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Water balance for landfills of different age

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Abstract

Water-related processes in landfills are discussed with emphasis on internal processes such as field capacity, moisture variation in time and space, and macropore flow. Runoff production and evaporation from landfills in Sweden of different age are investigated. It is clarified in what ways and for how long a closed municipal landfill differs from an ordinary land area from a hydrological point of view.

1. Introduction

The main environmental problem of sanitary landfills is the potential risk of groundwater pollution and subsequent influence on surface water quality. The total pollutant load to the environment is dependent on the quantity and the quality of the water that percolates through the landfill and reaches the groundwater. The subsurface runoff water, i.e. the drainage water, from a landfill is called leachate, and subsequently the quality of this water, leachate quality. The quality of the leachate depends on the initial waste composition of the landfill and on the biological, chemical and hydraulic state of the landfill. As long as a landfill is used, and for some years after it has been closed, the site can be superintended and the leachate collected and treated. In a longer perspective, the site must be regarded as a part of the environment and the emissions should be harmless to the environment. To design landfills and manage them so that the emissions become small, it is necessary to determine the quantity and quality of the leachate. The first step is, therefore, to determine the water balance of a landfill. This depends on meteorological conditions (intensity and distribution of precipitation and potential evaporation), on the hydrau-

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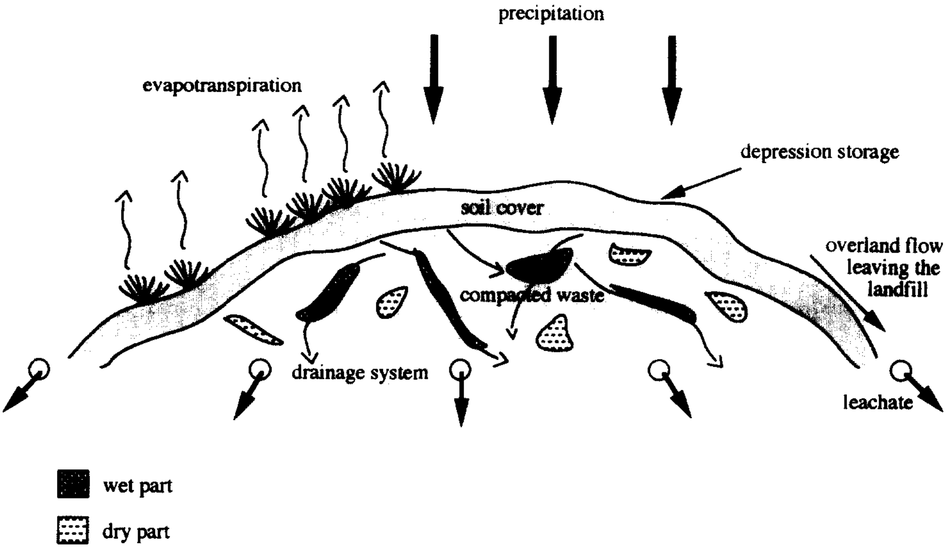

Fig. 1. Water fluxes in a landfill with cover.

lic characteristics and the initial conditions of the waste material, and on biological processes within the landfill. The conditions within the landfill change with time; the character of the biological processes and the hydraulic characteristics change, resulting in changing water balance conditions with time. The way the landfill is managed also influences the water balance, e.g. leachate can be recirculated, waste water treatment sludge can be added, and the landfill can have a more or less permeable surface cover.

In the present paper, first external fluxes from landfills in the form of evapotranspiration and overland flow are discussed. Thereafter, internal water-related processes are dealt with, emphasizing the water storage capacity of the waste material relative to its initial moisture content. With this information, data on leachate production presented in the literature are analysed with respect to seasonal and long-term distribution. Having the theoretical background, the water balance for landfills of different age in the city of Malmö in the southern part of Sweden is quantified on a monthly basis. The storage of water in the landfills is calculated and its influence on the distribution of water discharge from the landfills is shown. Drainage volumes and evapotranspiration from the various landfills are compared, and also compared with the runoff from small agricultural basins.

2. Water fluxes in a landfill

Water is introduced into a landfill through the moisture of the deposited waste, in some landfills with waste water treatment sludge, and as precipitation. Some of the precipitation may run off as overland flow, and some may evaporate from the waste material or be removed by transpiration from a vegetation cover. Some water may be consumed by biological processes. The remainder must accumulate or be discharged by drainage. The water fluxes in a landfill with cover are shown in Fig 1.

