

## **Water budget analysis—a tool to minimize leachate production**

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**Abstract** Uncontrolled leakage of polluted leachate from landfills is the largest long-term hazard of environment disturbance from landfills. Large efforts should be made to control the leakage. Depending on the type of waste, different water transport regimes are desirable. For municipal waste with a large fraction of organic matter, high water transport through the landfill is advantageous during landfill operation time. Large water transport benefits biological decomposition and the attendance time can be reduced. For coal and peat ashes that produce leachate where we lack practical applicable methods today to reduce the environmentally hazardous concentrations, the water flux through the deposit has to be small to minimize leachate production from such deposits. For tailings with a large sulphide content, oxidation (producing acid) can be reduced by using a saturated cover-layer. Actions undertaken must be of such sustainability that the landfills then can be left without supervision. Water budget analysis is a useful tool when tailoring water flow through landfills. Effects of location (recharge/discharge area), bottom and top liners, surface drains, capillary barrier and vegetation covers are discussed.

### **Analisis de balance hidraulico—un utensilio para limitar la producción de lixiviado**

**Resumen** Derramamiento no controlado de lixiviado de depósitos de desechos a largo plazo la amenaza más grande de perturbación del medio ambiente de depósitos de desechos. Dependiendo de los distintos tipos de desechos son deseables distintos tipos de sistemas de transporte de agua. Para la basura municipal con una cuota grande de materia orgánica es conveniente usar un gran transporte de agua a través del basurero durante el tiempo de operación. Un gran transporte de agua beneficia la decomposición biológica y se puede reducir el tiempo de supervisión. Para ceniza de carbón y turba que produce lixiviado para el cual hoy en día no existe métodos aplicables para reducir las concentraciones peligrosas para el medio ambiente, el transporte de agua a través del depósito tiene que ser poco para reducir la producción de lixiviado. Para desechos de minas que contenga mucho sulfuro, la oxidación (producción de ácido) puede reducirse usando una capa empapada de agua. Las medidas aplicadas tienen que ser de tal duración que sea posible dejar los depósitos sin supervisar. El análisis de balance hidráulico es un utensilio practicable para diseñar el transporte de agua a través de depósitos de desechos. Se discute los efectos de ubicación (área de influjo/derrame), capas de fondo y encima, barreras capilares, canales de superficie y capas superpuestas de vegetación.

## **INTRODUCTION**

Uncontrolled leakage of polluted leachate from a landfill to the environment is the largest long-term hazard of environment disturbance from a landfill. Consequently large efforts should be made to control the leakage. Since it is not very likely that

leachate from landfills will be collected and treated during the hundreds or thousands of years that leachate is expected to be formed, the actions undertaken must be of long duration. Depending on the type of landfill, transport of different quantities of water through the landfill is desirable. For municipal waste with large fractions of organic material, a high water transport through the landfill is desirable during the landfill operation time. A large water transport (large leachate production) through the landfill benefits biological decomposition and hence the time the landfill needs attendance can be shortened. When the decomposition processes have ended (or have been reduced) and the contaminant concentrations in the leachate have been reduced to an acceptable level, these landfills may be left without attendance. The actions undertaken should be such that the landfill then can be left without supervisory control. For coal and peat ashes that produce leachate where we lack practical applicable methods today to reduce the environmentally hazardous concentrations, the water flux through the deposit has to be small to minimize leachate production from such deposits. Water budget analysis is a useful tool when tailoring water flow through landfills.

