

Long-term observation of alternative landfill capping systems – field tests on a landfill in Bavaria

U. Henken-Mellies and E. Gartung

Abstract

This paper describes large-scale field tests which were conducted in order to test the effectiveness of landfill capping systems. The test setup involved the construction of large-scale lysimeters on a landfill site from which water flowing out of the system can be measured precisely. A simple landfill cap consisting of a thick layer of loamy sand was placed in one of the large lysimeters; the other lysimeter was filled with a more elaborate capping design (1 m of top soil, a drainage geocomposite and a geosynthetic clay liner – GCL). The water balance of the landfill capping system inside each of the lysimeters was measured during a four-year period. The results are presented in this paper. The simple mineral landfill cap in test field 1 had only limited effectiveness in preventing percolation. During the winter months it is inevitable that a large percentage of precipitation percolates through the cap into the landfill. This process resembles groundwater recharge in natural systems. In test field 2, less than 1% of precipitation seeped through the GCL. The landfill capping design of test field 2 proved to be an effective alternative to the standard system as specified in the European regulations.

Key words: landfill, surface sealing, water balance, field test, geosynthetic clay liner

INTRODUCTION

The EC landfill directive defines in article 1(1) a general aim 'to reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment [...] from landfilling of waste, during the whole life-cycle of the landfill.' The surface sealing has special importance as a long-term barrier in the realisation of this ambitious goal.

The surface sealing of a landfill serves as a long-lasting barrier between the body of waste and the atmosphere and biosphere. Its main tasks are to minimise infiltration of water into the landfill, to prevent the escape of landfill gas and dust, to facilitate landscaping and sustaining cultivation of the surface. According to German waste disposal and landfill regulations (TA Siedlungsabfall 1993), untreated municipal waste may only be deposited in landfills until the year 2005. Landfills, which do not meet the standards of the EC landfill directive and its German counterpart, will have to stop operation by the year 2009. Therefore, during this decade, a large number of landfills will have to be closed and will eventually have to be covered with an adequate surface sealing system.

The basis for the design of surface sealing systems is given in the EC landfill directive and – for Germany – in the German '*Deponieverordnung*' of 2002. The '*Deponieverordnung*' gives specific regulations for a standard surface sealing system consisting of (for municipal solid waste landfills) from bottom to top:

- artificial sealing liner (geomembrane; $d \geq 2.5$ mm);
- mineral sealing layer ($d \geq 0.5$ m; $k \leq 5 \times 10^{-9}$ m/s);
- protection layer;
- drainage layer ($d \geq 0.3$ m; $k \geq 1 \times 10^{-3}$ m/s);
- top soil cover ($d \geq 1.0$ m).

Alternative surface cover systems may be permitted, if they consist of functionally equivalent system components.

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Research concerning landfill construction in Germany in recent years has focused on surface cover systems. The main interest was to test the efficiency of alternative surface cover systems and materials (such as geosynthetic clay liners (GCL), capillary barriers and others). Some research projects investigated the efficiency of existing, simpler mineral surface covers. In this paper we present the results of two research projects along these lines, which were financially supported by the Bavarian State Ministry for Regional Development and Environmental Affairs.

CONCEPT OF THE STUDY

The expected performance of a surface cover system is often calculated on the basis of hydrological modelling, e.g. with the HELP-model (Schroeder *et al*. 1994; GDA E2-30 1998). The suitability of compacted clay liners (CCL) or GCL can be examined by excavation after a certain time span. Tests on exhumed samples provide only a snap-shot-view of the conditions of the materials. Comprehensive studies of the water balance of landfill cover systems are possible through large-scale lysimeter test fields, which are installed at landfill sites.

The lysimeter test fields discussed in the present paper cover an area of some 500 m² and are equipped at their base with an HDPE geomembrane which acts as a collection pan. The surface sealing system under scrutiny is built inside the large lysimeter on a 1:1 scale. The lysimeters are equipped with devices to separately collect and measure surface runoff, drainage flow and seepage through the sealing layer. Finally, the surface cover is vegetated and exposed to the natural climatic conditions of the landfill site.