To minimize emissions to the groundwater, measures are taken to keep the volume of drainage water low. The waste deposits are covered by soil through which, to obtain the goal of minimizing the drainage volumes, as little precipitation water as possible should percolate into the waste deposits. A vegetative cover is usually established to favour evapotranspiration. When rain falls in seasons of the year with little potential evaporation, infiltrating water still percolates into the waste material. Therefore, to prevent this percolation and to promote overland flow from the landfill, a layer of clay is laid as part of the soil cover. Too low moisture content in waste deposits is, however, disadvantageous in that biological processes are slowed down, and the leachate quality remains poor for a very long time.

The production or drainage water from a landfill is strongly controlled by the soil cover of the landfill. Although rather impermeable soils are used as cover, fractures develop and the overland flow is minor (Ham and Bookter, 1982; Karlqvist, 1987; Booth and Price, 1989; Nyhan et al., 1990). For two landfills in southern Finland, Ettala (1987) showed that the infiltration rate exceeded 60 mm h^{-1} although a clay with very low hydraulic conductivity was used as cover. Booth and Price (1989) attributed the absence of overland flow to the existence of large fracture zones and subsidence depressions. They suggested that there is lateral flow within the soil cover toward permeable zones. Bengtsson et al. (1992) found similar flow conditions for meltwater in frozen agricultural clay soil. When figures on overland flow have been given (e.g. Blakey, 1992), the overland flow has been estimated using runoff coefficients and has not been measured. Using small-scale lysimeters, Ham and Bookter (1992) in the USA found cells covered with clay soils to produce overland flow at the expense of reduced evaporation compared with noncovered cells. From the investigation by Blakey, it is also clear that large overland flow manifests itself in low moisture content in the soil cover and low evaporation rates.

Water is lost from a landfill by evaporation. The evaporation losses may be different from those of a meadow or agricultural field. The potential evaporation may be higher if heat is conducted from the interior of the landfill to the ground surface, but the actual evaporation may be lower if there is no or only a thin soil cover and rather dry waste material below. According to Caffrey and Ham (1974), the high temperature during aerobic decomposition is effective in evaporating moisture. However, when anaerobic conditions prevail, the temperature in a landfill is only of the order of 20°C or less. Still the interior temperature is slightly increased compared with natural soils, and this may enhance the potential evaporation. Temperature measurements in the landfills reported in this paper show that the downward increasing temperature gradient in the cover is less than 1°C m^{-1} in the winter. In the summer the temperature decreases downwards. The temperature in the central parts of old waste deposits is about 15°C. Simple steady-state heat conduction calculations show that the heat conduction to the atmosphere is 1–2 W m^{-2}, which means that the contribution from the increased temperature to increased potential evaporation can only be about 1 mm $month^{-1}$.

The evaporation rate depends on the potential evaporation and the moisture conditions in the surface layer of the landfill. Karlqvist (1987) showed that the moisture in an uncovered landfill in the Malmö region was much too low to maintain evaporation near the potential rate. The annual evaporation was 265 mm as compared with the potential value of 550 mm. With a cover, the evaporation loss was closer to the potential evaporation, but still below it, at 342 mm. The regional basin evaporation is 400–450 mm (Lindh, 1983). For landfills in Germany, Ehrig (1989) gave annual evaporation of 450 mm for newly covered landfills, which is about 100 mm less than the regional basin evaporation.

Blakey (1992) showed in a study near London the importance of vegetation growing on the landfills for evaporation losses. If water balance calculations are done for a London landfill, from which water is directed as overland flow, using data on precipitation, leachate and estimated overland flow given by Blakey, the evaporation is found to be small. However, as the overland flow was only estimated and not measured, it might have been in error.

Soil cover plays an important role in leachate production as discussed above. The thickness and the macro-scale conditions of the cover as well as the moisture status of the waste material seem to be crucial for evaporation and for the possibilities of accumulating water in the landfill and thus for leachate production. Booth and Price (1989) found only small seasonal changes of moisture in the bottom part of a soil cover, which may indicate that, if the soil cover is sufficiently thick, the moisture conditions in the waste are independent of season and that the discharge from a landfill is constant over the year.