## WATER BUDGET EQUATION

The water budget equation for an area with negligible water production is:

incoming water volume = outgoing water volume + change in storage

For an undisturbed area, the precipitation,  $P$  equals the sum of the evapotranspiration (evaporation + transpiration),  $E$ , the net discharge,  $Q$  from the area and the change in storage,  $\Delta M$  within the area. The water budget can be written in numerically equivalent  $\text{kg year}^{-1}$ ,  $\text{l year}^{-1}$  or  $\text{mm year}^{-1}$ , since for water  $1 \text{ l} \approx 1 \text{ kg} \approx 10^{-3} \text{ m}^3 \text{ m}^{-2}$ . Precipitation and evaporation are normally given in  $\text{mm year}^{-1}$  and comparison between landfills of different sizes is facilitated when using  $\text{mm year}^{-1}$ , so that notation is adopted here. For a landfill the water budget including water production becomes (Fig. 1):

$$P + Q_{\text{in}}^{\text{Surf}} + Q_{\text{in}}^{\text{Ground}} - Q_{\text{Out}}^{\text{Surf}} + V + B = E + G + L + \Delta M \quad (1)$$

where  $P$  is precipitation and leachate recirculation,  $Q_{\text{in}}^{\text{Surf}}$  is the surface discharge to the landfill,  $Q_{\text{in}}^{\text{Ground}}$  is the net groundwater discharge to the landfill,  $Q_{\text{Out}}^{\text{Surf}}$  is the surface discharge from the landfill without production of leachate,  $V$  is water added with the waste,  $B$  is the biological net production,  $E$  is the evapotranspiration,  $G$  is water loss as vapour,  $L$  is leachate production (i.e. the water polluted by the waste) and  $\Delta M$  is the change in the water content of the waste during the time,  $\Delta t$ .

The precipitation  $P$  in humid areas is of the order of several  $100 \text{ mm year}^{-1}$  or more and the evapotranspiration  $E$  is a little less, while the biological net production  $B$  and the outflow of water vapour  $G$  in connection with gas production in landfills with organic materials may be  $10\text{--}20 \text{ mm year}^{-1}$  (Ehrig, 1983; Baccini *et al.*, 1987). The storage term  $\Delta M$  may have rather large importance during the formation of a landfill and when comparing individual years. However when determining the long-term average of leachate production for an abandoned landfill it can be neglected.

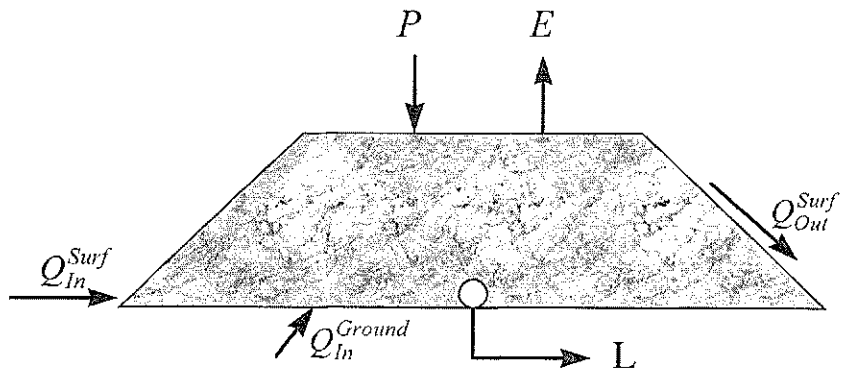


Fig. 1 The larger terms in the water budget for an abandoned landfill.

For an abandoned landfill (neglecting the smallest terms) the relationship becomes:

$$L = P + Q_{in}^{Surf} + Q_{in}^{Ground} - Q_{Out}^{Surf} - E \quad (2)$$

## LANDFILL WITH MINIMIZED LEACHATE PRODUCTION

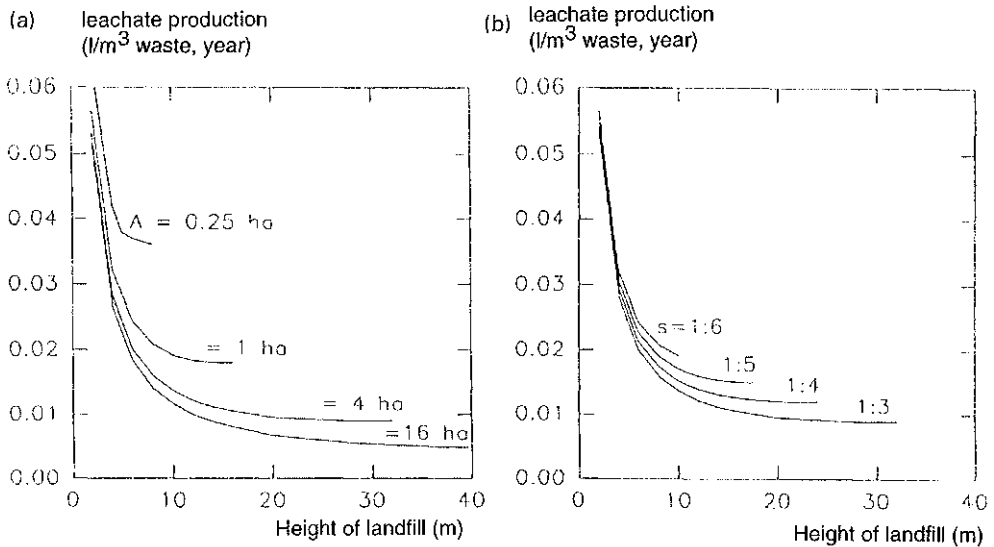
A landfill where the leachate production is to be minimized was chosen to illustrate the water budget analysis. To minimize the leachate production one should (according to equation (2)) reduce the precipitation, the surface discharge and the groundwater discharge to the landfill while the evapotranspiration and the surface discharge from the landfill should be maximized.

### PRECIPITATION

By altering the geometry of the landfill, the leachate production per  $m^3$  waste can be minimized. The larger the waste volume that can be stored within a certain area, the smaller the contribution to leachate production from precipitation per waste volume. A large landfill area gives lower leachate production per  $m^3$  waste than a small area even for the same height  $h$  of the landfill (Fig. 2(a)). Large landfills can be made higher and thus the leachate production per  $m^3$  can be further reduced. A steep slope of the landfill gives a lower leachate production per  $m^3$  than a flat slope (Fig. 2(b)). The advantages of a large and steep landfill have to be evaluated with regard to geotechnical disadvantages (hazards of soil- and slope-instability) and disturbance in the landscape. Leachate production per tonne of waste can be reduced by compressing the waste.

### SURFACE FLOW TO THE LANDFILL

The quantity of polluted water from a landfill can be reduced by minimizing the surface discharge to the landfill. This can be made with ditches orthogonal to



**Fig. 2** (a) Surface area  $A$  and landfill height  $h$  influence on leachate production (groundwater recharge  $P - E$   $100 \text{ mm year}^{-1}$  and slope of 1:3 was assumed); (b) landfill slope  $s$  influence on leachate production (groundwater recharge  $P - E$   $100 \text{ mm year}^{-1}$  and landfill area  $A$  of 4 ha was assumed).

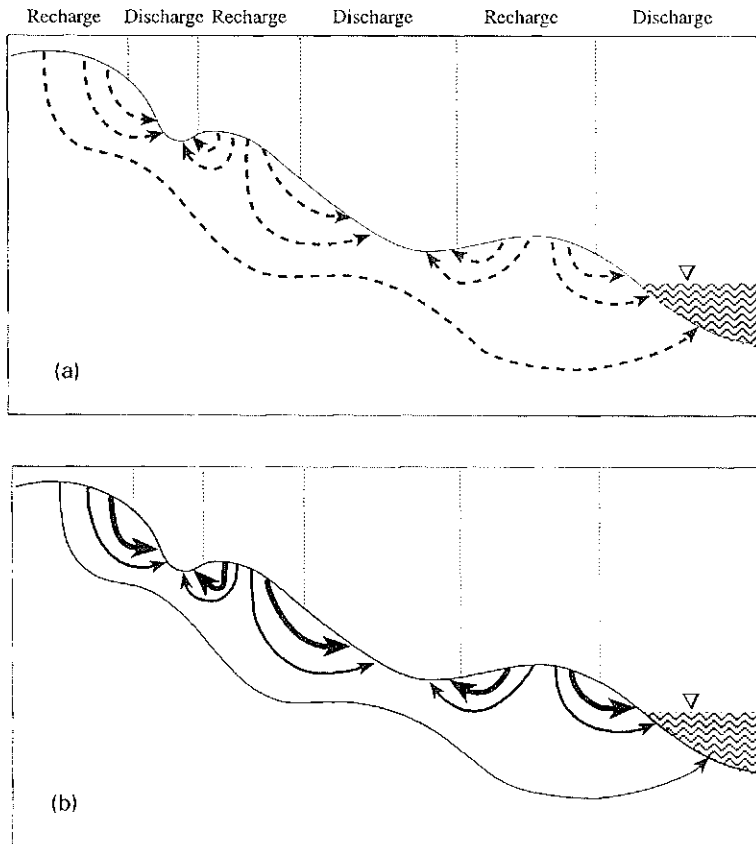
the flow direction that divert the discharge from the landfill. The closer the ditches are located to the landfill, the smaller the quantity of surface water that will be polluted.

