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Serial water balance method for predicting leachate generation in landfills

This paper presents the "Serial Water Balance" method for predicting leachate generation in landfills. This procedure makes it possible to calculate the total leachate likely to be generated, by estimating an individual cell by cell water balance. This new development considers the interaction effects between cells, through the execution of simple field capacity tests on solid waste samples under different loading conditions. The procedure described in this paper simulates the effect induced by fluid percolating from a cell at an upper layer to cells in the immediately subjacent layer.

The method described here was applied to the landfill in Nuevo Laredo, Tamaulipas (Mexico), after first ascertaining information regarding: duration of construction time, exposure time, surface area, the quantity of waste, number of confining cells, and local weather conditions.

In a full-scale test case the suggested method has predicted 67% of the leachate produced in a period of 4 years. Further testing and more detailed analysis of the composition of the waste used in the calculations, may improve the accuracy in predicting leachate production.

Even though this SWB methodology was applied to a landfill subject to extreme climatological conditions (high daytime temperatures), it is possible to adapt the methodology to solid waste disposal sites in regions with more humid or moderate climates.

Ma. Teresa Orta de Velásquez
Reynaldo Cruz-Rivera
Neftalí Rojas-Valencia
Ignacio Monje-Ramírez
Institute of Engineering, Cub.214 Coordination of Environmental Engineering, National Autonomous University of Mexico, Post Box 70-472, Coyoacán 04510, Mexico D.F.

Jorge Sánchez-Gómez
SICA S.A de C.V. Nubia 52, Col. Clavería, Azcapotzalco, 02080 Mexico D.F.

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Corresponding author: Ma. Teresa Orta de Velásquez, Instituto de Ingenieria, Cub. 213, Coordinación de Ingenieria Ambiental, Universidad Nacional Autónoma de Mexico, Coyoacan 04510, Mexico D.F.
Tel: (52)(55) 622–3320 Extn. 17, Fax: (52)(55)616–2164
E-mail: tol@pumas.iingen.unam.mx

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Introduction

Leachates are fluids generated by the release of excess water from solid waste, and by seepage of rain water through a strata of solid waste that is basically in a state of decay (Uguccioni 1997). Leachate is characterised by its high content of organic constituents, metals, acids, dissolved salts, and micro-organisms. These characteristics constitute a flow highly aggressive to the environment, with a contamination potential exceeding that of several industrial-waste materials (Orta *et al.* 1999). Pollution of aquifers by leachates renders the aquifers unavailable for exploitation for a long time, because their rehabilitation can take several years. An estimate of leachate generation throughout the life of a landfill is valuable in order to minimise the impact of this on the environment (Khanbilvardi *et al.* 1995, Orta *et al.* 1999).

Several computer programmes for estimating leachate generation have been developed, for example: Hydrology Evaluation Leachate Performance (HELP) (U.S. EPA 1984), FULLFILL (Noble 1991), and SOILINER (Johnson 1986). All of them are based on the so-called Water Balance Method (WBM) developed by the U.S. Environment Protection Agency (Fenn *et al.* 1975). Other programmes also provide one-dimensional numerical solutions by using finite difference tools. Each programme has inherent advantages regardless of its general limitations. These limitations are:

1) only a single level is taken into account for the calculation without considering changes suffered by the material on top, or by the solid waste when the depth or height of the landfill is increased;
2) the fact that cells are not built simultaneously, nor at the same season of the year and because many disposal sites that want to profit from the available space at the site, fail to close the cell on a daily basis with the recommended layer of soil (El-Fadel *et al.* 1997);
3) the interaction between cells induced by the construction of adjacent cells to produce strips, and/or the construction of other cells on top to create layers is not taken into account;
4) these models fail to simulate the space and time distribution of leachate production at the landfill during operation and subsequent to closing of the cell with the layer of soil.

The purpose of this paper is to present the Serial Water Balance method for estimating leachate generation at solid waste disposal sites. The method incorporates the following additional elements: cell construction time and the length of time a cell is exposed to the weather; field capacity and its variation according to the increasing depth or height of a landfill; plus those parameters affecting water balance analysis, such as rainfall, evapotranspiration, field capacity and water infiltration. Using this information it is possible to calculate a water balance for each cell within the landfill, and thus to calculate the quantity of water percolating through the solid waste, or the quantity of water required to provoke the start of leaching; and the interrelation of cells within the landfill.

Methodology of the SWB

The Serial Water Balance (SWB) method was developed at the Environmental Engineering Department of the Institute of Engineering, UNAM (National Autonomous University of Mexico). It was first implemented at the landfill in Nuevo Laredo, Tamaulipas (currently one of the best managed landfills in Mexico), operated by SETASA (Servicios de Tecnología Ambiental S.A.), a private subsidiary of ICA (Ingenieros Civiles Asociados), the largest private engineering company in Mexico.