The Aurach landfill is located some 60 km south-west of Nuremberg in a region of gentle hills at an elevation of 500 m above sea level. It was operated as a municipal waste landfill for the Ansbach district from 1978 until 1998. Two lysimeter test fields were constructed on the south slope (inclination: 20%) of the landfill in 1996 and 1998. Test field no. 1 was built to investigate the performance of a simple mineral landfill cover. In test field no. 2 the performance of a surface cover system using geosynthetic elements (drainage geocomposite and a GCL) was examined. Results of the four-year monitoring period of these test fields are presented in this paper.

Test field 1: simple mineral surface cover

The surface cover under scrutiny in test field no. 1 duplicates the surface capping system of the first phase of construction of the Aurach landfill, which represents the state of the art of the late 1980s. It consists of 0.2 m of topsoil underlain by 1.5 m of a low-quality mineral cover made of locally available cohesive sand which was placed without specification regarding the degree of compaction, hydraulic conductivity or other soil parameters. Examination of the existing mineral cover gave hydraulic conductivity values with a wide scatter of data from 10^{-7} to 10^{-10} m/s. The test field was intended to duplicate as closely as possible the conditions of the existing surface cover.

The profile of the lysimeter test field is shown in Figure 1. A seepage collection system (drainage layer plus geomembrane) is situated below the mineral cover. Two water flows are collected and measured separately:

Q_S = surface runoff,
Q_L = seepage through mineral cover.

The surface runoff is collected in a gravel-filled drainage trench at the toe of the test field. Seepage water is collected in the drainage layer below the mineral cover. Water flows are measured continuously by hydraulic equipment installed in a monitoring container. Readings are taken automatically, with the data being stored on a PC.

Test field 2: surface sealing system including a GCL

A second test field was installed at the landfill of Aurach in 1998, which was designed for studying the water balance and the performance of a surface cover system, including a Geosynthetic Clay Liner (GCL) and a drainage geocomposite. A profile of the cover system in the test field is shown in Figure 2. It consists of the following layers:

- restoration layer; topsoil: loamy sand (0.2 m);
- restoration layer; subsoil: slightly loamy sand (0.8 m);
- drainage geocomposite;
- GCL;
- regulating layer (loamy sand);
- seepage collection system (drainage geocomposite and HDPE-geomembrane).

A calcium-bentonite GCL was used in the test field in order to avoid changes in material properties due to ion-exchange effects, which are known to occur in sodium-bentonite GCL (e.g. Egloffstein 2000). The lower swelling capacity and higher hydraulic conductivity of Ca-GCL compared to Na-GCL is accounted for by the higher mass per unit area for the Ca-GCL. The product which was used in the test field has a mass per unit area of 9500 g/m² and a permittivity ψ of 8.3 ×

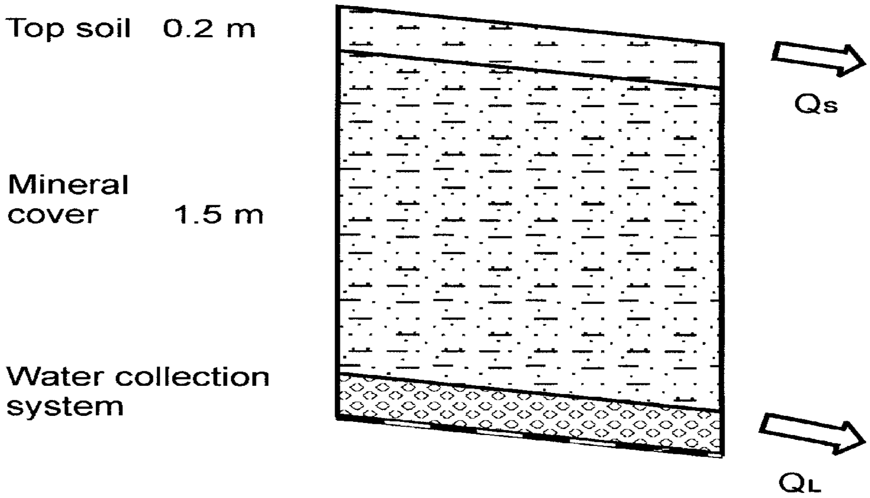

FIGURE 1. PROFILE OF THE TEST FIELD NO. 1 AT AURACH LANDFILL SITE

10^{-9} s^{-1} (permittivity = hydraulic conductivity divided by thickness).

