Infiltration water dating from tritium measurements in mining dumps: methodic specifics and case study

Jens Mibus[1], Peter Szymczak[2], Detlef Hebert[3]

[1] Forschungszentrum Rossendorf e.V., Institute of Radiochemistry, P.O. Box 51 01 19, D-01314 Dresden / Germany
[2] G.E.O.S. Freiberg Ingenieurgesellschaft mbH, P.O. Box 1162, D-09581 Freiberg / Germany
[3] Freiberg University of Mining and Technology, Institute of Applied Physics, Bernhard-von-Cotta-Straße 4, D-09596 Freiberg / Germany

Abstract. The utilization of lumped parameter models for the determination of groundwater residence times is restricted to steady state hydraulics. However, for mining objects such as pits and dumps a transient behaviour is more typical even after closure. Nevertheless information on the mean residence time is needed for risk assessment. Therefore, a combination of the linear and the piston flow model is proposed to take the transient aspect into consideration. The application to a mining dump is discussed.

Introduction

Mine waste dumps and industrial tailings often emit toxic substances such as sulphuric acid, heavy metals, or radionuclides through seepage discharge. An important parameter to characterize these transfer processes is the mean residence time τ_m of the infiltration water usually determined from tritium measurements. Lumped parameter models are used among others for the evaluation of concentrations of environmental tracers in groundwater (Maloszewski and Zuber 1982, Richter and Szymczak 1994). Investigations in abandoned mining areas require an application of these aquifer models to mining dumps. However, some specifics are to be considered to prevent misinterpretations.

Technological depositions with a thick unsaturated zone exhibit a strong heterogeneity of flow paths. This spatial variability is ignored by lumped parameter models. Hence stochastic approaches are used for modeling (van Genuchten 1991).

On the other hand there are sources of systematic errors. Mining dumps exhibit a transient hydraulic behaviour during the deposition of waste material, where lumped parameter models are not applicable. In praxis information is needed on the turnover time of infiltration water for risk assessment and to design remediation measures. An attempt is made to give a reasonable approximation for the problem using an adequate combination of lumped-parameter models.

Hydrogeologic problem

In recent mining periods mine wastes usually were dumped cone-shaped with a total volume of several million cubic meters. In coarse grained, high permeable material large portions of the dump are flown through by infiltrating water unsaturatedly. Water saturation is reached in deeper parts of the dump as shown schematically in Fig. 1. The mean residence time in the unsaturated zone is much higher than that in the saturated zone. The latter works as hydraulic short circuit, where all age components are mixed.

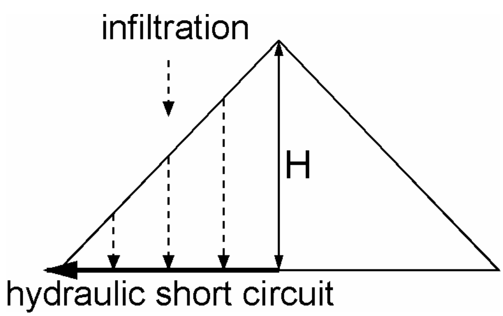

Fig. 1. Geometric set up and simplified flow scheme in a cone-shaped dump

The geometrical set-up and the simplified flow scheme of the dump is sufficiently approximated by the linear model. The linear model represents an unconfined aquifer with linear increasing thickness H. The weighting function f(t) is characterized by an equipartition of all age components from $\tau = 0$ to $\tau = \tau_{max}$ (Maloszewski and Zuber, 1982) as shown in Fig. 2a.

The model applicability explicitly assumes steady state hydraulics, i.e., volume and flux have to be constant. In the course of the deposition of the dump the reservoir size (volume and thickness) increase more or less continuously. The infiltration water is partly or even completely consumed to build up a static reservoir of adhesive water in the initial dry pores. The water percolation begins not until the field capacity is reached. This deceleration depends on deposit rates, recharge rates and capillary capacity and increases the portion of older components in the effluent waters compared to model assumptions. The rigorous application of the linear model results in an systematic overestimation of the mean residence time. They even may exceed the life span of the dump, which is not plausible.

