

Environmental Impacts of an Old Mine Tailings Deposit – Modelling of Water Balance, Alkalinity and pH

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A diversity of hydrological and hydrochemical data is the foundation for an integrated modelling study of a leaching tailing deposit at Bersbo in southern Sweden. A distributed conceptual water balance model system combined with empirical hydrochemical subroutines are used to describe the variation pattern in runoff, alkalinity and pH of the outlet of the drainage basin. Examples of the sensitivity of the model output to perturbations of some of the model parameters are shown.

Introduction

The hydrological and hydrochemical observations at Bersbo, as described in a companion paper by Allard *et al.* (1987), give opportunity to develop and test integrated conceptual water balance and hydrochemical models. Problems associated with the interaction between water balance components of the model and hydrochemical processes can partly be overcome by careful use of the diversity of data from various locations in the area.

The total size of the investigated basin is 0.9 km², of which the deposit covers approximately 0.08 km². For the modelling exercise, the area is divided into four subbasins, as illustrated in Fig. 1. Three of these basins consist of unaffected forested areas, while one is the tailing deposit itself. Thus, each one of the subbasins can be modelled separately and verified against data, representing each individual sub-basin.

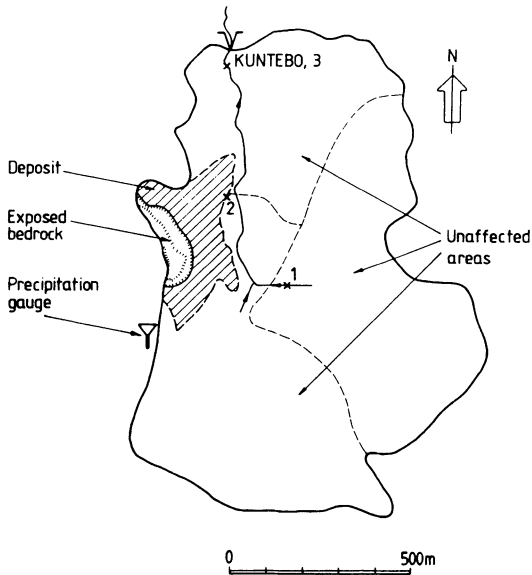


Fig. 1. Subdivision of the study area for the model application. 1, 2 and Kuntebo, 3, represent sampling points.

Steps in the Modelling Exercise

The aim of the modelling exercise is to describe the variation pattern in runoff, alkalinity and pH at the Kuntebo runoff station. This requires the following four submodels:

- A model for the water balance of the deposit.
- A model for the water balance of surrounding forested areas.
- A model for the quality of leaching water from the deposit.
- A model for the quality of water from surrounding forested areas.

Once these submodels are at hand, the integrated output at Kuntebo can be calculated by a simple mixing procedure. The four submodels are not established or calibrated entirely independently. For example, the modelling of the water balance of the deposit is made simultaneously with the calibration of its hydrochemical counterpart.

Data Base

The data base to our disposal is described in detail by Allard *et al.* (1987). It can be summarized as follows:

- Daily totals of runoff and hydrochemistry of variable frequency at Kuntebo.
- Hydrochemistry of variable sampling frequency from the area upstream of the waste dump (site 1 in Fig. 1).

- Hydrochemistry of variable sampling frequency of the small streams, which leave the waste dump (site 2 in Fig. 1).
- Daily totals of precipitation on top of the waste dump.
- Daily mean air temperature from Malmslätt 35 km northwest of the area.
- Estimates of seasonal monthly means of potential evapotranspiration according to Penman's formula (Eriksson 1981).

The chemical observations consist mainly of weekly analyses of pH, conductivity, oxygen, sodium, potassium, calcium, magnesium, chloride, sulfate, carbonate, aluminium, iron, manganese, copper, zinc, cadmium and lead. Periodically automatic sampling has been used with a frequency of 2-3 samples per day. Unfortunately, the total length of the hydrological and hydrochemical data base is too short to permit a split sample model application. This means that there is an obvious risk for overfit of the model. However, previous experience from model applications of this type (see for example Bergström *et al.* 1985) leaves us with some confidence, in particular as the number of model parameters is small and the model is calibrated on both hydrological and hydrochemical time series simultaneously. The total information to our disposal for model calibration is therefore substantial although rather variable for the different sub-basins.

