Monitoring piezometers in recharge areas: Is one 'upstream' and two 'downstream' adequate?

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Abstract

Common practice by regulatory agencies and the groundwater industry is to install one piezometer 'upstream' and two 'downstream' of contaminated sites. 'Upstream' and 'downstream' usually refer to 'up-gradient' and 'down-gradient' with respect to the groundwater table. The 'up-gradient' piezometer is intended to show the unaffected chemical background condition of the groundwater; the 'down-gradient' piezometers are intended to detect subsurface contaminants leaving the disposal site.

This practice is based on the widely held belief that shallow groundwater must flow down-gradient parallel to the groundwater table. In fact, this is only valid for limited parts of groundwater flow systems between recharge and discharge areas. Groundwater flow is oriented subvertically downwards in recharge areas and subvertically upwards in discharge areas. This is especially valid in the commonly occurring case where higher permeable layers exist beneath less permeable layers in the subsurface.

The example of an industrial waste disposal site in Bielefeld-Brake (Germany) demonstrates the costly mistakes which result if these unjustified assumptions are applied to monitoring design and remediation measures in recharge areas. Based on the assumption of lateral flow at this hilly site, a great number of piezometers were installed around the perimeter of the waste disposal site. Since these piezometers did not detect any contaminants, it was assumed an unknown, and as yet undiscovered, mechanism had confined the contaminants to the site. As a preventative measure, a slurry wall and pumping wells were installed around the perimeter of the waste disposal site at an estimated cost of $20-25 million.

A nearby, previously existing deep well showed downward migration of dissolved contaminants typical of recharge areas. This downward migration could not have been detected with the piezometers installed to monitor the assumed lateral contaminant migration. At present, there are no plans to investigate the downward migration of the contaminant plume.

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Introduction

When investigating landfills or other contaminated sites it is common practice among regulatory agencies and within the groundwater industry to install one piezometer 'upstream' and two piezometers 'downstream' of contaminated sites. 'Upstream and 'downstream' usually stands for 'up-gradient' and 'down-gradient' with respect to the groundwater table. The 'up-gradient' piezometer is intended to show the unaffected chemical background condition of the groundwater; the 'down-gradient' piezometers are intended to detect subsurface contaminants leaving the disposal site.

This practice is based on the widely held assumption that shallow groundwater must flow down-gradient parallel to the groundwater table. This, however, is only valid for limited parts of groundwater flow systems between recharge and discharge areas. Recharge areas prevail by far over discharge areas. Also in recharge areas groundwater tables are normally much further below the surface than in discharge areas. Accordingly most landfills are located in recharge areas.

By means of the example of the industrial sludge disposal site Bielefeld-Brake in Germany we will show that the general application of the above assumption contains a major pitfall with regard to the detection of migrating contaminants. The assumption of groundwater flowing parallel to the groundwater surface can lead to costly errors if this concept is applied for monitoring design and remediation measures in recharge areas.

At the Brake landfill site it was *a priori* assumed that groundwater flow was lateral and parallel to the groundwater table. A great number of shallow (approximately 6m deep) and a lower number of deep (20-25m deep) piezometers were installed around the disposal site. As these piezometers did not detect any contaminants migrating from the site, it was assumed that an unknown mechanism had trapped the contaminants at the site. A suitable mechanism was, however, neither proposed nor looked for.

The Brake landfill contains known toxic contaminants, however, no subsurface migration of these contaminants was detected. Nor were there or are there known any mechanisms which would prevent the contaminants from leaving the site.

The solution to this apparent paradox is presented in this paper.

Basic principles of groundwater flow systems

The universal principles of potential theory (Hubbert, 1940, 1957; Tóth, 1962, 1963; Freeze and Witherspoon, 1966, 1967) demonstrate that gravitational groundwater flow is oriented subvertically downwards in elevated recharge areas and subvertically upwards in discharge areas, usually in valleys. This is especially valid in the commonly occurring case where higher permeable layers exist beneath less permeable layers in the subsurface.