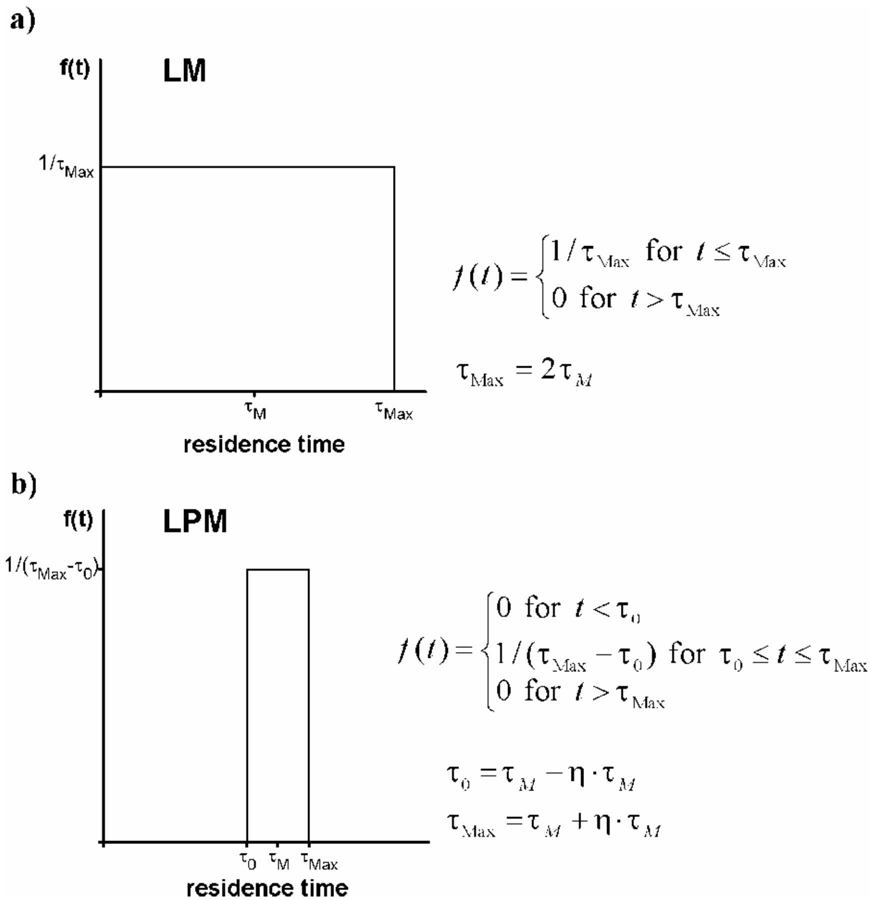

Fig. 2. Weighting function of the linear model LM (a) and the combined linear and piston-flow model LPM (b). Parameters are explained in the text.

Enhanced model

Two extreme cases are to be considered at first.

1. During deposition the volume increase is large enough, to completely accumulate the infiltration water. For this case applies:

$$\theta_{FC} \frac{dV}{dt} \geq v_R \cdot A$$

where θ_{FC} is the volumetric water content at field capacity, v_R the infiltration or recharge rate, V the volume and A the base area of the dump. In this case no flow occurs. The tritium concentration depletes only by radioactive decay.

2. The volume of the dump does not change (e.g. after termination of mine waste dumping). Over long time periods the dump is stationary percolated by infiltration water. The storage volume is not used.

Case 1 requires very high deposition rates of waste material or very low infiltration rates which are not to be expected in reality. It can rather be assumed that a certain portion of the infiltration water is stored and an excess portion starts to percolate (hereinafter referred to as *excess infiltration*). Both basic processes occur simultaneously and may be described by a parallel connection of two lumped parameter models (Fig. 3).

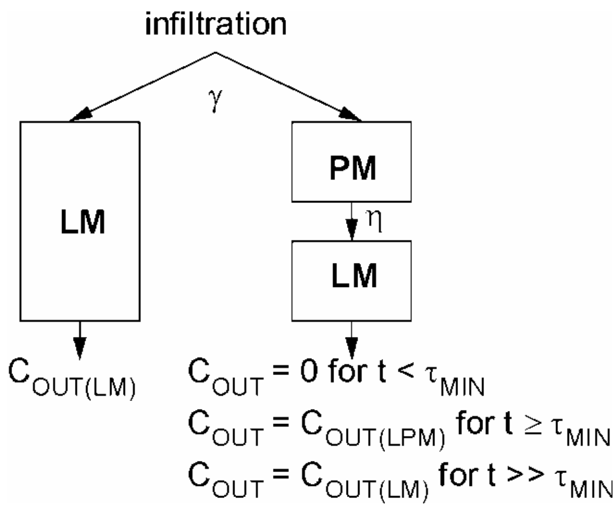

Fig. 3. Scheme of the combination of lumped-parameter models. Parameters are explained in the text.

Box 1 represents the reservoir percolated from the begin of the deposition of the dump. This process is approximated by a linear model (LM). The sole model parameter is the mean residence time τ_m.

Box 2 represents the storage set-up during the deposition of the dump. After termination of the deposition this reservoir is percolated analogue to box 1. This deceleration due to storage set-up results in a time shift of the weighting function by a dead time τ_0. The behavior of this reservoir may be described by a series connection of a linear and a piston-flow model (LPM). Model parameters are the mean residence time τ_m and the percentage of the LM at the LPM (η) where dead time τ_0 and maximal residence τ_M time are derived from (Fig. 2b).

The overall model is formulated as a mixing equation:

$$C_{OUT} = \gamma\, C_{OUT,LM} + (1-\gamma)\, C_{OUT,LPM}$$

C_{OUT}: output-function of the overall model
$C_{OUT,\,LM}$: output-function of the instantaneously percolated reservoir (LM)
$C_{OUT,\,LPM}$: output-function of the reservoir with retarded outflow (LPM)
γ: weighting coefficient

The output-function C_{OUT} is equivalent to the tritium concentration in the seepage (in *tritium units* T.U., 1 T.U. = 0.118 Bq/kg H_2O; Moser and Rauert, 1980). The weighting coefficient γ is estimated from the volume fraction of the percolating excess infiltration at the total infiltration volume.

$$\gamma = \frac{V_{\text{excess infiltration}}}{V_{\text{total infiltration}}}$$

With proceeding time the percentage η of the LM within box 2 (LPM) moves. Immediately after termination of deposition only the piston-flow model works. The parameter η increases with increasing exchange of the stored water to reach 100 % at stationary flow. Then the overall process may be described by a LM.