Assumptions

The SWB makes some assumptions regarding landfill operating data, and the behaviour of leachate inside a landfill.

Firstly, to make the SWB method adaptable to most landfills in Mexico, and to other landfills around the world, the SWB assumes that landfills are constructed according to a standard configuration, as shown by Tchobanoglous *et al.* (1993). The confining cells are placed in layers, each cell being constructed above two cells in the layer below (see Fig. 1). Thus, the leachate produced in an upper cell filters down proportionally to the area of the two underlying cells (see Fig. 2).

Secondly, the SWB assumes that the leachate only flows down vertically, according to Darcy's Law for flow in saturated zones. Flows horizontally between cells in the same layer are not considered relevant for the calculations. This assumption was found to be justified because no leak of leachate was observed from the Nuevo Laredo macro-cell's

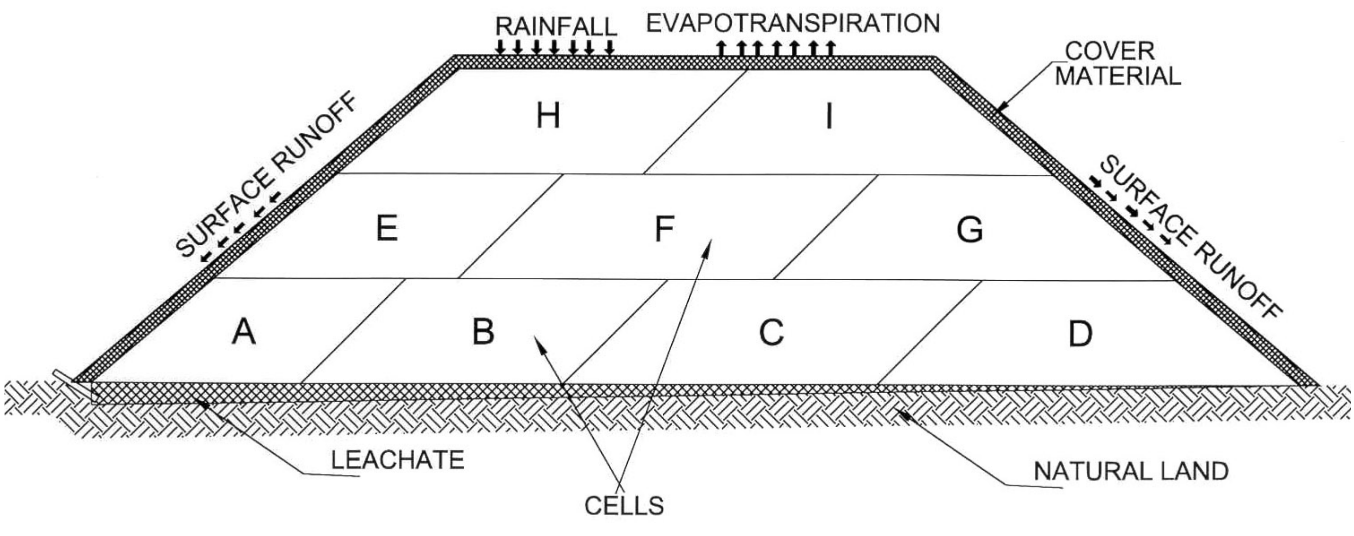

Fig. 1: Macro-cell showing the Function of the SWB Method.

lateral slopes. In other words, the leachate only filtered downward vertically inside the landfill.

Third, the evapotranspiration from a covered cell is taken into account only on rainy days, and for one day after each rainy day, until the water available is exhausted (Sánchez *et al.* 1996). This process occurred in each cell, until the cell was covered by new overlying cells.

The evapotranspiration was calculated as follows: first, the daily evapotranspiration height was calculated, as given by Fenn *et al.* (1975). Then the average number of rainy days in each month was calculated assuming that precipitation only occurred on alternate days. For example, if in March there were 5 rainy days, then rain was assumed to have fallen on days 2, 4, 6, 8, and 10, signifying that there was water available for evapotranspiration on those days plus on one day after each rainy day (i.e. also on days 3, 5, 7, 9 and 11). Thus it was assumed that, in March, there were 10 days with water available, resulting in a total evapotranspiration of 10 times the daily value of the evapotranspiration height, as calculated for each geographic location. For the rest of March, the evapotranspiration was considered to be minimal as there would have been no water available for evapotranspiration (see Sánchez *et al.* 1996). In actual fact, of course, rain does not always fall according to any set pattern. For example, it may rain according to different patterns (i.e. not only on alternate days) whilst still giving the same total number of rainy days. However, the SWB assumes the conditions that will create the smallest production of leachate, assuming the maximum number of days with water available water for evapotranspiration. In other words, the SWB underestimates the generation of leachate.