In topographically higher areas, groundwater flows downward from the water table into the groundwater body because of the force of gravity. The resistance of the soil/rock system to the flow of groundwater uses up energy. Therefore, in a recharge area, water levels in deeper piezometers are lower than the elevation of the groundwater table.

Under topographically lower lying areas, in discharge areas, deeper groundwater flows upwards to the surface due to energy stored by compression of the water (Weyer, 1978). Piezometers placed in the deeper parts of the rising groundwater stream are therefore flowing. Flowing piezometers are an indication of discharging groundwater.

The Brake landfill site

The Brake landfill site alerted the German public to the perils of waste disposal much the same way as the Love-Canal in the United States did for Americans. Houses built on the Brake landfill were removed upon rediscovery of the subsurface conditions.

The digital elevation model of Figure 1 shows the location of hills and valleys around the Brake landfill allowing us to estimate the location of recharge and discharge areas in the vicinity of the waste disposal site Brake. The hilly areas are recharge areas, the deeper lying valleys are discharge areas. We have marked two flowing wells at the sites 22 and 23. Whereas well 23 flows out of deeper layers, well 22 flows out of the same Jurassic claystone containing the Brake waste disposal site.

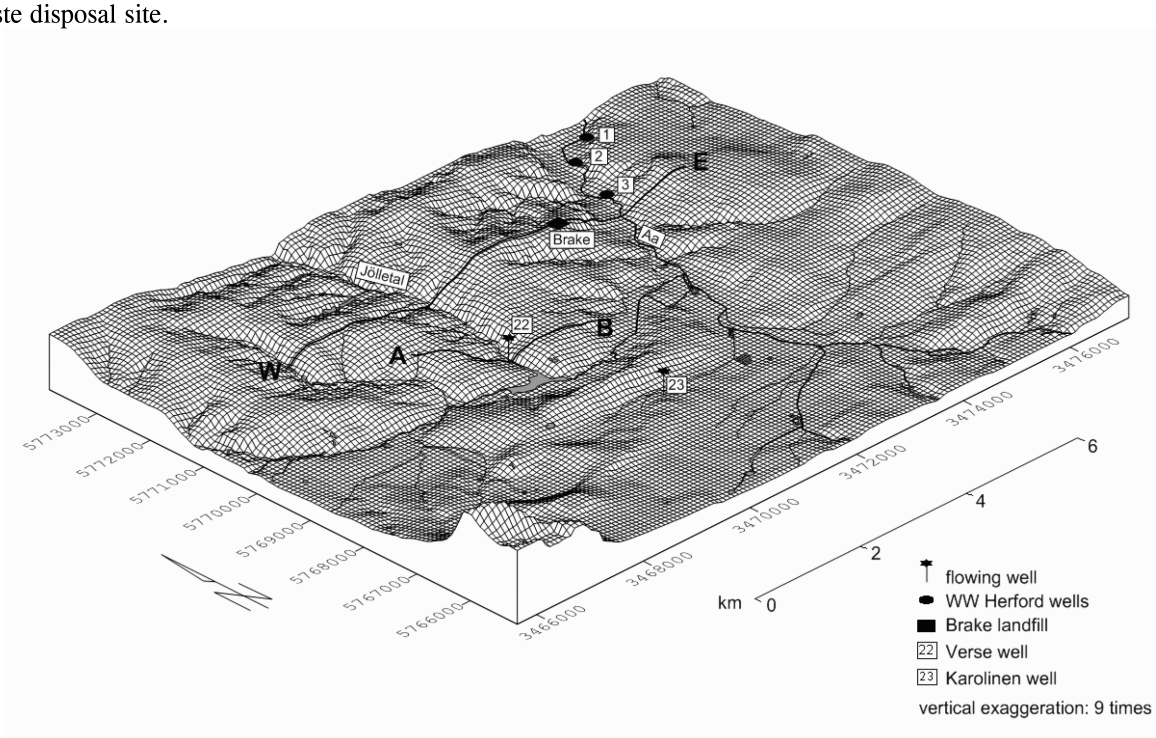


Fig. 1 Digital elevation model of the area around the industrial waste disposal site Brake, location of flowing boreholes, Verse well in Jölletal (22) and Karolinen spring (23). The location of the crossection for which groundwater flow has been calculated is shown. [After Weyer, 1995, Fig.58]