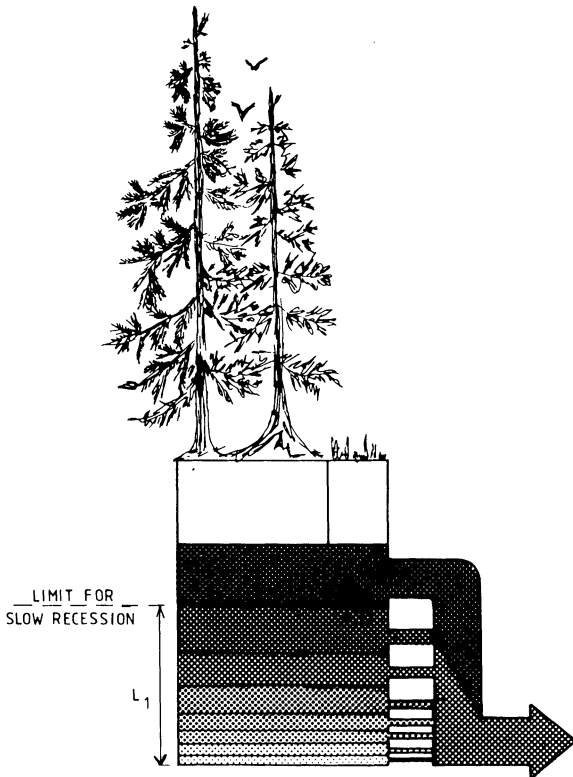


Fig. 2.
Principal sketch of the drainage of an aquifer in the PULSE model.

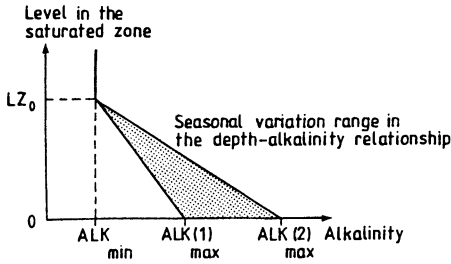


Fig. 3. Principal relationship between the depth and alkalinity/acidity in the saturated zone of the PULSE model.

Basic Model System

The foundation of this modelling study is the PULSE model system described by Bergström *et al.* (1985), which is a development of a conceptual runoff model (Bergström and Forsman 1973, and Bergström 1975). The PULSE model integrates hydrology and hydrochemistry in a simple manner. The basic idea is that the hydrological pathways are governing short term variations in alkalinity and pH in running water. The fundamental concept is that the alkalinity of the water is determined by the groundwater level in the aquifer which drains into the river. This relation is shown in Fig. 2, where also a seasonal variation in the depth/alkalinity relationship is indicated with higher alkalinity in summer than in winter for a given groundwater level. The hydrochemical subroutine is normally calibrated after calibration of the water balance of the model and requires another four model parameters.

The PULSE model can be distributed into submodels, which makes it feasible for application to the Bersbo area with its different land use.

One relatively unique feature of the PULSE model is that each pulse of snow-melt or rainfall is traced separately through the model without assumption of complete mixing, as illustrated in Fig. 3. This makes it particularly applicable to problems, where the level in an aquifer is a significant factor. The procedures illustrated in Figs. 2 and 3 give us a continuous model output of the water balance and the climate-induced variability of the alkalinity of the water. The alkalinity is finally transformed to pH with a relationship according to Fig. 4.

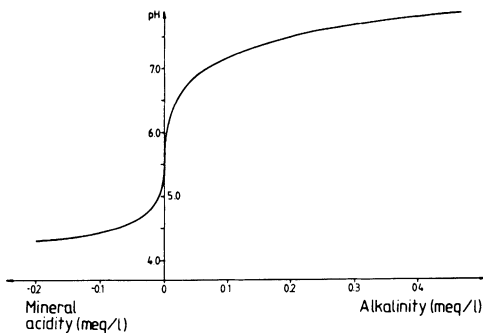


Fig. 4. Relationship between alkalinity/acidity and pH in the PULSE model.