Using the same scenario of an average of five rainy days in a given month, it is also possible to over-estimate the generation of leachate. This would happen if rain fell on days 1, 2, 3, 4, and 5, signifying that evapotranspiration would occur on those five rainy days plus on day number 6, because water would only be available for evapotranspiration on those days. Thus, if on those five days a total rainfall of 10 mm were precipitated, and if the daily evapotranspiration were 1 mm, a total of 6 mm would be evapotranspirated in that month, and the rest of the water (4 mm) would have filtered down into the ground away from the phenomenon of evapotranspiration, thus contributing to leachate production.

One final assumption made by the SWB is that evapotranspiration ends when the water has filtered down to a depth of more than 30 cm (see Sánchez *et al.* 1996). This assumption was taken as valid for both covered cells as well as for cells still being constructed, because there was no information available regarding cells still in the process of construction.

Description of the procedure

The calculations are made using a simple Microsoft^y Excel spreadsheet. The SWB method takes a macro-cell as the basic unit for calculating the generation of leachate. This macro-cell in turn comprises other independent confinement cells located contiguously on both a horizontal plane and a vertical plane. Fig. 1 shows an example of a small macro-cell divided into nine cells.

The spreadsheet is constructed by dividing the information into 4 main categories:

Phase I (Data regarding the confining cells)

The first phase of the spreadsheet comprises seven columns, set out in the following manner.

Column 1 records the sequence of the confining cells that constitute the macro-cell (from the 1st to the 9th), where the 1st cell is the oldest and the 9th cell is the most recent.

Column 2 records the time during which the cells were being filled.

Column 3 records the length of filling time, plus the time after the cell was filled with refuse but before it was covered with soil. This time (filling time plus exposure time) is of vital relevance to the SWB method because it helps to determine the amount of water seeping into each cell because of rain, or evapotranspiring out of each cell.

Column 4 records the surface area of each confining cell, which can generally be taken as a constant value.

Column 5 records the amount of solid waste in each cell, calculated using Equation 1:

$$B_i = T_i \times Dd \quad (1)$$

where B_i is the refuse content in tons of cell i; T_i is the time taken in days for the construction of cell i; and Dd is the daily disposal of municipal solid waste at the landfill, given in tons/day.

Column 6 records the field capacity of the municipal solid waste, which was determined for five different depths using the methodology and the customised device designed for this experiment, as shown in Orta *et al.* (1999). The field capacity is expressed in cubic metres per ton of dry base solid waste.

Column 7 records the dry base waste content in tons, calculated using Equation 2:

$$S_i = B_i \times (1 - Hr) \quad (2)$$

where S_i is the amount of dry waste in tons; B_i is the amount of waste material contained in cell i; and Hr is the relative moisture of the waste material determined at the field and expressed as a percentage.

Phase II (weather parameters)

This phase records the climatological parameters, in Columns 8 to 10.

Column 8 records the rainfall height in mm, that the cell has collected during the time it was exposed to the weather. This information was obtained from historical data recorded at the Nuevo Laredo site, considering particularly the months during which each cell was exposed to changing climatic conditions. The rainfall height in mm was calculated using Equation 3:

$$hp_i = \sum_{i,j}^{9,12} D_{i,j} x\ (P_j / N_j) \qquad (3)$$

where hp_i is the rainfall height in mm recorded at i-th cell; $D_{i,j}$ is the number of days of exposure of the i-th cell during the j-th month; P_j is the rainfall height in mm during the j-th month; and N_j is the total number of days in the j-th month.

Column 9 records the adjusted evapotranspiration height in mm, as calculated from historical data on temperature and using equations given by C.W. Thornthwaite (Fenn *et al.* 1975). The results of the adjusted evapotranspiration height are expressed in monthly evapotranspiration heights. Determination of the total evapotranspiration height for each cell is made using climatological records corresponding to the different seasons of the year in which the cells were exposed to the weather, and using Equation 4:

$$ETp_i = \sum_{i,j}^{9,12} D_{i,j} x\ (ETp_j / N_j) \qquad (4)$$

where ETp_i is the evapotranspiration height in mm of the i-th cell; $D_{i,j}$ is the number of days of exposure of the i-th cell in the j-th month; P_j is the height of evapotranspiration during the j-th month; and N_j is the total number of days in the j-th month.

Column 10 records the percentage of rainfall loss through surface run-off, as a function of soil characteristics (Fenn *et al.* 1975). For this example, the value of the co-efficient (Ke) was taken as 0.13, the co-efficient for an intermediate sandy soil with a gradient of between 2% and 7%.

Phase III (water balance)

Phase III, Columns 11 to 16, comprises data related to the water balance.