A drainage geocomposite was used as drainage layer above the GCL. Under a load of 20 kPa it has a thickness of 11 mm and a water flow capacity of q_{20} = 0.7 L/(s × m) at i = 0.1.

The main objective of measurements was the precise determination of the relevant water fluxes (see Figure 2):

- surface runoff (Q_S);
- drainage flow (Q_D);
- seepage flow through the GCL (Q_L).

The water fluxes are measured continuously at high precision in a measuring container. In addition, soil moisture measurements by tensiometers and FDR-probes are carried out in the restoration profile.

RESULTS

Measurements at test field 1 (mineral surface cover)

The continuous measurements of precipitation and fluxes from the test field were conducted in the period from April 1997 to March 2001. The daily sums of precipitation and discharge are shown in Figure 3.

Annual precipitation during the observation period ranged from 780 mm to 970 mm, which is above the average annual precipitation of approx. 750 mm at the landfill site. The precipitation shows a pattern typical of cool temperate, humid conditions which prevail in Bavaria, where rainfall occurs throughout the year. Peak daily precipitation reaches 50 mm. Precipitation is almost evenly distributed over the years, without prominent wet or dry seasons. The surface runoff and leakage through the landfill cover, however, show distinct seasonal differences:

At the test field with a 20% gradient, surface runoff occurs principally in the course of heavy winter rains, when the quantity of precipitation exceeds the water take-up capacity of the soil. In the winter of 1998/99, runoff peaks of up to 16 mm/d were recorded. On the other hand, heavy summer rainfall only produced minimum surface runoff. This was mainly due to the intense vegetation. Only in the early summer of 1997, when the vegetation cover had not yet fully developed, was there occasional surface runoff.

Seepage through the landfill cover occurs almost exclusively during the winter season, while during summer months practically no seepage is observed. Obviously, precipitation during the summer months is stored temporarily in the cover soil layer. Subsequently it leaves the system via evapotranspiration. Note that in the summer of 1997, when the vegetation was still sparse, there was some seepage. Depending on the weather conditions during autumn, seepage may begin at the end of September (as in 1998) or only in December (as in the drier autumns of 1997 and 1999).

Seepage continues through March and, in extreme cases, until May (as in the wet winter of 1998/1999).