3. Hydraulic conditions within a landfill

Moist conditions are required for anaerobic biological processes to be effective. Water is consumed in the microbiological processes within a landfill. Carbon dioxide and methane are the major gaseous products produced in the anaerobic process when acetic acid is broken down. There is water vapour in the biogas emitted from a landfill.

When gas production is measured, water consumption can be calculated as shown for example by Young (1990). The gas production from the landfills in Malmö has been measured. Knowing the gas temperature and assuming moisture saturated gas, the water losses to the atmosphere with the biogas are calculated to be 1 mm year^{-1}. The annual gas production from the test cells, containing 3400 tons of domestic waste and extending over an area of 1600 m^2, is about 68 000 m^3, of which about 50% is methane. From the general law of gases, it is calculated that it requires 0.25 l of water to produce 1 m^3 of methane. Thus, 16 500 l of water is consumed, which means a water loss per unit area corresponding to 10 mm year^{-1}. Thus, in annual or monthly water balances, microbiological processes within a landfill are negligible.

Water is stored in a landfill for shorter or longer periods within waste material, e.g. in package material or in wood, in voids in loose organic material, in macropores or holes between densely packed waste or above impermeable layers, e.g. above large plastic bags. Water does not percolate downwards from a part of a landfill until this part has reached field capacity. Because the field capacity is different for different parts of a landfill, leachate can be generated from a landfill even when the degree of saturation in large parts of the landfill is well below field capacity, as pointed out by, for example, Harris (1979). Holmes (1983) and Blakey (1992) used the term absorptive capacity to denote the condition in a landfill when leachate is just barely produced, but this is not a generally accepted term.

The local field capacity in different parts of a landfill, as well as the absorptive capacity, change with increasing age of the landfill. As long as field capacity is not reached in all parts of a landfill, some of the water percolating into the waste deposits is stored. In some parts of a landfill infiltrating water can accumulate and be stored for years before any water leaves the landfill. In old landfills the effect of the moisture storage is to distribute water infiltrating during rainy months as discharge water over longer periods. Studies by Blakey (1982), Ehrig (1983) and Nyhan et al. (1990) showed that in not very new deposits, the annual storage of water is minor. However, in some of Blakey's test cells water was still accumulating after several years, and even after 18 years Harris (1979) found dry spots in a landfill test cell.

Although in soil science soil moisture is given as volume per unit volume, moisture in landfill waste deposits is often given as volume per unit dry weight. When converting field capacities given for municipal waste as volume per unit dry weight by Quasim and Burchinal (1970), Reinhardt and Ham (1974), Harris (1979), Holmes (1983) and Blakey (1992), the volumetric soil moisture at field capacity is about 0.4. Initial moisture content converted to volumetric soil moisture is in the range 0.15–0.20 when volume per unit dry weight values given by Quasim and Burchinal (1970), Campbell (1983), Holmes (1983) and Farquhar (1989) are used. For test cells, Newton (1977) reported water accumulation corresponding to 0.2 l kg^{-1} dry weight after 2 months, and a final accumulation, at equilibrium between water input and output, of 0.4–0.6 l kg^{-1} dry weight, which is a volumetric moisture increase of about 0.25. The soil moisture increase from initial state until any drainage water leaves a landfill is less, of the order of 0.10 or less (Campbell, 1983; Holmes, 1983; Blakey, 1992). In the southernmost part of Sweden, the annual basin runoff is 200 mm, which, as overland flow is almost non-existent, is the total percolation below the topsoil from which evaporation losses occur. For waste material of initial volume by volume moisture content 0.20 and field capacity 0.40, it takes 1 year for a landfill layer of 1 m to reach field capacity. Thus, for a landfill of 10 m height, it should take 10 years before the leachate production corresponds to the regional basin runoff, provided there is no overland flow and the evaporative losses correspond to the basin value. By comparing the discharge from landfills and small basins it should be possible to estimate when a landfill would reach natural state.

There are also small-scale spatial heterogenities within a landfill because of the presence of large and more or less continuous voids, referred to as macropores, and characterized by higher hydraulic conductivity than the surrounding matrix. Kmet (1982), in discussing the appearance of drainage water before the attainment of field capacity, attributed early leachate production to channelling effects, as also did Blight et al. (1992). It has been found from many studies (Bouma et al., 1980;

Beven and German, 1981), that although macropores make up only a small portion of the total voids, they dominate the unsaturated vertical flow recharging groundwater, especially during periods of large water input, as shown by Wild and Babiker (1976) and by Bengtsson et al. (1992). In the study by Bengtsson et al. it was found that cracks develop in frozen clay soils, but close up as the soil thaws and becomes wetter. Robinson et al. (1987) also found cracks to open, close and change character, and attributed this to drying and wetting of the soil. Thus, the macropore structure and therefore the character of preferential flow change in time and space.