Column 11 records data on water seeping down through the covering layer, and reaching the waste material inside the cells. This column, Column 11, corresponds to the algebraic sum of Columns 8 to 10 as calculated using Equation 5:

$$I_i = (hp_i - hp_i Ke) - ETp_i \qquad (5)$$

where I_i is the percolation height in mm of the i-th cell; ETp_i is the evapotranspiration height in mm of the i-th cell; hp_i is the rainfall in mm, recorded for the i-th cell; and Ke is the surface run-off co-efficient.

Column 12 records the height of moisture in mm contributed by the waste material within each of the confining cells, as calculated using Equation 6:

$$HB_i = (B_i \text{ x Hr x } 1000) / A \qquad (6)$$

where HB_i is the height in mm of moisture contributed by the waste material inside a confining cell; B_i is the weight in tons of waste material contained in cell i; Hr is the relative moisture of the waste material determined in the field and expressed as a percentage; and A is the surface area of the cell, in m^2.

Column 13 records the water height required to reach the field capacity of the solid waste, calculated using Equation 7:

$$HCc_i = (Cc \text{ x } S_i \text{ x } 1000) / A \qquad (7)$$

where HCc_i is the water height in mm required by the field capacity of the solid waste; Cc is the field capacity in mm of the solid waste; S_i is the weight in tons of dry waste; and A is the surface area of the cell, in m^2.

Column 14 records the amount of water required by the field capacity of the covering material. This data, relating to different kinds of soils, was presented by Fenn *et al.* (1975). The value for the example given in this paper is 300 mm/m, assuming a sandy mud soil 30 cm thick covering each cell.

Columns 15 and 16 record the result of the algebraic sum of Columns 11 to 14, to determine the height of water in mm percolating down into the confining cell, as calculated using Equation 8:

$$P_i = (I_i + HB_i) - (HCc_i + HCcMc) \qquad (8)$$

where P_i is the height of water in mm percolating into the cell; I_i is the height of the infiltration in mm coming from the surface; HB_i is the height of water in mm contributed by the waste materials; HCc_i is the height of water in mm required by the field capacity; and HCcMc is the height of water in mm required by the field capacity of the covering material.

If the result of Equation 8 is positive, in other words, if there is excess water which means that there is water percolation, the result is recorded in Column 15. If the result of Equation 8 is negative, this means water is lacking, and the result is recorded in Column 16. The water balance has been calculated thus far using the traditional approach and applying it to each individual cell.

Phase IV (Effect of the influence between cells)

Phase IV considers the influence existing between cells at different levels. The SWB assumes that each confining cell within a macro-cell satisfies totally or partially its own demand for moisture. Therefore, some cells will produce leachate, whereas others will fail to do so, as shown in Fig 2. This phenomenon that some cells produce leachate, but others do not is attributed to the time the cells remained exposed to the weather, and to the season of the year in which the cells were constructed. This is why in the case of landfills leachate may appear shortly after the construction of a new macro-cell has started, and/or before the time predicted for the start of leachate production using the WBM. Traditionally, the WBM calculation does not take into account the relationship between the individual confining cells (Khanbilvardi *et al.* 1995; Uguccioni 1997).

The main effect deriving from the relationship between the confining cells is that the leachate produced by any cell in an upper layer contributes to the moisture content of the immediately subjacent cell. If that subjacent cell receiving moisture from above, in addition to its own moisture, satisfies its water absorption demands, then a new leachate is produced. This process then affects the cells in the layer below, and so on downward to the bottom of the landfill, whence the leachate flows out into the collecting network, as shown in Fig. 2.

In the case of the example given in this paper, the Nuevo Laredo landfill which has the characteristics set out in Tables 1 and 2 the macro-cell will not begin generating leachate in the period 1st March 2001 (when construction was begun) to 1st July 2004, because there is a moisture deficit in the refuse confined within the landfill.

For example in Fig. 2, if cell G does not receive enough water from cell I to reach its own field capacity, there would be no possibility of water percolating down to cells C and D. If cells E and F produce leachate, they will contribute water to the cells below them (cells A, B and C). However, if cells A, B, C, and D have not satisfied their own water demand, even though some of them (A, B and C) have received water from other cells (E and F), no leachate will appear from the first level of the macro-cell. Tables 1 and 2 are the spreadsheet of the SWB method as applied to this example.

Application to the Nuevo Laredo case

Some assumptions had to be made regarding the Nuevo Laredo landfill, as the SWB method was being applied to a real case of an already existing landfill. It was necessary to make these assumptions because much of the data about the operation of the landfill was not accurate, for example: the surface area of each cell (some were in fact smaller and others larger), and the daily disposal rates were only average values of diverse data. The assumption was also made that data such as density, relative moisture and field capacity do not change, whereas in fact the kind of solid waste does change throughout the year.