The Brake waste disposal site was constructed in former clay pits and lies on a hill in a pronounced recharge area. The pit was carved out of Jurassic claystone. At greater depth it is underlain by more permeable Triassic layers. Table 1 schematically lists the sequence of layers and the relative permeabilities assigned by us.

Numerous piezometers and a limited number of piezometer nests are situated in the vicinity of the Brake landfill (Figure 2). Loss of circulation occurred during the drilling of the deep wells of nests 12, 16, and 17, indicating the presence of water transmitting fractures. Measurement of the orientation of 29 fractures from outcrops A1 and A2 indicate a predominant NE-SW fracture trend (Figure 2; rose diagram).

Table 1. Geology and assigned relative permeabilities near Brake

Formation Name	Geology	Permeability [m/s]
Liassic		
weathered Liassic	weathered clay	1
Lower Liassic	limestone layers & marl	10
Keuper		
Rät	clay & sandstone	20
Gipskeuper	fractured marl & gypsum	500
lower Keuper	marl, dolostone	50
Muschelkalk	limestone	1000

Water levels at Brake piezometer nests

Water level data were collected by the City of Bielefeld for 135 piezometers in the vicinity of the Brake landfill. The available data cover the period October 1970 to January 1991; most data were collected from 1986 to 1990.

Water levels in neighbouring piezometers, screened at different depths, indicate recharge conditions in that water levels in deeper piezometers are lower than in shallower piezometers (Figure 3; piezometers 12, 17, 31, Plöger well). The water levels were the same in the deep and shallow wells of some of the piezometer nests in figure 3 (nests 4, 16, and 19). Drilling records for these sites indicate that insufficient or no sealants had been installed in the wells of these nests and that natural sealing did not occur, resulting in similar water levels in the piezometers of a nest because of downward flow of water along the boreholes.

The hydrographs of deep and shallow piezometers in nests 20 and 31 show the typical pattern for downward flow in recharge areas (Figure 4). In nest 20 a slight time lag occurs between the response of the shallow and the deeper piezometers, probably due to entrance resistance at the screen of the deeper piezometer. The difference in water levels between the shallow and deeper piezometer is about 3.5 meter at this nest. Thus, field data confirm that the sludge disposal site lies in a discharge area with strong hydraulic gradients directed downwards.

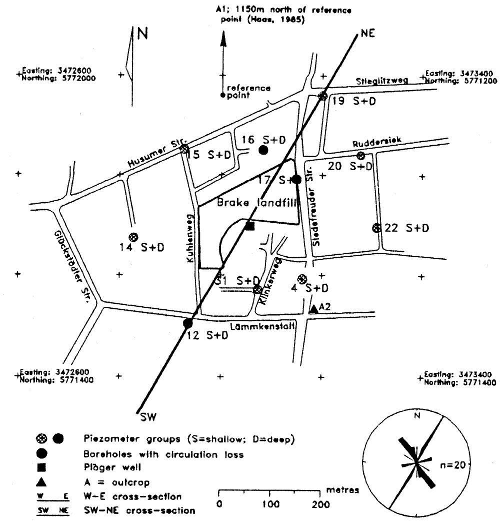


Fig. 2 Brake landfill: location of piezometers, boreholes with circulation loss, the Plöger wells and outcrops A1 and A2. Rose diagram after Haas, 1985, app. 5.5). The NE-SW cross-section line refers to figure 4. [After Weyer, 1995, Fig.42]

Previous hydrogeological concepts at Brake sludge disposal site

It has been suggested that groundwater flow at the Brake site is lateral and parallel to the groundwater table (Figure 5, modified from Heil et al., 1989). The weathered clay layer between an 'upper aquifer' and a 'lower aquifer' was assumed to provide a barrier preventing cross flow. Differences in water levels between shallow and deep piezometers were taken as proof for an impermeable barrier between the so called 'upper' and 'lower' aquifer. In fact, this layer does not exist within the landfill because it has been mined out by the excavation of the former clay pit.