4. Leachate production

There are a number of studies in which landfill discharge has been measured (e.g. Meijer, 1979; Ham and Bookter, 1982; Barber and Maris, 1984; Ehrig, 1989; Blakey, 1992; Blight et al., 1992). Sometimes water balance calculations have been used (Fenn et al., 1975; Kmet, 1982) to determine leachate production. The given volumes of drainage water are difficult to evaluate, as the production rates are for single test cells or landfills and for limited periods of time and are often related to annual precipitation only.

As discussed in the previous sections, the discharge from a landfill depends, apart from rainfall and its distribution in time, primarily on evaporation losses and the redistribution in time of infiltrating water in the soil cover and in the waste deposits. The discharge varies over the year. During periods of high precipitation much water may percolate into the waste deposits below the soil cover. When there is little or no evaporation loss, the discharge increases (e.g. Farquhar, 1989; Nyhan et al., 1990; Blight et al., 1992). For landfills of rather fresh deposits, the seasonal discharge fluctuations seem to be large and the response to rain storms recognizable (Ehrig, 1989). However, the discharge from newly closed landfills is small. Ehrig observed daily peaks of 1 mm day^{-1} for landfills closed less than 1 year before, but there were periods when the discharge almost ceased. The annual volume of drainage water was about 200 mm. The fact that water is drained from a landfill before field capacity is reached, and that the discharge fluctuates and sometimes ceases, indicates that the percolation through the landfill, at least to some extent, is preferential flow and occurs in macropores.

On an annual basis, as long as the moisture content is below field capacity, the annual leachate volume from a landfill is reduced as compared with the volume of percolated water. After some time, of the order of many years, the annual drainage volume corresponds, provided there is no overland flow, to precipitation reduced by evaporation. The discharge from old landfills is rather constant throughout the year (Blakey, 1982; Ehrig, 1989), which means that only little of the drainage water travels in macropores. The annual volumes of drainage water produced from old landfills are larger than those from new ones, as shown by Blakey (1982) and Ehrig (1983). This is in agreement with the previous discussion about moisture storage in landfills. However, as previously pointed out, in some landfills water is still accumulating after 10–20 years.

Summarizing the literature survey and the qualitative theoretical discussion above, it is found that precipitation water is continuously accumulating in waste deposits in landfills for many years. Thus, the leachate production from young landfills is minor. There are macropores in these young landfills, and much of the drainage occurs as preferential flow. In old landfills, the macropores are partly closed or in other ways less effective in transporting percolating water. Instead, water probably percolates through the waste deposits, saturated to near field capacity, as flow through a matrix. The discharge does not show large fluctuations.

5. The Spillepeng landfills in Malmö

The leachate from three landfills at Spillepeng, Malmo was studied on a monthly basis for a 4 year period. These are an old landfill, test cells which were covered 5 years ago, and active biocells. Comparison is made with runoff from two agricultural basins. The landfills are managed by SYSAV, a waste management company owned by nine cities and communities in the very southwestern part of Sweden. SYSAV is responsible for the discharge measurements for the old and the active landfill.

The old landfill was established 40 years ago. The drainage water from a part of the landfill, in which the waste is 3–13 years old, is collected via a drainage system, which drains 50 ha. Parts of the landfill, 15 ha, received municipal waste until 1990. The last part of the old landfill was finally covered in 1991. The height of the landfill is 10–25 m. The whole area is covered with grass and some bushes. The refuse in the old landfill is waste from municipal activities, including households, businesses, shops and light industries. All kinds of refuse were disposed of together.

To study biogas production, landfill leachate quality and their dependence on waste composition, test cells were built, each with an area of 1600 m^2 and of 10 m height at the highest end and sloping at 15% to 2 m height at the other end. They were covered in 1988 with a 1 m depth of clay soil on which grass grows. The test cells are lined by clay and a plastic liner. The leachate from each cell is separately collected via a drainage system. Biogas is withdrawn from the test cells. Two test cells, which contain mixed municipal waste from households and light industry, were used in the present study. A section of a test cell is shown in Fig. 2.