In a normal case, the calculation of evapotranspiration height is made as mentioned within the Assumptions

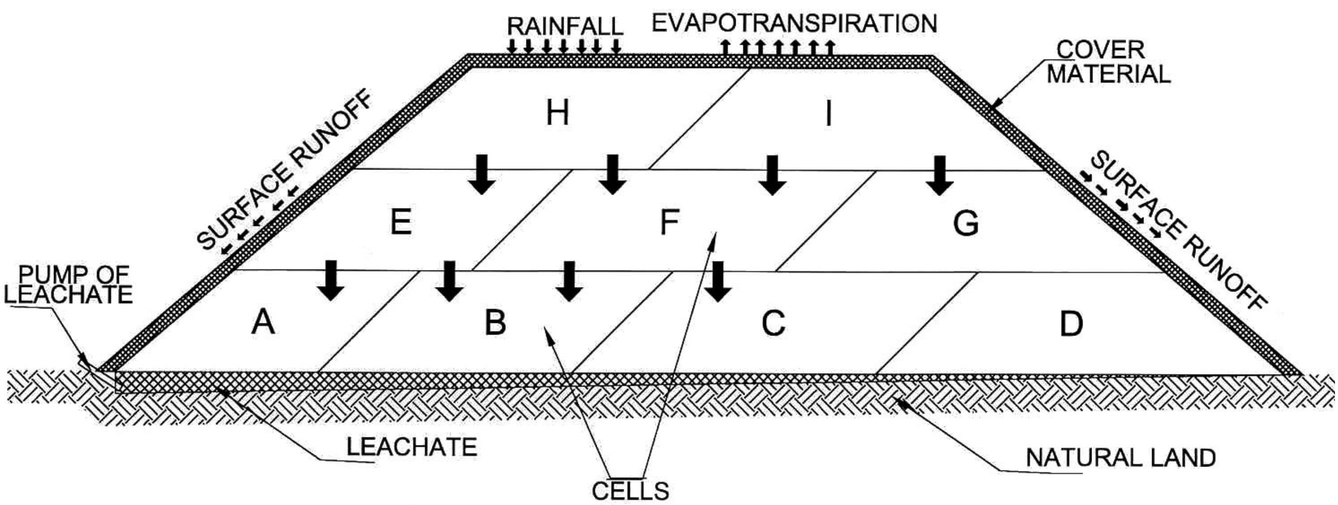

Fig. 2: Water Content Difference in Landfill Cells.

Table 1: Phases I and II of the SWB Method.

CONFINING CELLS										WEATHER PARAMETERS					
1	2				3				4	5	6	7	8	9	10
CELL	CONSTRUCTION TIME				EXPOSURE TIME				AREA A	WASTE CONTENT $B_i=T_i x Dd$	FIELD CAPACITY Cc	DRY WASTE CONTENT $S_i=B_i(1\text{-}Hr)$	RAIN FALL hp_i	EVAPO-TRANSP-PIRATION ETp_i	SURFACE RUN-OFF Ke
	START		END	DAYS	PERIOD										
				T_i	START		COVERED	D_i	m^2	tons	m^3/tons	tons	mm	mm	
A	01-Mar-01	to	15-Mar-01	17,00	01-Mar-01	to	10-May-01	70	2400	5440,00	0,48	4280,736	68,43	22,82	0,13
B	16-Mar-01	to	31-Mar-01	16,00	16-Mar-01	to	23-May-01	68	2400	5120,00	0,48	4028,928	98,50	26,64	0,13
C	01-Apr-01	to	15-Apr-01	16,00	01-Apr-01	to	08-Jun-01	68	2400	5120,00	0,48	4028,928	133,55	33,66	0,13
D	16-Apr01	to	30-Apr-01	15,00	16-Apr-01	to	15-Jun-01	60	2400	4800,00	0,48	3777,12	131,52	33,14	0,13
E	01-May-01	to	15-May-01	12,00	01-May-01	to	30-Jun-01	60	2400	3840,00	0,5	3021,696	150,10	38,33	0,13
F	16-May-01	to	31-May-01	13,00	16-May-01	to	08-Jul-01	53	2400	4160,00	0,5	3273,504	123,78	35,90	0,13
G	01-Jun-01	to	15-Jun-01	14,00	01-Jun-01	to	15-Jul-01	44	2400	4480,00	0,5	3525,312	98,12	33,24	0,13
H	16-Jun-01	to	30-Jun-01	13,00	16-Jun-01	to	01-Jul-04	1111	2400	4160,00	0,52	3273,504	1573,14	424,85	0,13
I	01-Jul-01	to	15-Jul-01	12,00	01-Jul-01	to	01-Jul-04	1096	2400	3840,00	0,52	3021,696	1571,07	424,85	0,13

Table 2: Phases III and IV of the SWB Method.