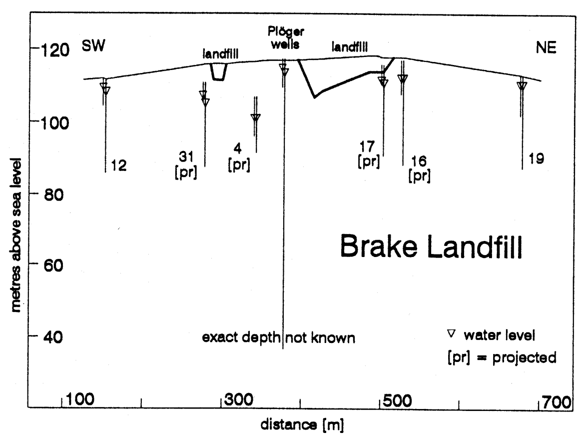
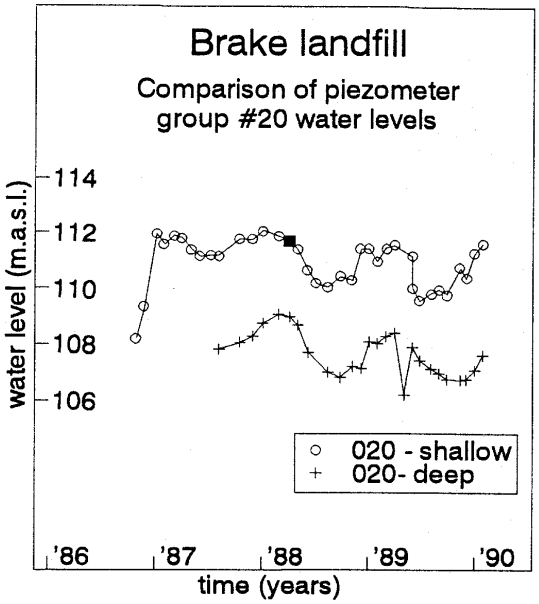


Fig. 3 SW-NE cross-section (see Figure 2 for location). [After Weyer, 1995, Fig.54]

Measurements of the pH of sludges and fluids within the landfill returned values between 9.6 and 12.6. Background values for groundwater in shallow and deep wells in the surroundings were between 6.6 and 7.6. The Plöger wells, shown in Figures 2 and 3, returned pH values between 8.9 and 12.4 during four field tests between January and July 1984. [Haas, 1985, App. 9.2 and 12.1)].

Thus, chemical measurements confirm that the contaminants do migrate and that the direction of migration is sub-vertically downwards. This is expected based on the hydrodynamics in a recharge area with higher permeable layers at depth.



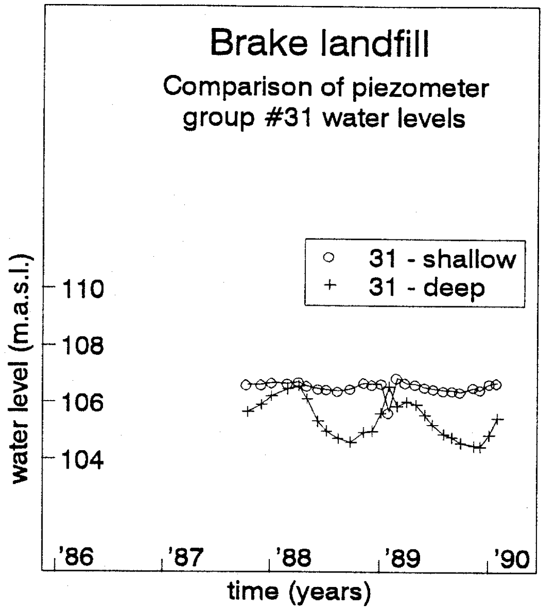


Fig. 4 Comparison of water levels in piezometer groups 20 and 31 (#20: shallow piezometer = 7.5 metres and deep piezometer = 25.7 metres, #31: shallow = 5.5 metres and deep = 23.35 metres) indicating downward flow conditions in a recharge area. [After Weyer, 1995, Fig.50]