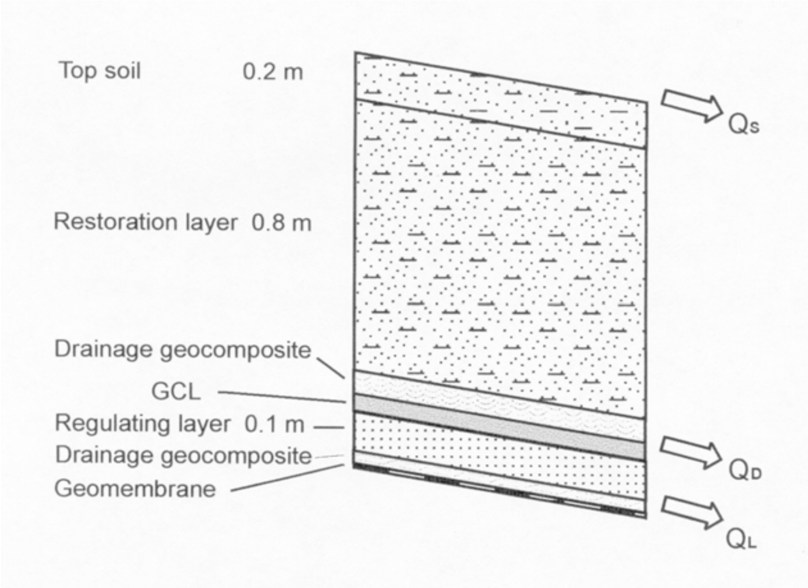

FIGURE 2. PROFILE OF THE TEST FIELD NO. 2 AT AURACH LANDFILL SITE

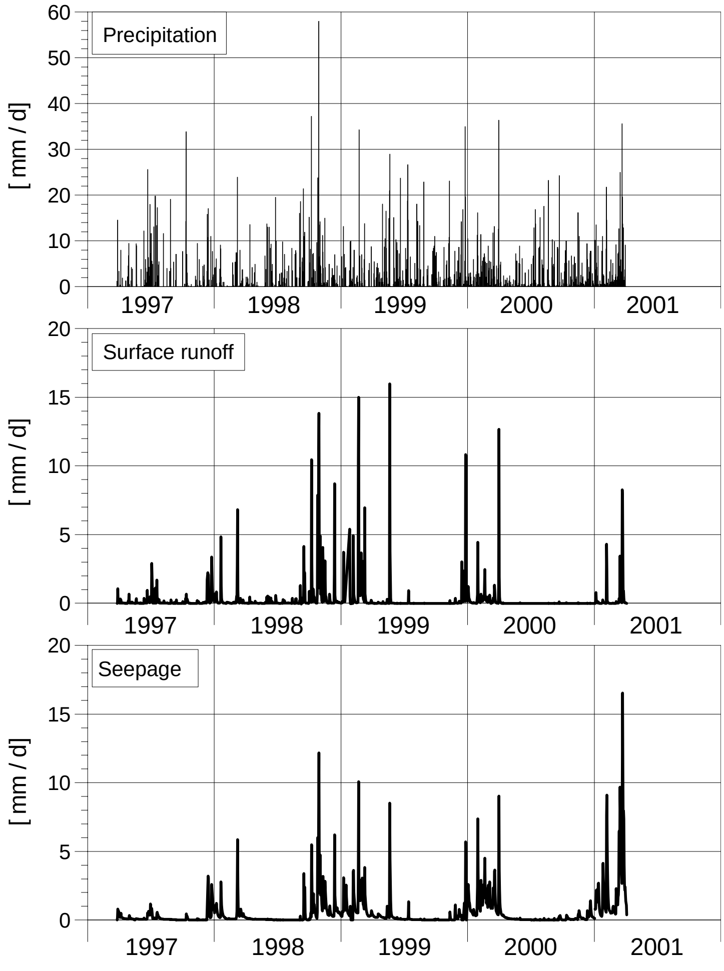

FIGURE 3. DAILY MEASUREMENTS (MM/D) OF RAINFALL, SURFACE RUNOFF AND SEEPAGE OF THE LYSIMETER TEST FIELD 1 AT AURACH (BAVARIA)