The active landfill, which consists of three biocells, was established in 1990. It covers an area of 5 ha. It is built up in layers of 2 m height. At present, 1993, the height is 8–10 m. The landfill is lined by boulder clay. The leachate is collected in a drainage system at the bottom of the landfill. Biogas is collected from the landfill. The refuse in the biocells is mixed municipal waste, including garden waste, and also waste water treatment sludge with high water content.

The agricultural river basin Höje, the runoff of which is compared with the leachate volumes from the landfills, is 223 km^2. At low flow in the river Höje, the contribution to the flow from the waste water treatment plant in Lund is considerable (Hogland, 1986; Berndtsson, 1990). Therefore, the discharge from the plant has been withdrawn from the measured river discharge when comparing runoff and leachate volumes. The

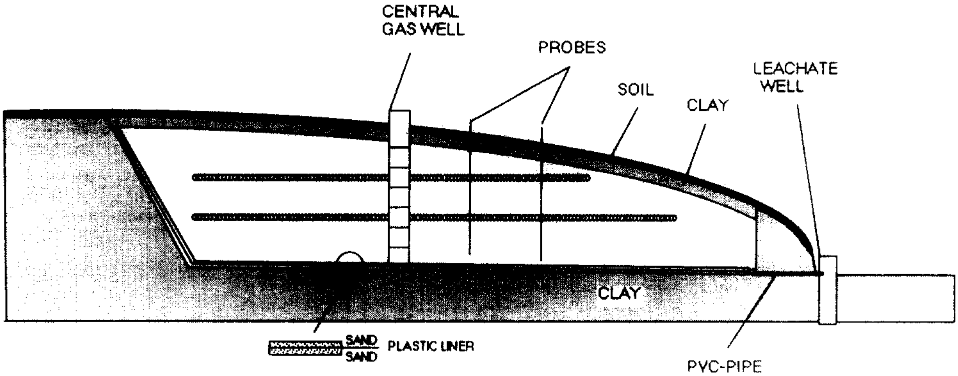

Fig. 2. Section of a test cell.

Höje river basin is flat and well drained. It consists of about 70% arable land. Comparison is also made with the runoff production from the small (about 1.5 km^2) agricultural basin Värpinge (Lindh, 1983).

There is no overland flow from the active landfill nor from the flat old landfill. The test cells slope at 15%, but there are many depressions in the surface cover. As previously discussed and shown, the infiltration capacity for a whole landfill is much higher than the low hydraulic conductivity of the cover material because of fractures in the soil. Summer storms have not been observed to produce overland flow from the test cells, but some minor overland flow has been observed during prolonged rainfall periods in the winter, when the depressions in the cover become full. Still, the annual production of overland flow should be very small.

6. Leachate production from the Spillepeng landfills

The measured monthly leachate production from the old landfill and from the two comparable test cells is shown in Figs. 3–5. Net precipitation, as precipitation minus

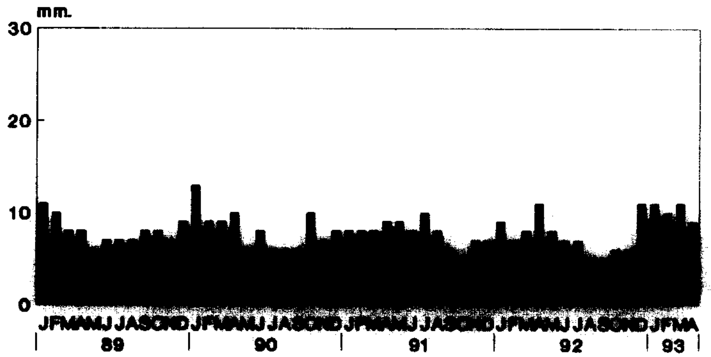

Fig. 3. Leachate production from the old SYSAV landfill at Spillepeng.