The neglect of the diffusive exchange of water between both reservoirs is a possible source of error. This causes an equalization of both residence times to a certain degree. A consideration within the lumped-parameter models is not possible here.

Application

Hydrological and geochemical investigations were carried out at a mining dump (former shaft "Koenen II" near Nienstedt) of Kupferschiefer mining in the southeastern Harz foreland (Dunger, 1999; Mibus, 2001). Tritium concentrations in the seepage were analysed by TRICAR Laboratory at the Freiberg University of Mining and Technology over a time period of about two years (07/1995 to 01/1998). The dump was built up from 1964 to 1990. It consists of mainly carbonatic dead rock, has a total volume of V = 5 million m^3, a height of H = 100 m, and a base area of A = 11 hectares.

Application of the LM to the tritium measurements results in a mean residence time of $\tau_m = 20 \pm 5$ a. For the LM applies $\tau_{max} = 2\,\tau_m$. The life span of the dump, however, was only 32 a. So the tritium-age is systematically to high.

Assuming a typical value for field capacity of a sandy gravel of $\theta_{FC} = 5$ % (Busch and others, 1990) and an initial water content of the hard rock of 1 % a static reservoir of about 200,000 m^3 in the whole dump has to be set up. According to model balances from Dunger (1999) the mean infiltration rate is 115 mm/a. Over the time period of t = 32 a total water volume of about 400,000 m^3 infiltrated. Thus about one half of the infiltration is retarded in the storage volume ($\gamma = 0.5$).

The combined model is applied to measured values using the computer code MULTIS (Richter and Szymczak, 1994). The estimation of the parameter η (percentage of the LM the LPM within box 2) is difficult. Since the termination of deposition in 1990 portions of the stored old water are washed out, the solution for η = 5 % is proposed here.

The application of the combined model results in two mean residence times.

mean residence time of the LPM:	22 a
mean residence time of the LM:	16 a
mean quadratic deviation:	1.75 T.U.

The mean residence time of the LPM corresponds to retarded outflow of the storage reservoir. The mean residence time of the LM in contrast represents the unretarded outflow.

Discussion

These values of residence times derived with the combined model exhibit a better consistency with the life span of the dump compared to the application of the sole LM. Potentially the difference of both residence times is even higher due to neglecting the exchange between the reservoirs.

The continued wash out of stored old water causes further decrease of the PM and thus the mean residence time within the LPM. The finally stationary percolation of both reservoirs, each described by one LM, does not necessarily result in a unique mean residence time. It is rather to be assumed that the percolation of the excess infiltration follows preferential flow paths and thus is bound to coarse grained and disturbed zones. The storage in contrast occurs in fine grained regions. This classification is in concordance with the conception on the heterogeneity of flow in the vadose zone. Thus the weighting function of the seepage always contains a fast component and a temporarily stored component which is not only determined by the thickness of the aeration zone.

Conclusions

The proposed extension of the modeling approach for the determination of residence time of seepage in mining dumps facilitates the simplified consideration of the transient process of deposition. The implementation provides results, consistent with the physical life span of the dump and permits a reasonable interpretation. The mean residence time of the water in the dump has consequences for the prediction of pollutant discharge (such as salts, metals, or radio nuclides) in the future (Mibus 2001).

References

Busch K F, Luckner L, Tiemer K (1990) Geohydraulik. Gebrüder Borntraeger, Berlin Stuttgart

Dunger C (1999) Sickerwasser- und Schadstoffbewegung aus ausgewählten Bergehalden Sachsens und Sachsen-Anhalts. Ph.D. thesis. Freiberg University of Mining and Technology, Freiberg

Maloszewski P, Zuber A (1982) Determining the turnover time of groundwater systems with the aid of environmental tracers 1. Models and their applicability. J. Hydrol. 57: 207-231

Mibus J (2001) Geochemische Prozesse in Halden des Kupferschieferbergbaus im südöstlichen Harzvorland. Ph.D. thesis. Freiberg University of Mining and Technology, Freiberg

Moser H, Rauert W (1980) Isotopenmethoden in der Hydrologie. Gebrüder Borntraeger, Berlin Stuttgart

Richter J, Szymczak, P (1994) MULTIS - Ein Computerprogramm zur Auswertung isotopenhydrogeologischer Daten auf der Grundlage konzeptioneller Boxmodelle. Freiberg University of Mining and Technology, Freiberg

van Genuchten M Th (1991) Recent progress in modeling water flow and chemical transport in the unsaturated zone. In: Kienitz G, Milly P C D, van Genuchten M Th, Rosbjerg D, Shuttleworth W J (eds.) Hydrological interactions between atmosphere, soil and vegetation. IAHS Publication No. 204, 169-183