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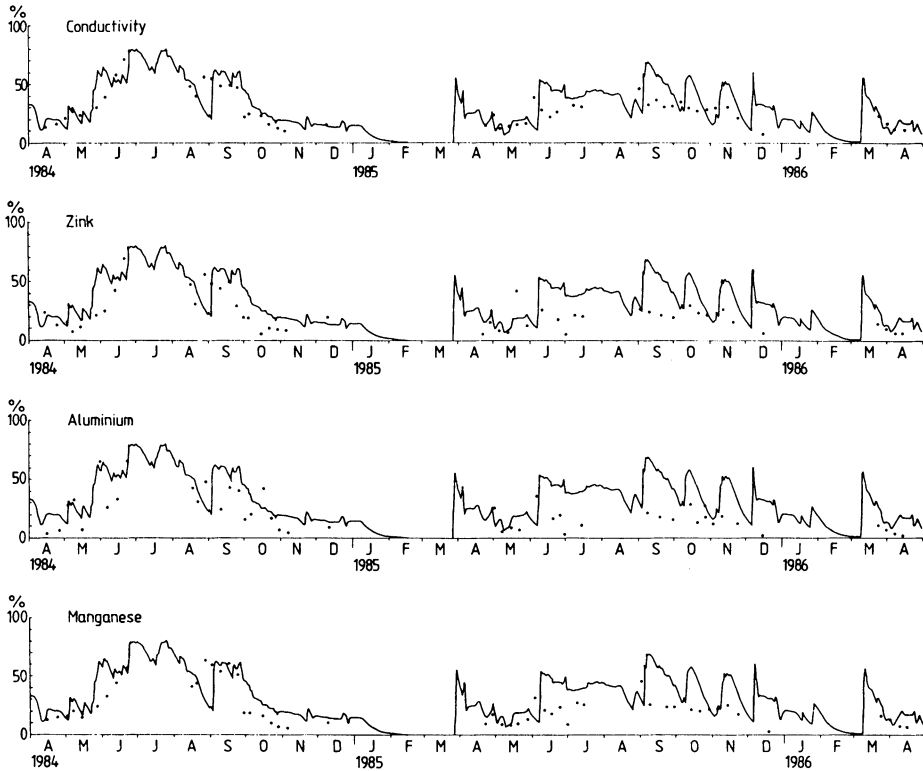


Fig. 5. Indirect comparison between the modelled fraction of runoff from the deposit and corresponding estimates based on concentration analyses at three points.

Water Balance of the Deposit

The water balance of the tailing deposit was modelled by one submodel. The effect of the soil moisture accounting procedure was drastically reduced, as there is no soil and only a minimal vegetation cover. There were no possibilities to measure runoff from the deposit directly. The model was therefore indirectly controlled by comparisons between the modelled fraction of total runoff from the area and corresponding estimates from the hydrochemical observations at sites 1, 2 and 3, Kuntebo. In Fig. 5 this comparison is shown for conductivity, zink, aluminium and manganese.

The concentrations of ions at the three points were thus used as internal sources of information and helped us determine the storage and drainage coefficients of this submodel. The results in Fig. 5 show relative large deviations during some time periods. This is due to the fact that the hydrochemical model (described below) was calibrated simultaneously, which forced us to a certain amount of compromising. It was not possible to get a best fit of the hydrochemical model and the water balance model of the deposit with identical model parameters.

Water Balance of Forested Areas

The water balance of the forested areas was modelled by the water balance component of the PULSE model. The model was calibrated against runoff data for Kuntebo, which means that runoff from the deposit is included. This calibration was therefore integrated into the modelling of the water balance of the deposit. The results are presented together with the water quality simulations in Fig. 8.

Hydrochemistry of the Deposit

The original PULSE model has a seasonal depth/alkalinity relationship for the aquifer. For the quality of water leaving the waste dump, the temperature was considered a more significant parameter, since it effects the weathering processes in the waste. The drainage water from the deposit is thus assumed to become increasingly acidic with depth and with higher temperatures. This is modelled by a 60 days running air temperature relationship according to

$$ALK_d = ALK_0 - C_1 d T_{60}$$

where

ALK_d – alkalinity of water contributing from level d of the deposit aquifer,

ALK_0 – alkalinity of water at the surface of the deposit aquifer,

d – depth in the deposit aquifer,

T_{60} – running 60 days air mean temperature,

C_1 – empirical coefficient.

In Fig. 6 the results of the calibration of the model versus the variations in pH in the water that leaves the waste deposit are shown. The result is, as described above, to some degree a compromise, as the optimum parameters did not match the water balance of the deposit completely.

Hydrochemistry of the Forested Areas

The pH and alkalinity of the forested areas were modelled by a conventional calibration of the hydrochemical subroutine to observations from the area upstream the deposit (site 1). Support from flow data was lacking, but the water balance model parameters were rather well under control by the previous calibration against runoff data for the total basin of Kuntebo and agreed well with experiences from the PULSE model in other applications. Results from the calibration of the hydrochemical model parameters for the unaffected forested area are shown in Fig. 7. The optimum chemical model parameters obtained for this part of the basin were then assumed to be valid for the total unaffected forested part of the basin.