WATER BALANCE						EFFECT OF THE INFLUENCE BETWEEN CELLS			
11	12	13	14	15	16				
SUPERFICIAL INFILTRATION I_i	HEIGHT OF MOISTURE HB_i= $(B_i \times Hr \times 1000)/A$	HEIGHT OF FIELD CAPACITY: SOLID WASTE HCc_i= $(Cc \times S_i \times 1000)/A$	COVERING MATERIAL HCcMc	PERCOLATED WATER P_i	REQUIRED WATER Cc	WATER QUANTITY IN EACH LEVEL OF MACRO-CELL			VOLUME OF LEACHATE $V_i=(P_i \times 1000)xA$
						3rd	2nd	1st	
mm	mm	mm	mm	mm	mm	mm	mm	mm	m^3
36,71	483,03	856,15	60	0,00	(396,41)			(388,59)	0,00
59,06	454,61	805,79	60	0,00	(352,11)			(260,96)	0,00
82,53	454,61	805,79	60	0,00	(328,64)			(201,02)	0,00
81,29	426,20	755,42	60	0,00	(307,94)			(307,94)	0,00
92,26	340,96	629,52	60	0,00	(256,30)		15,6		0,00
71,78	369,37	681,98	60	0,00	(300,82)		255,2		0,00
52,13	397,79	734,44	60	0,00	(344,52)		(60,40)		0,00
943,78	369,37	709,26	60	543,89	0,00	543,89			0,00
941,98	340,96	654,70	60	568,24	0,00	568,24			0,00

N.B. The numbers in ( ) signify the quantities of water required.

section, but due to the high daytime temperatures in Nuevo Laredo, the evapotranspiration was considered to be nil on dry days. In other words, the evapotranspiration was calculated only for rainy days. The final assumption made was to exclude the influence of consolidation of the landfill on the variation of the field capacity of the waste, because the only information available referred to the field capacity of fresh solid waste.

Application

Fig. 3 is a plan and cross section drawing of the layout of the confining cells, identified by number. This layout corresponds to the network used in the spreadsheet reporting this study. In the case of a macro-cell still at the planning stage, the SWB method can still be applied if data is available regarding the macro-cell and the individual confining cells that make up the given macro-cell.

The SWB method was applied to macro-cell no.1 at the Nuevo Laredo landfill. Construction was begun in November 1994 and completed in July 1997. The macro-cell is shown in Fig. 3, together with the order in which the confining cells were built. This same layout was used in the spreadsheet (Tables 1 and 2) where data in Column 1 was entered in a downward sequence, Cell no.1 at the top being the oldest and Cell no.83 at the bottom being the most recent. Other data was also used, such as: daily

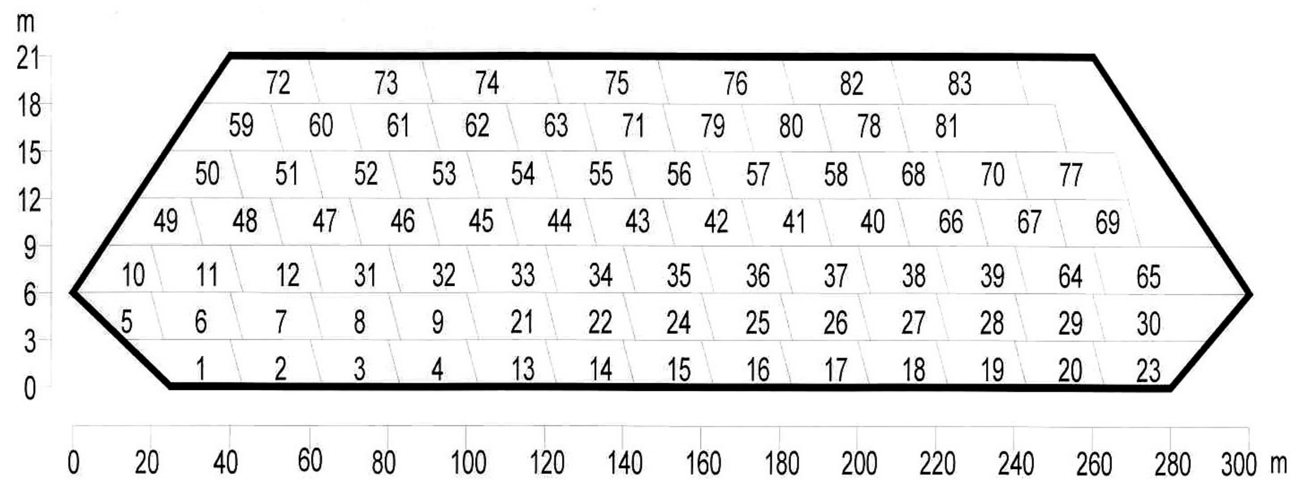

Fig. 3: Dimensions in Metres of Macro-cell no. 1 at the Nuevo Laredo Landfill.

disposal rates of solid waste at the landfill (320 tons), relative moisture of the solid waste (21.31%), the surface area of individual confining cells (2,400 m^2), and the thickness of the cover over each cell (30 cm). This data was obtained from the environmental monitoring of the landfill (Orta *et al.* 1999).