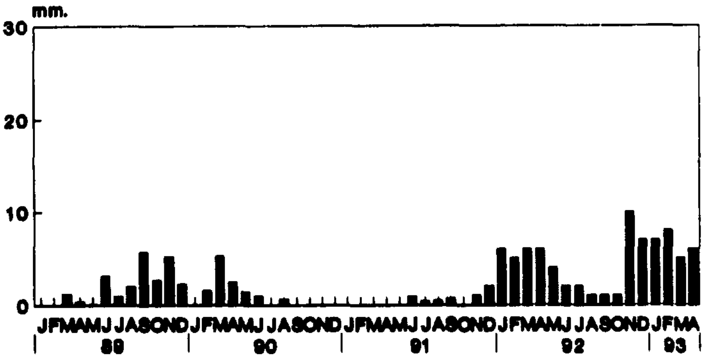

Fig. 4. Leachate production from Test Cell 1, Spillepeng.

potential evaporation, which may be lower than precipitation reduced by actual evaporation, and thus less than the runoff when averaged over time, is given in Fig. 6, to show when leachate could be expected to be produced. The discharge from the old landfill was rather constant, somewhat less than 10 mm month^{-1}, with less leachate in the autumn (5–6 mm month^{-1}) than in the winter and the spring (9–13 mm month^{-1}). The discharge from the test cells was very low (0–2 mm month^{-1}), except for early 1990 and early 1992, when the production was about 5–8 mm month^{-1} for 4-month periods. As a consequence of high precipitation (130 mm) in November 1992, 17 mm of leachate was produced from one of the test cells in November and 20 mm left the cell in December 1992. The drainage rate remained high, and in March 1993 was still 11 mm. The annual volume of drainage water from the old landfill was in the range 80–96 mm and from the two test cells 5–51 mm and 15–82 mm, respectively. These volumes are less by 100–200 mm than values reported by Ehrig (1983) for a region in Germany with 100 mm higher precipitation than in Malmö.

The leachate from the active landfill has, since the measurements started in 1991, excluding the very first month when the production was 44 mm, been in the range 13–27 mm month^{-1}. More water is added to the landfill from waste water treatment

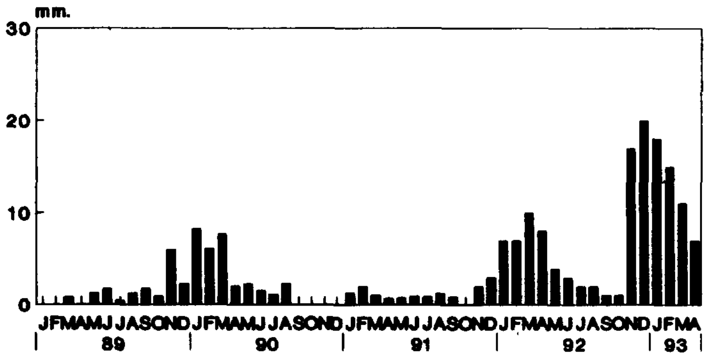

Fig. 5. Leachate production from Test Cell 2, Spillepeng.

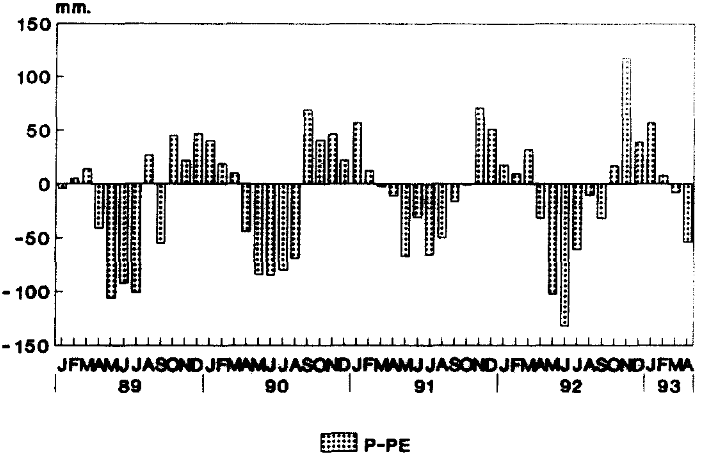

Fig. 6. Precipitation reduced by potential evaporation, Spillepeng.

sludge (about 23 mm $month^{-1}$) than is released through the drainage system. The water input, precipitation plus water added with the waste water treatment sludge, is compared with the landfill discharge in Fig. 7. The discharge did not respond to the large precipitation in November 1992. The leachate volume in 1992 was 257 mm, which corresponded rather closely to the water added with the sludge, 291 mm.