## GROUNDWATER FLUX

### Recharge and discharge areas

An important factor to consider when locating a landfill is whether it is to be located in a recharge or in a discharge area. Recharge areas are found on and close to water divides while discharge areas are found in the valleys (Fig. 3(a)). The groundwater flux has a downward direction in the recharge areas and an upward direction in the discharge areas. Clean groundwater may enter a landfill located in a discharge area, while for a landfill located high up in an area, the polluted groundwater becomes diluted and there are good chances for sorption of the polluted water by the soil; on the other hand, the polluted water can move long distances and reach deeper groundwater levels. If the landfill is located in a local recharge area the dilution becomes smaller, the transported distance shorter and the polluted water does not reach deep layers. If the aim is to minimize the water transport through the landfill a recharge area should be chosen, or alternatively, the border between a recharge and a discharge area.

The flow lines in the homogenous soil in Fig. 3(a) are drawn so that the flux in each stream tube is approximately equal. Most natural soils are not homogenous: the hydraulic conductivity usually decreases with depth due to greater biological activity



**Fig. 3** (a) The distribution of recharge and discharge areas, and groundwater flow lines, in a homogeneous aquifer (the absolute scale is arbitrary but the figure has the same length and height scale); (b) schematic picture of the groundwater flow (after Grip & Rodhe, 1985) (the size of the arrows is approximately proportional to the size of the fluxes).

in the top soil (worms, roots etc. causing macropores). This makes the velocities higher in shallow soil layers resulting in a flow pattern similar to the one shown in Fig. 3(b). Geological conditions are often very heterogeneous and there is often a mixture of anisotropic soils and rocks with greatly varying hydraulic conductivity. It is thus important to make a thorough geohydrological survey of each landfill to determine the local conditions.

A recharge or a discharge area can be identified by measuring the location of the groundwater level (or the piezometric level) at several depths at one location. If the groundwater level in the shallow tubes is lower than in the deeper tubes it is a discharge area (Fig. 4). In a clay soil the total potential (the sum of pore pressure and geometric height) for the two levels are compared.

When locating a landfill, large groundwater aquifers such as sand and gravel formations, or limestone and sandstone should be avoided. These could be used for drinking water. An existing recharge area can, by location of a large landfill in it, be