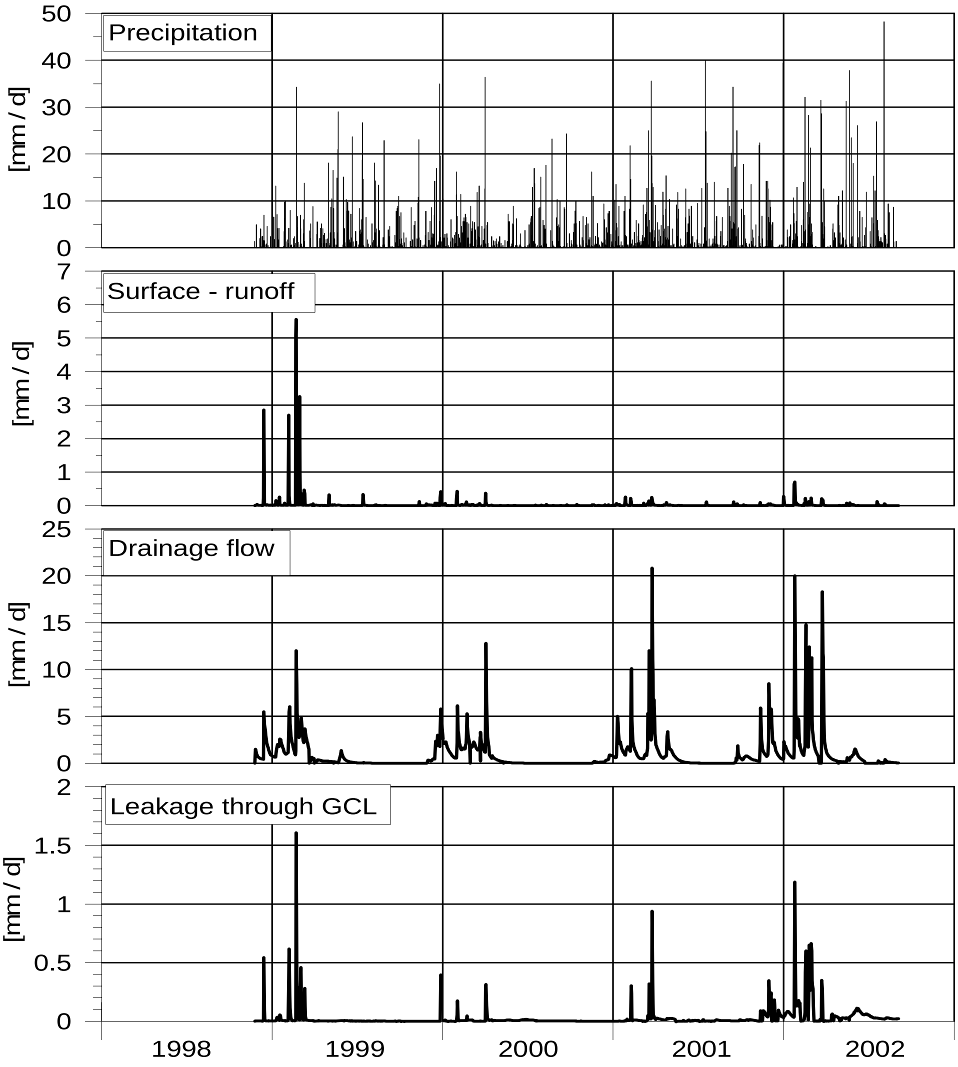

FIGURE 4. DAILY VALUES OF PRECIPITATION AND WATER FLOWS IN TEST FIELD 2 AT AURACH, BAVARIA.

The plot of seepage vs. time is characterised by sharp maxima of short duration (1–2 days) followed by a rapid decrease. Several maxima of 5–10 mm/d were recorded each winter. The overall maximum of 16 mm/d was recorded in March 2001. The peaks of the liner-seepage curve occur simultaneously with maxima in rainfall and surface runoff.

Results of test field 2 (GTD)

Measurements in test field 2 started in November of 1998. The results of the precipitation and discharge measurements are shown in Figure 4 as daily values in mm/d.

Noteworthy surface runoff occurred only in the first winter season, while the vegetation on the recultivation layer was still sparse. After this initial period only minimal surface runoff is recorded, which is restricted to a few events in the wintertime.

Drainage flow shows a systematic pattern of seasonal variability: substantial drainage flow is recorded in winter during the months of October through March. During the summer half-year from April to September there is little drainage flow. In summer, even heavy rainfall associated with thunderstorms does not result in drainage flow. The maximum daily drainage flow which occurred during the observation period was 21 mm/d during the generally wet month of March 2001. Daily values of > 5 mm/d occur a couple of times each winter. Peaks in drainage flow occur simultaneously to precipitation events. Following a flow event, drainage flow rapidly decreases again to values below 1 mm/d. Drainage flow is recorded by high-resolution measure-

Table 1. Semi-annual sums of precipitation (in mm) and discharge measurements (given in mm and in % of precipitation) in the test fields