Groundwater flow in the vicinity of the Brake landfill

Mathematical modelling of groundwater flow within a regional geological cross-section through the Brake waste disposal site also confirms what has already been derived from a re-interpretation of existing field data (see Figure 1 for location of cross-section W-E). The pattern of groundwater flow systems within the cross-section were calculated with the FLONET code (Guiger et al., 1991). The position of the groundwater table (topographic surface) and the schematic geologic structure adopted for the model are shown in Figure 6. Figure 6 and Table 1 list the relative permeabilities adopted by us for the numerical model.

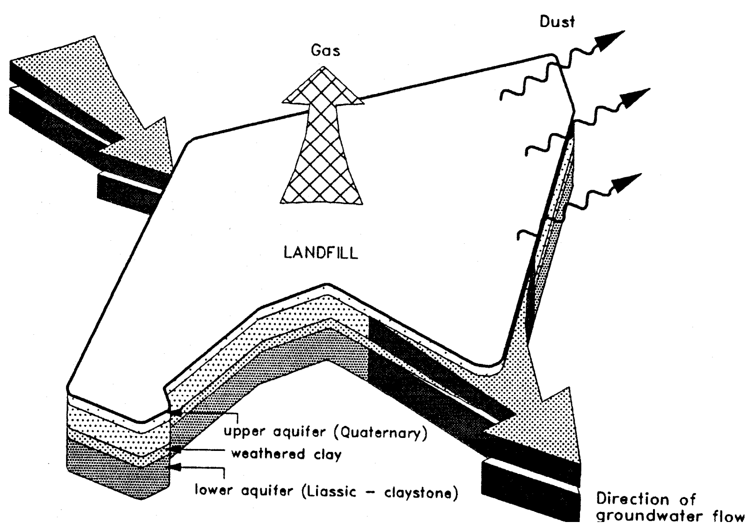


Fig. 5 Block diagram of assumed migration pathways for contamination at the industrial waste disposal site Brake [Modified after Heil et al., 1989, Fig.4].

The calculated flow lines indicate that the Jölletal is a discharge area with upwards directed flow. This had already been indicated by the existence of the flowing well 23 (Verse well) within the same valley. At the site of the landfill Brake groundwater moves steeply downward beneath the landfill, into the gypsum-marl. Flowing laterally along this unit it eventually resurfaces in the valley of the Aa, the major regional discharge area. The steeply dipping flow lines beneath the landfill are the reason that no contamination is seen in any of the piezometers situated around the landfill. They simply have not been installed deep enough to encounter the migrating contamination.