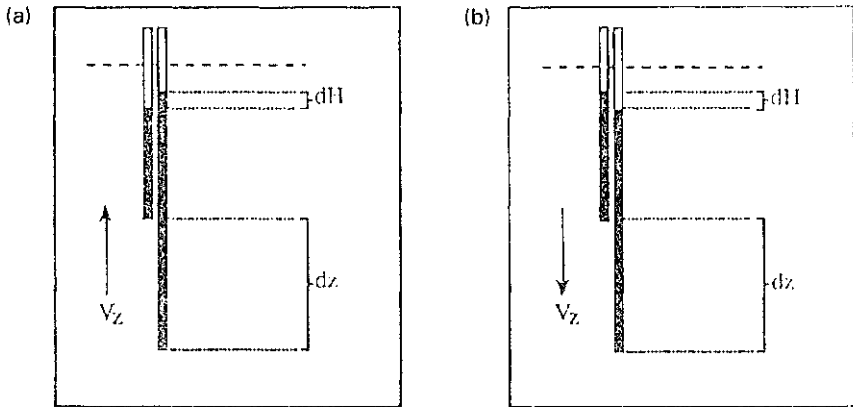


Fig. 4 (a) Location of the groundwater in a discharge area (groundwater flux directed upwards); and (b) location of the groundwater levels in a recharge area (groundwater flux directed downwards).

turned into a discharge area since the direction of the groundwater flux then may be altered.

**Bottom liners and base drains**

In order to reduce the exchange between the landfill and the groundwater (i.e. to minimize the flow of unpolluted groundwater to a landfill located in a discharge area or the outflow of polluted leachate to the groundwater in a recharge area), the landfill should be located on a naturally hydraulically impermeable strata (e.g. clay) or on an artificial liner (Fig. 5). In a recharge area the low-permeability bottom liner is only useful if there is some kind of treatment of the leachate since the amount of leachate is not influenced, only the fraction which infiltrates into the groundwater is reduced.

The vertical groundwater velocity  $v_z$  (with or without bottom liner) can be calculated according to:

$$v_z = Kdh/dz \tag{4}$$

where  $dh$  is the difference in height between the groundwater levels (Fig. 4) in two groundwater tubes at different depths in a profile,  $dz$  is the thickness of the soil layer over which this difference is measured and  $K$  is the hydraulic conductivity of the soil

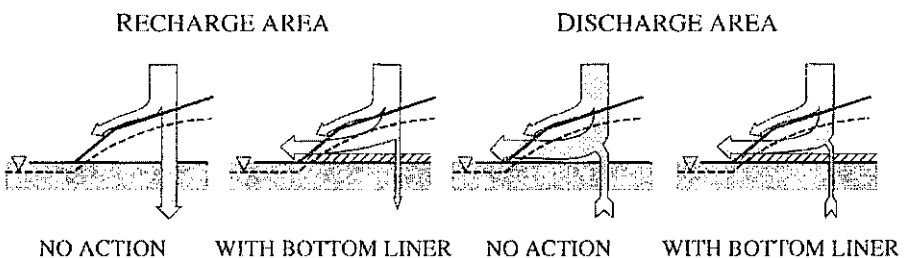


Fig. 5 The principal influence of bottom liners in recharge and discharge areas.

layer. With a layer thickness  $dz = 2$  m, a difference in groundwater level (or total potential)  $dh = 0.1$  m and a hydraulic conductivity  $K$  of  $10^{-7}$  m s<sup>-1</sup> the vertical velocity  $v_z$  becomes 155 mm year<sup>-1</sup>. With a soil with the hydraulic conductivity of  $10^{-9}$  m s<sup>-1</sup> the vertical velocity becomes only one hundredth of the first example. Increasing the thickness of the low permeable layer has only marginal effect since doubling the thickness of the layer the only halves the velocity.

The hydraulic conductivity (m s<sup>-1</sup>) for some liners and soils with hydraulic conductivity low enough to be used as liners are: clay:  $10^{-8}$ – $10^{-10}$ , to  $10^{-5}$ – $10^{-8}$ , soil mixed with bentonite:  $10^{-8}$ – $10^{-10}$ , concrete mixed with ash:  $10^{-8}$ – $10^{-10}$ , bentonite:  $10^{-9}$ – $10^{-10}$ , fly ash mixed with waste products (e.g. lime or bio-sludge):  $10^{-7}$ – $10^{-9}$ . For a landfill located in a discharge area, the groundwater inflow to the landfill can be minimized by locating a drain beneath the landfill under the liner. More information about construction and effects of liners and drains can be found in e.g. McEnroe (1989a, b). Great care should be taken when constructing artificial bottom and top liners since damage in these may completely ruin their efficiency. Drying cracks may occur in the liners if they are allowed to dry in the open (Mishra & Miller, 1988).