A detailed analysis of the discharge from the old landfill shows that the monthly peak flow, 12 mm in January 1990, occurred after an autumn which was drier than normal. The local precipitation for October 1989–January 1990 was 200 mm and the drainage volume 35 mm. Thus, the peak cannot be attributed to the rainfall in the preceding few months. The drainage volume in October 1990 was 10 mm as compared with only 6 mm in September. In this case, the peak was caused by large rainfall amounts in September (130 mm). Also, from November to December 1992 the

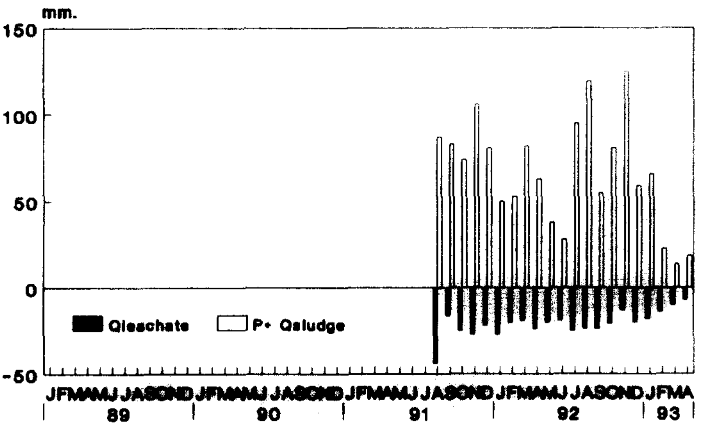

Fig. 7. Monthly water input as precipitation and waste water treatment sludge compared with discharge, SYSAV active landfill, Spillepeng.

monthly leachate production increased from 5 mm to 10 mm as a consequence of a large rainfall amount (120 mm) in November. Although there is some response to high monthly rainfall on the leachate production, there is no clear correlation.

The discharge from the old landfill was low (5–6 mm $month^{-1}$) in July–September 1990, October 1991 and August–November 1992. It seems that evaporation losses do not manifest themselves in reduced drainage until late summer or early autumn. The slow and very reduced response of the discharge from the old landfill to the surface processes, precipitation and evaporation, indicates that the percolation through the landfill occurs mainly as matrix flow and that macropore flow is not significant.

The monthly discharge fluctuations for the two test cells are pronounced, but the monthly drainage volumes are still small. The response to rainfall is not clear. Daily rainfalls of 30 mm are not recognized as increased drainage, not even in wet periods in the autumn when evapotranspiration does not occur. Small prolonged discharge peaks are often observed the month after high monthly precipitation, as for Test Cell 1 in September 1989, and for both test cells in November 1989, and all through the winter 1992–93. However, the very high rainfall (130 mm) in September 1990 did not produce any leachate.

The difference between the discharge hydrographs from the test cells, which show monthly fluctuations and cessation of flow, and from the old landfill, from which the flow is almost constant, indicates that some macropore flow occurs in the test cells. The main difference is, however, that the drainage volumes from the test cells are much smaller than from the old landfill. Water is continuously accumulating in the test cells.

Thus, a comparison of the drainage characteristics of the three different landfills shows that it is only in the test cells that the leachate production is, and only sometimes, influenced by high monthly precipitation. The test cells have an average height of only 5.5 m, and some macropores may still form a continuous system. In the much higher old landfill, evaporation losses in the summer do not manifest themselves in reduced drainage until in the early autumn. Increased monthly discharge is due to accumulated precipitation over many months.

7. Comparison between landfills and natural land

In a long-term perspective, a landfill is a natural part of the environment. By comparing the water balance terms for the landfills and for the two agricultural basins Höje and Värpinge, some information about how fast the landfills are approaching natural conditions, from a quantitative physical hydrological point of view, can be obtained. By taking the difference between precipitation (adding waste water treatment sludge contribution) and runoff or leachate production, the sum of evaporation losses and accumulated water storage over the year is determined. The results for several years and the various landfills are given in Table 1. Comparison is made with the Höje river discharge and the small tile-drained experimental basin Värpinge. No measurements were performed in Värpinge in the period 1989–1992; instead mean values for the period 1971–1980 were used. The annual precipitation

Table 1
Annual precipitation (p) and the sum of evaporation and accumulation of water in landfills and basins (mm)

Year	p	Old	Test Cell 1	Test Cell 2	Active	Höje	Värpinge
1989	452	358	429	436		369	–
1990	576	480	563	537	–	427	–
1991	638	544	633	623	–	399	–
1992	556	476	505	474	590	375	–
Mean	556	465	533	518	590	392	441

was 589 mm, the evaporation 441 mm, the drainage 113 mm and the deep groundwater discharge 28 mm.