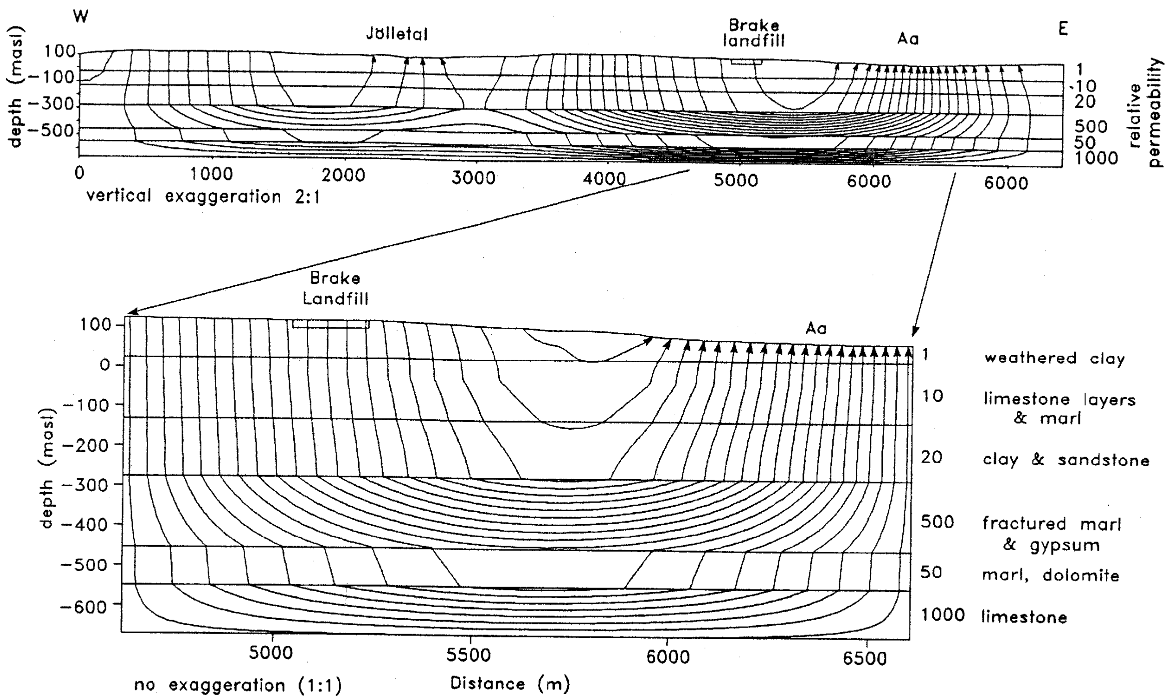


Fig. 6 Regional W-E cross-section through the Bielefeld-Brake landfill with groundwater flow lines, calculated with the FLONET program (Guiger et al., 1991). See figure 2 for the location of the crosssection. The formation names and the relative permeabilities are shown to the side of the section. [After Weyer, 1995, Fig.62]

We have used a numerical simulation and re-interpretation of existing data to suggest the principal contaminant migration pattern between the landfill site and the river valley, namely the downward migration of the contaminants. Further investigations with respect to groundwater dynamics would have to be undertaken to determine the directions and pattern of the actual flow paths between the landfill site and the valley of the Aa river. The orientation of the geologic and model cross-section was arbitrarily chosen by us. At this time there are insufficient data available to determine the position of the discharge point, in the valley of the Aa river, of the migrating plume of contaminants.

Remediation

At the site of the Brake landfill remediation measures have already been put into place based on the lateral groundwater flow concept of Figure 5. Total costs are said to exceed $50 million, twenty to twenty-five million of which have been spent on a ring-like slurry wall, pumping wells, and on a clay cover over the site. There may not have been a need for a slurry wall, considering the downward migration of the contaminants.

Discussion and conclusions

At present, the actual migration pattern of the contaminants has not been determined satisfactorily; neither have the chemical consequences of the migration of the high pH plume through the subsurface been determined. It is not known whether the contaminant plume has reached the river Aa valley.

At the Brake landfill, groundwater does not flow parallel to the water table, as assumed as a base for remediation measures. It has been shown on the basis of field measurements (water levels and pH in wells), and on the basis of the numerical modelling that, since the Brake landfill site is located in a recharge area, the groundwater instead flows vertically downward beneath the landfill.

Clearly, the common practice of investigating the migration of pollutants from contaminated sites by installing one piezometer 'upstream' and two 'downstream' can be a waste of money, if the actual groundwater flow directions have not been determined before the final design of the monitoring network.

It is recommended to first evaluate all available data and undertake inexpensive vertical two dimensional sensitivity model evaluations of likely groundwater flow pattern for the wider area of planned or existing landfills. The final three-dimensional design of a monitoring network of piezometer nests should then be based interactively on the results of all previous piezometers as they are being installed.

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