**Effect of settlement and of chemicals on the hydraulic conductivity of liners**

The soil beneath a landfill, if it is sensitive to settlement, will settle as a response to the weight of the landfill. Since the landfill is highest in the central part, the weight is largest there, and the settlement will therefore be largest in the middle (homogeneous underlying soil). The size of the settlement will depend on the kind of underlying soil. Settlements of 2.75 m have been observed on peat ground (Jasper *et al.*, 1985) and settlements of 1 m have been observed on clay soil (Meijer, 1993). In the bowl created in this manner there is often an increased groundwater level. The long-term effect of using liners and drains on soils sensitive to settlement should be questioned. The settlement may crack the liner or alter the inclination of the liner, in which case, the liner will not work satisfactorily. Most capillary raising soils are sensitive to settlements.

Interaction between the waste (or its leachate) and a clay liner may increase the hydraulic conductivity of the clay liner. Gray (1989) reviews studies of the influence of leachate and waste on the underlying clay layer. He concludes that some of the large increases (several orders of magnitude) of hydraulic conductivity reported in the technical literature were caused by the experimental procedure. But no single

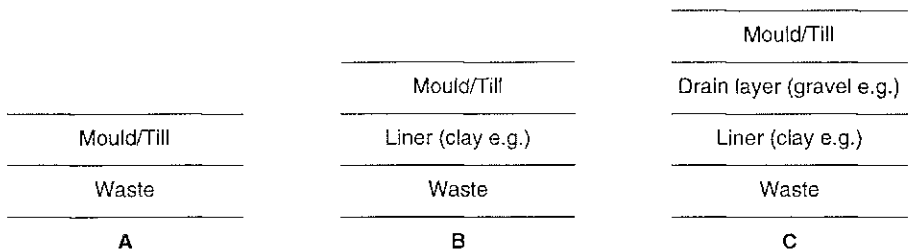


Fig. 6 Common top covers.

available lining material appears suitable for long-term impoundment of all kinds of wastes. Wastes which are highly ionic, contain salts, strong acids or strong bases can be aggressive to soils, soil cement, asphalt concrete and to some of the commercial polymeric membranes, especially those containing plasticizers. Wastes which had organic compounds were often aggressive toward polymeric membrane liners and towards asphalt materials. Oily wastes, in particular, tended to cause swelling and degrade desirable physical properties (e.g. elasticity) in the membrane liners. It is thus important to perform exposure tests prior to the selection of liners for specified wastes and to ensure that only those specified wastes are placed in that particular landfill.

## **SURFACE DISCHARGE FROM THE LANDFILL**

If you can increase the amount of water discharged at the surface of the landfill without contact with the waste you can also decrease the amount of leachate. This can be performed by increasing the slope of the landfill surface and by covering it with several strata of different types (together called top covers). The overall effect of the top covers depends on co-operation between the different strata. Three different kinds of common top covers are shown in Fig. 6. The mould/till (topsoil) influences the evaporation from the landfill and will be treated in the next section.

### **Top-liners**

The top-liner in case B (Fig. 6) increases the part of the water that will discharge to the side instead of percolating down to the waste, and it also creates a local groundwater level on top of the top-liner. Water will be capillary transported to the mould and hence increases the evaporation. If a top-liner should have any larger effect on the percolation rate its hydraulic conductivity should be less than  $10^{-7} \text{ m s}^{-1}$ . This can be visualized by using equation (4) with the hydraulic conductivity  $dh/dz = 1$ ,  $K = 10^{-7} \text{ m s}^{-1}$  and converting the resulting velocity to  $\text{mm year}^{-1}$  ( $300 \text{ mm year}^{-1}$ ). A crack on a top-liner not only causes leakage of the groundwater created just above the crack, but also a great part of the water formed on the landfill upstream of the crack will leak into the landfill.