Term	Precipitation (mm)	Test field 1				Test field 2					
		Q_S		Q_L		Q_S		Q_D		Q_L	
		mm	%	mm	%	mm	%	mm	%	mm	%
Summer 1997	329	17	5	23	7						
Winter 1997/98	296	43	14	68	23						
Summer 1998	340	18	5	16	5						
Winter 1998/99	520	174	34	230	44	25	5	240	46	7	1
Summer 1999	537	22	4	37	7	1	0	24	4	0	0.0
Winter 99/2000	525	74	14	161	31	3	1	228	43	2	0.3
Summer 2000	354	1	0	17	5	0	0	46	13	1	0.4
Winter 2000/01	538	36	7	247	46	2	0	244	45	3	0.6
Summer 2001	565					1	0	66	12	1	0.2
Winter 2001/02	592					4	1	407	69	15	2.5
Summer 2002	501					1	0	46	9	5	1.1
Sum test field 1	3439	386	11	800	23						
Sum test field 2	4132					38	0.9	1300	31	35	0.8

ments. The drainage flow reached a maximum short-time value of 3.1 L/(s × ha).

Leakage flow through the GCL is shown in the lowermost graph of Figure 4. Note the difference in scale of the y-axis of this graph, compared to the other y-axes. Leakage flow occurs only on a few days of each year, when the drainage flow exceeds 5 mm/d. Then the leakage flow reaches daily values of 0.2 to 1.6 mm/d.

Water balance

Semi-annual sums of precipitation and fluxes in both test fields are given in Table 1. In both test fields there is a systematic pattern of low fluxes during summer (sum of combined fluxes range from 4% to 13% of precipitation) and high fluxes during winter (the sums of fluxes range from 45% to 78% of precipitation). The water-balance elements which are not measured quantitatively in the test fields are evapotranspiration and change of soil water content.

During the months from April to September, the water balance is dominated by evapotranspiration, which during these months exceeds precipitation for the average location in most parts of Germany. Hence there is only low discharge during the summer half of the year. Exceptions to this rule are connected to extreme conditions, such as the cool and wet autumnal weather, which started in mid-September 1998, or the extremely wet summer of 2002. During the winter half of the year (October to March) evapotranspiration is low. Precipitation during this time of the year initially leads to replenishment of the soil water reservoir and then to substantial discharge. This general pattern applies to both test fields.

The sums of the respective rainfall and flows from the four-year observation periods are given in the bottom lines of Table 1. For both test fields two thirds of the precipitation is evapotranspirated, while the combined fluxes amount to one third of the sum of precipitation. But there are great differences concerning the type of flow from the test fields:

Test field 1 with its single-layer design allows either only surface runoff or seepage through the soil layer. Due to the relatively low permeability of the surface cover, heavy rainfall during the winter season results in surface runoff. But, considering the permeability coefficient (from 10^{-7} to 10^{-10} m/s), it is inevitable that there is considerable seepage. Looking closer at the ratio of surface runoff to seepage in subsequent winters, it becomes obvious that it decreases from 2:3 in the first winter to 1:7 in the fourth winter. This shift of the ratio is caused by the combined effects of thickening vegetation (reducing runoff) and loosening of the soil structure (increasing seepage).

The three-layer design of test field 2 results in a completely different distribution of fluxes: there is only marginal surface runoff (<1%), due to the moderate permeability of the top soil cover. Water which percolates through the soil cover reaches the highly permeable drainage geocomposite, resulting in drainage flow.

DISCUSSION

The observations made in the test fields give insights into the water balance of landfill cover systems. Under Middle-European climatic conditions the water balance at most locations shows distinct seasonal differences: during the summer months evapotranspiration exceeds the amount of rainfall. In addition, soil water is extracted from the soil by plant roots and evapotranspirated. During the winter season, precipitation is higher than evapotranspiration. The soil water reservoir is replenished. When the field capacity of the soil is reached, additional precipitation percolates down into deeper layers. This process, which in natural soils leads to groundwater recharge, has repeatedly been observed in lysimeter test fields on landfills as drainage flow and seepage flow (Breh and Hötzl 2000; Henken-Mellies *et al*. 2001; Siegmund *et al*. 2001).