Other parameters, such as the local climatological parameters, are very extreme. The general climate is very dry, and the amount of annual rainfall is relatively small. Relevant differences can be noted between the different seasons of the year, and from one month to the next. The annual rainfall distribution is not symmetric, it is unbalanced and presents sharp oscillations. Dry and humid periods alternate, but variations are even noted for different years. However, a general trend can be taken in that most rainfall usually occurs between April and September, with October to March being relatively drier. The total annual rainfall and the height of the potential evapotranspiration [ETp] were calculated from the meteorological data available for Nuevo Laredo, and for Laredo, Texas.

Monthly rainfall, and the number of rainy days per month, were obtained from a 37-year period (1960-1996) of statistical data recorded in the statistical yearbook of the State of Tamaulipas (IMTA 1997). This data is given in Table 3.

The height of water contributed by the rainfall received by each confining cell was calculated using Equation 3. It was possible to make this calculation because data about the length of time and the actual months during which each cell was exposed to the weather, was available in the information provided by SETASA.

Calculation of the height of the potential evapotranspiration [ETp]: This parameter was calculated from the data given in Table 3. Evapotranspiration figures were corrected by applying the equations given by Fenn *et al.* (1975). The actual number of days in a given month, and the maximum number of daylight hours, in terms of the local latitude, were noted. These results are given in Table 4.

The height of water lost by each cell from evapotranspiration was calculated using Equation 4. The height of rainfall was calculated using Equation 3, and this was possible because the weather information was also available. The height of water in mm, percolating from above into a confining cell, was calculated using Equation 8. As mentioned above, if the result obtained from this Equation is positive, it is recorded in Column 15. If the result is negative, it is recorded in Column 16, and represents the water still

Table 3: Total Monthly Rainfall in Nuevo Laredo.

Rainfall (mm)	J	F	M	A	M	J	J	A	S	O	N	D
Average 1960-1996	25.1	6.0	8.3	33.9	81.3	68.8	60.6	88.5	77.6	30.9	15.4	20.4
Rainy days	5	5	2	4	5	5	3	4	6	3	3	4
Total rainfall, 1960-1996	5,773											
Temperature °C	J	F	M	A	M	J	J	A	S	O	N	D
Ave. 1964-1996	12.8	15.8	20.0	24.4	27.1	29.6	30.7	30.5	27.8	23.7	18.6	14.9

Table 4. Calculation of the Real Evapotranspiration (ETp)

MONTH	RAINY DAYS	DAYS WITH NO RAIN	ETp/month [mm]	ETp/day [mm]	ETp/rainy days [mm]	*Days with water available	ETp/days with no rain [mm]	TOTAL OF ETp [mm]
JANUARY	5	26	15.86	0.51	2.56	0	0.00	2.56
FEBRUARY	5	25	27.65	0.92	4.61	0	0.00	4.61
MARCH	2	29	63.17	2.04	4.08	0	0.00	4.08
APRIL	4	26	110.51	3.68	14.73	0	0.00	14.73
MAY	5	26	168.89	5.45	27.24	0	0.00	27.24
JUNE	5	25	214.38	7.15	35.73	0	0.00	35.73
JULY	3	28	243.83	7.87	23.60	0	0.00	23.60
AUGUST	4	27	228.76	7.38	29.52	0	0.00	29.52
SEPTEMBER	6	24	159.74	5.32	31.95	0	0.00	31.95
OCTOBER	3	28	97.57	3.15	9.44	0	0.00	9.44
NOVEMBER	3	27	44.97	1.50	4.50	0	0.00	4.50
DECEMBER	4	27	23.70	0.76	3.06	0	0.00	3.06

required before percolation can begin.

The procedure up to this point is the same as that explained for the theoretical example using a macro-cell made up of 9 confining cells. Some cells will produce leachate, which at the same time will contribute to the water flowing into and through the cells below. Other cells will not be able to satisfy their own water requirement, and therefore will not produce leachate. The analysis was completed after analysing the relationship between all the confining cells making up that macro-cell, and on measuring the quantity of leachate produced by the first layer of the macro-cell. This height of leachate is multiplied by the surface area of each confining cell in that first layer, thus determining the volume. The sum of the quantities for all the cells in that first layer, is the total volume of the leachate percolating out of the Nuevo Laredo macro-cell, from the start of construction until a given date assigned as the limit for the calculation. This date can be established randomly, even before construction of the macro-cell is complete.

