard deviation of P

$\sigma_{\frac{dW_{S_2}}{dt}}$ is the standard deviation of $\frac{dW_{S_2}}{dt}$

$\sigma_{P\frac{d\overline{W_{S_2}}}{dt}}$ is the covariance between P and $\frac{d\overline{W_{S_2}}}{dt}$

$\sigma_{\frac{d\overline{W_{S_2}}}{dt}}$ is the standard deviation of $\frac{d\overline{W_{S_2}}}{dt}$.

Results show a correlation coefficient equal to 0.54 both for the hydrological balance method and for the section discretizing method, indicating a minor correlation between precipitation and leachate volume variation in comparison with Scarpino 1.

5. Conclusions

Rainfall infiltration processes significantly affect the leachate production with relevant problems on landfill slopes stability, due to the accumulation of leachate into landfill body, and on storage and depuration treatment.

The paper describes the experimental module of a real-time monitoring system for a complex and peculiar landfill in the Italian Apennine mountains near Genoa city. Data series, acquired from the beginning of September 2013 to end of June 2014, a period characterized by many rainfall episodes which also affected the leachate production with a high increase of its level in the landfill body and the saturation of reservoirs system, are reported and discussed in this paper.

The monitoring system is able to provide useful information for the overall hydrological response assessment of the landfill, characterized by complex dynamics, due to the morphological characteristics of the site, the dump heterogeneity, and the plant specificities (subdivision into different accumulation areas, waterproofing system, drainage system, etc.). These preliminary information, available during this first phase of the monitoring system development, are useful to reconstruct a qualitative-quantitative trend of the landfill hydrological balance on a monthly scale. It is possible to evaluate the hydrological response of the landfill, subjected to rainfall events of different intensities with the production of leachate volumes. The Scarpino 1 shows an almost direct response to precipitation, since it is not hydrologically separated from the areas surrounding the landfill which forms part of the catchment basin and it does not have a definitive dump cap yet. On the other hand, the Scarpino 2, in particular the area affected by Lot I, shows a much less significant response to precipitation, relying on a disconnection of the external catchment area, and on a partial waterproofing between the two lots.

Although in its initial development state, this monitoring system shows which measures are necessary in order to evaluate the hydrological water balance of landfill overall, and to assess the main conclusions on landfill hydrological behaviour. Last but not least, the monitoring of hydrological fluxes is an important issue to define the forecasting and control of leachate production.

Appendix

The monitoring system consists of the following components: meteorological measures, soil moisture profiles, groundwater levels, leachate and surface water flow monitor. In particular, three subnets are installed in parallel and in a continuous and remote-controlled way:

• Adcon network, composed by measures of open pipe piezometers and Sentek humidity probes at different depths: the wireless communication with the main board is at 400 MHz of frequency with data recorded every 5 or 30 minutes (according to the instrument);
• Campbell network which conveys the wireless signal of the vibrating wire piezometers at 2.4 GHz of frequency with data recorded every 30 minutes;
• Isco network sends the signal of the flow meter Area-Velocity with data recorded every 5 minutes and transmitted via GSM modem module.

Soil moisture probes provide ground humidity measures of the covering surface of landfill. Each probe is equipped with 3 or 4 sensors, in order to control the moisture level of different layers of the capping.

This groundwater level monitoring system is composed by two kinds of instruments (Adcon and Campbell):

• Adcon: open pipe piezometers equipped with piezo resistive sensor: the precision of the sensor is equal to 0.1% of maximum measured value. Range of measure: 0-3 bar, temperature range: -40°C/+80°C

• Campbell: vibrating wire piezometers with a range of measure of 0-10 bar and a precision of 0.5% and temperature range between 0/+80°C

The leachate flow station is equipped with a pressure-velocity ultrasonic sensor, while the surface water flow stations are equipped with level sensors located upstream of a triangular thin-plate weir.

Each measuring station is equipped with a datalogger and modem which receives the collected data from instruments and sends them to the monitoring central station using radio signals.

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