The values in Table 1 are higher for the landfills than for the agricultural basins. It was stated above that heat conduction does not contribute to increased evaporation from landfills as compared with that from grass-covered fields. It was also shown that internal processes within the landfill have little influence on the water balance. Therefore, water is accumulating in all the landfills. As a mean, found as the difference between landfill values and Höje basin values in Table 1, 70 mm year^{-1} is accumulated in the old landfill, but the accumulation is much higher in years when precipitation is high. The accumulation in the test cells corresponds to an increased volumetric moisture content of 0.10 over 4 years.

The height of the active landfill is increased by about 4 m year^{-1}. In the previous discussion, it was shown that the moisture content of municipal waste must increase by about 0.1 for leachate to appear and by 0.25 for the landfill to reach field capacity. For a layer of 4 m thickness, these two volumetric moisture contents correspond to storages of 400 mm and 1000 mm, respectively. The sum of evaporation and increased storage given for the active landfill in Table 1 is within this range. It may thus to a large extent represent annual accumulation of precipitation and waste water treatment sludge, indicating that evaporation from the active landfill is minor. Although there is no soil cover on the active landfill, high monthly water input is not reflected in high monthly drainage. The fact that the discharge is not lower in the summer than in the winter (Fig. 7) also indicates that the evaporation is small.

The leachate production for several years is summarized in Table 2. The net

Table 2
Annual discharge, q, from test cells and from the old landfill as a whole, annual discharge regarding 30% of the old landfill as being comparable with the test cells, q^*, and annual water accumulation, Δ, for the old landfill and from the two test cells at Spillepeng (given as mm year^{-1}); the values are rounded to the nearest 10 mm

Mean	$p-e$	$q_{\text{Test Cell 1}}$	$\Delta_{\text{Test Cell 1}}$	$q_{\text{Test Cell 2}}$	$\Delta_{\text{Test Cell 2}}$	q_{old}	Δ_{old}	$q_{\text{test-mean}}$	q^*_{old}	Δ^*_{old}
1989	80	20	60	20	60	100	−20	20	135	−55
1990	150	10	140	40	110	100	50	25	130	15
1991	240	10	230	20	220	90	150	15	120	120
1992	180	50	130	80	100	90	90	65	100	80
Mean	160	30	130	40	120	95	70	30	120	40

precipitation, determined as the precipitation at the site reduced by the calculated evaporation from agricultural basins, is compared with measured annual leachate volumes. The net precipitation always exceeds the drainage volume from the test cells, but in the old landfill, water stored in previous years can contribute to higher annual drainage than precipitation excess.

Annual storage in the landfills is calculated to be 125 mm in the test cells and 70 mm in the old landfill. As the leachate production from the old landfill does not vary much from year to year, the annual accumulation of water depends very much on the precipitation volumes. In years with little precipitation, as in 1989, there is a net loss of water. The volume of drainage water from the test cells varies from year to year, but is much less than from the old landfill. Water accumulates in the young waste in the test cells also in dry years.

As 15 ha, or 30%, of the old landfill is comparable with the test cells, i.e. the waste is only a few years old, the water balance computation for the old landfill can be divided into two parts, the test cell water balance being applicable to 30% of the landfill. As the mean annual leachate from the test cells was 35 mm and the leachate from the old landfill, including the 30% of rather new waste, was 95 mm, it means that the mean leachate production from the 70% of the landfill consisting of old waste is 120 mm year^{-1} and the annual accumulation of water $(p - e - q)$ is 40 mm year^{-1}. Thus, annual storage is of importance also for the part of the landfill which consists of only old waste.

8. Conclusions

The hydrology of a landfill is greatly controlled by the soil cover in the sense that the evaporation losses and the time distribution of the percolation into the waste material depend on the thickness of the cover and on the vegetation on it. If the soil cover is not thin, the evaporation corresponds to the regional evaporation. Much water can be stored within the waste deposit. In young landfills the leachate production is minor, 30–40 mm year^{-1}, and percolation through the waste deposits occurs as preferential flow. Water is still accumulating in 10-year-old deposits. From landfills of this age, the rate at which drainage water leaves the landfill is rather constant in time, with only small, much delayed, seasonal fluctuations.

9. Acknowledgements

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