For this study at the Nuevo Laredo landfill, it was possible to verify the accuracy of the results obtained using this SWB method, because information regarding the actual amount of leachate generated to date was available in the information provided by SETASA. The volume of leachate obtained as a result of applying this SWB method, to data regarding macro-cell no.1 of the landfill at Nuevo Laredo (for the period 23rd November 1994 to 8th December 1998), is equal to 1129 m^3. The volume of leachate production pumped during the same period, as registered by ICA-SETASA, was 1671 m^3, with an estimated residue at the pump sump of 3 m^3, giving a total of 1674 m^3.

Discussion

The quantity of leachate calculated by applying the SWB method is satisfactory, despite this difference of 33% between the SWB result and the volume registered by the Nuevo Laredo landfill pump. It should be remembered that the SWB calculation was made on the basis of what is not very precise climatological information, because of the scarcity of weather stations in Mexico. This information is available to the operators of any landfill in Mexico. The SWB is useful precisely because it still functions even with less, or less accurate, climatological information, a condition which does not hold true for other programmes such as HELP. It should also be pointed out that comments made by landfill personnel suggest that leachate pumping activity at the Nuevo Laredo landfill is not well supervised, and thus the quantities registered may have been overestimated.

Table 5: Sensitivity Test of the SWB in the Nuevo Laredo Case.

Variable	Volume of leachate production at Macro-cell 1 in Nuevo Laredo, Tamaulipas (m^3) % of variation of the variable used in the SWB method									
	20%	40%	60%	80%	100%	120%	140%	160%	180%	200%
Field capacity	65,465	44,160	22,855	5,013	1,129	194	0	0	0	0
Relative moisture	0	0	0	447	1,129	2,861	8,624	20,146	33,353	46,630
Precipitation	0	0	0	201	1,129	2,333	5,617	11,670	20,020	28,981
Evapotranspiration	2,959	2,217	1,725	1,421	1,129	837	545	254	37	0

One of the most important parameters in the application of the SWB, is the field capacity, i.e. the amount of water likely to be retained by the solid waste prior to the start of leachate production. In the application of the SWB to the Nuevo Laredo landfill, only 23 cells were leaching, because only these cells had reached their field capacity; the rest of the cells had not. In other words, the steady state of landfill had not yet been achieved.

A sensitivity test is given in Table 5, to show the significance of four variables in the application of the SWB method, on the amount of leachate produced during the four years of operation of the Nuevo Laredo landfill.

In Table 5, the 100% column represents the use of the given variables, without any variation, in the SWB calculation as applied to the Nuevo Laredo landfill for the period 23rd November 1994 to 8th December 1998, when the quantity of leachate production calculated using all the variables totalled 1129 m^3.

The 20% column in Table 5 represents the application of the SWB to the Nuevo Laredo landfill, using 20% of the original value of the variables given in Table 5 thus obtaining different quantities of leachate production in each instance.

The 200% column in Table 5 represents the application of the SWB to the Nuevo Laredo landfill, using 200% of the original value of the variables given in Table 5, and again obtaining different quantities of leachate production in each instance.

The above analysis of the variables in Table 5, shows that the most important variables are the physical characteristics of the solid waste, such as weight density, relative moisture, field capacity, etc., all of which are determined by laboratory testing. It should be noted that the SWB method could have been improved if there had been information available about the variation of the field capacity of solid waste during the process of consolidation.

The accuracy of the SWB method depends essentially on the input data regarding the physical characteristics of the solid waste, and on information about the order of cells that have been, or will be, built in the macro-cell. This makes it possible to calculate when and which cells have already produced leachate, and to identify the first cells which will produce leachate in a landfill yet to be built.

Using the results of this SWB method, it is possible to predict the quantity of leachate production, and the time during which leachate will be produced. This makes it possible to programme the management of this pollutant, which means that the SWB method would undoubtedly have economic significance for landfill operations in general.

Conclusions

The method described here as Serial Water Balance (SWB), is based on the traditional water balance method (WBM). The advantage of the SWB over the WBM is that the SWB calculates a balance on a cell by cell basis, by taking into account the time of exposure to weather; by considering the variation in the value of the field capacity of municipal solid waste when found at a greater depth; and by assuming the effect of the liquid percolating from a cell in the layer above into cells in the immediately subjacent layer.

The result obtained using the Serial Water Balance method for the Nuevo Laredo case is satisfactory, considering that not all the leachate pumping data is fully reliable, given that the volume in the field was measured using rather inaccurate procedures.

The SWB method can be applied to macro-cells with layers constituted by several strips, thus requiring a schedule for the building of the cells. In the Nuevo Laredo case, the macro-cell had already been completed. However, the SWB method is also useful for landfills yet to be built. In such a situation, information would be required regarding the confining cells and the macro-cells planned.

Special mention should be made that, although the zone where the Nuevo Laredo landfill is located is arid and the rainfall scant, the SWB method can be adjusted to regions where rainfall is moderate or high.

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