In the case of the simple landfill cap design consisting merely of a thick layer of loamy sand, a high amount of seepage into the landfill body is inevitable. Seepage is of the same order of magnitude as the annual groundwater recharge in the area, given similar conditions regarding soil-type and vegetation. Such simple covers are frequently used for abandoned landfills and contaminated sites. They may serve the purpose of recultivating the site, but it should be acknowledged that these soil covers admit substantial percolation. A landfill cover consisting of just one thick soil layer has recently been approved in an area in Eastern Germany, where average rainfall in winter is very low and annual groundwater recharge is close to zero.

Conditions can be greatly improved by introducing a drainage layer into the capping system. The main task of the drainage layer within the surface cover system is to drain the water that percolates through the topsoil cover and to minimise the hydrostatic pressure on the mineral sealing layer. Information about the potential quantity of water percolating through the top soil cover is necessary in order to appropriately design the drainage layer.

- the EU Landfill Directive only gives the specification ‘drainage layer > 0.5 m: required’;
- the German *Deponieverordnung* requires ‘drainage layer $\geq$ 0.3 m; with k $\geq 1 \times 10^{-3}$ m/s’ or equivalent;
- further recommendations in this respect are given for application in Germany in the ‘Technical Recommendations for Geotechnics of Landfills and Contaminated Land’ (GDA-Empfehlungen 1997; DGGT 1997). According to these recommendations, peak daily values for percolation of 25 mm/d should be taken into account in case of sandy recultivation layers. On 99% of days, percolation rates of less than 10 mm/d are to be expected.

These values, which are recommended for design calculations in Germany, have been verified by the observations in test field 2 (see Figure 4). Here the maximum percolation rate was 21 mm/d, and on 99% of days it was below 6 mm/d. Percolation through the recultivation layer and drainage flow are mainly restricted to the winter half of the year, when the soil moisture has reached field capacity. Heavy precipitation during summer does not penetrate down to the base of a 1 m thick recultivation layer, and hence does not cause drainage flow. The maximum short-term flow in the drainage composite was measured to be 0.006 L/(s $\times$ m) at the base of the 20 m slope of the test field. This value measured in the field is two orders of magnitude lower than the horizontal water diversion capacity of the drainage geocomposite of q_{20} = 0.7 L/(s $\times$ m) as measured in the laboratory.

Leakage flow through the GCL is of the order of a few millimetres per year, or 0.8% of the precipitation. The leakage through the GCL in the test field reported here is in the same range as in test fields elsewhere: Siegmund *et al*. (2001) made long-term observations at a test field in Thuringia. There, in the profile of the test field, a sandy buffering layer was placed between the drainage layer and the GCL, in order to reduce the risk of desiccation of the GCL. Here leakage flow amounted to 0.5% of precipitation or 4.6 mm/yr.

This measured performance of GCL is better than that reported for compacted clay liners, where seepage is in the range of 50 to 150 mm/yr (Huber 2003) and is of the same order of magnitude as seepage through capillary barrier systems, where 5 to 30 mm/yr are reported (e.g. Barth and Wohnlich 2003).

CONCLUSIONS

The results of the measurements at test field 1 of the Aurach landfill can be used as a basis for evaluating the water balance and the long-term performance of the large number of landfill covers, which similarly consist merely of a thick layer of compacted soil. Seepage through the cover is of the same order of magnitude as local groundwater recharge. A look at the hydrogeological data of the area may give an approximation of the expected percolation.

The performance of a drainage geocomposite and a Ca-GCL within the surface cover system of a landfill has been monitored in test field 2. The water balance of the four-year observation period shows that evaporation accounts for almost 70% of the water output. Thirty per cent of the annual precipitation drains off laterally in the drainage geocomposite, and only 0.9% seeps through the Ca-GCL. The results emphasise the importance of a properly designed landfill cover system, including a sufficiently thick recultivation layer to regulate the water balance of the surface cover system, an effective drainage layer, and a sealing layer which keeps its low permeability. In this respect the drainage geocomposite and the Ca-GCL proved to be effective elements within the landfill cover system.

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