### **Surface drain**

By locating a drain layer on top of the top-liner you can reduce the time with water on top of the top-liner that may percolate to the waste. The co-operation between the different top-covers is complicated and depends among other things on the thickness of the layers, their hydraulic conductivity, slope and storage capacity. Calculations to study the effect of the different factors have been made by Hollingshead *et al.* (1988), Oweis & Khera (1990) and Lindgren & Rasmussen (1989).

## Capillary barriers

By using a capillary barrier you can increase the surface discharge and thus further reduce the leachate production from a landfill. The barrier only works during unsaturated conditions (when you have both air and water in the pores of the soil). The principle of a capillary barrier is that during unsaturated conditions a soil with small grains contains more water and has a higher hydraulic conductivity than a coarser soil. With a fine sand on top of a coarse sand you get a capillary zone at the base of the finer material. With a sloping border between the two layers the water will move in the direction of the slope. Andersen *et al.* (1988) describe the principle and show some preliminary results. The technique is not yet well tested but the preliminary experiments are promising according to Melchior & Miehling (1988).

## EVAPORATION AND TRANSPIRATION

Evapotranspiration consists of three parts: evaporation from the bare soil, transpiration from vegetation and evaporation of the precipitation caught by the vegetation (interception). The factors that can be influenced with respect to evapotranspiration from a landfill are the vegetation and the wetness of the surface. The evaporation from a vegetated surface is larger than from an unvegetated surface. The difference in evaporation between a vegetated surface and bare soil may be several hundreds of mm during the vegetation period. For humid areas the evaporation of intercepted precipitation from forests is approximately one third of the precipitation (Lundberg, 1996). It is thus important when closing a landfill to make sure that it becomes vegetated. The vegetation should have a long growing season, large roots and large leaf area. It is best if it is possible to mix different kinds of vegetation. Since the precipitation caught by the vegetation evaporates quickly, trees and bushes are to be preferred to lower plants, but grass prevents surface erosion and is quickly established. In the long time perspective the landfill will, due to spontaneous vegetation of plants and trees, get the same vegetation as the surrounding terrain. Since some trees (e.g. spruce) have a strong tap root seeking down to large depths, the top-cover should be dimensioned with this in mind to make sure that the liner does not become penetrated. It is also important that deeper water can be transported up to the roots. A fine soil can transport water by capillary forces from deeper layers, but this is not possible for a coarser soil, so one should not choose too coarse materials as top cover.

## LANDFILLS WITH HIGH ORGANIC CONTENT

For municipal waste with high organic content where a large water flux is desired the inverse problem to the one illustrated above should be solved. When trying to maximize the water flow through such a landfill the hydraulic conductivity of the waste itself may be the limiting factor.

## DEPOSITS WITH OXYGEN BARRIERS

For tailings with large contents of sulphide it is desirable to reduce oxidation in order to minimize acid generation. Oxidation may be reduced by changing the oxygen diffusion coefficient. This coefficient may vary by four orders of magnitude, from the highest value in air to the lowest value in water. Placing mine tailings under water should thus be the most effective way to reduce the oxidation. This can be made by refilling the mine with tailings and thus placing the tailings under the groundwater level. Alternatively it is possible to raise the groundwater level with dense subsurface dams. Another possibility is to try to achieve an oxygen barrier by placing an almost saturated soil layer on top of the tailings (e.g. Collin & Rasmussen, 1986; Nicholson *et al.*, 1991). The single most important factor for the oxygen diffusion coefficient is the degree of saturation of the soil. The coefficient is most sensitive to the degree of saturation close to the saturation value and may decrease by three orders of magnitude when the degree of saturation is increased by 10% (Collin & Rasmussen, 1988). A technique similar to the capillary barrier should be possible to use, i.e. placing a fine material on top of a coarse material. Since the fine material can contain a large portion of water even high above a groundwater level, it is possible to achieve an almost saturated layer. The principle works in theory and in laboratory tests, but has not yet been tested in connection with evaporation and frost (Akindunni *et al.*, 1991).

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