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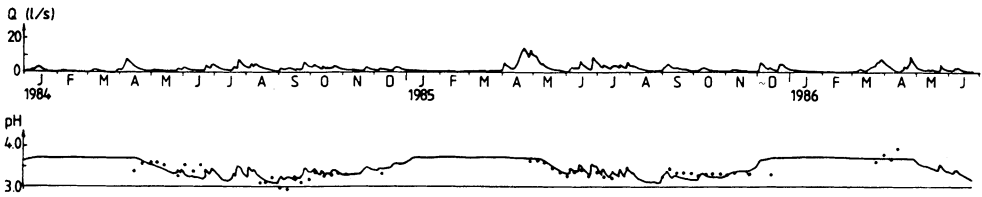


Fig. 6. Simulated runoff and pH from the deposit (site 2 in Fig. 1). Dots represent measurements.

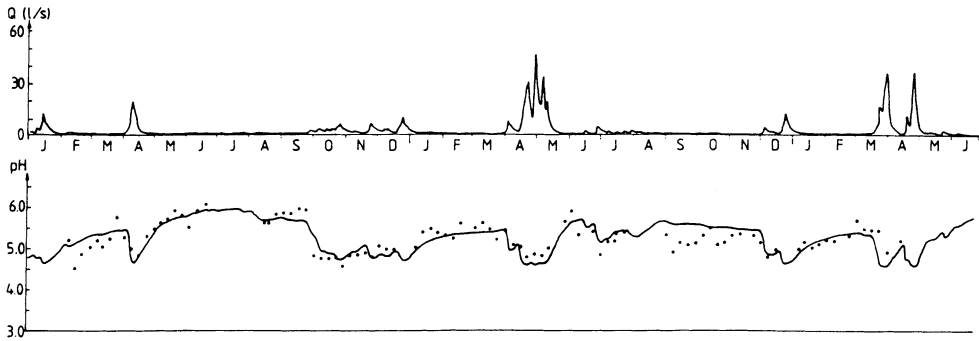


Fig. 7. Simulated runoff and pH at station 1, upstream the deposit. Dots represent measurements.

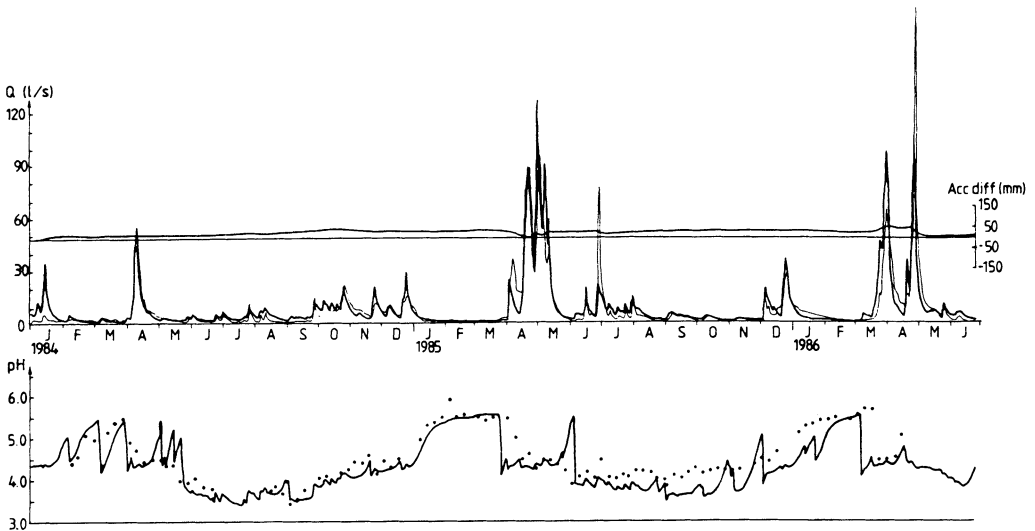


Fig. 8. Integrated simulation of runoff and pH at Kuntebo. Thin line and dots are measurements.



Fig. 9. Sensitivity of the model to a change in the upper recessions coefficient for the deposit. Values are 0.1, 0.2 and 0.3 (day^{-1}) respectively.

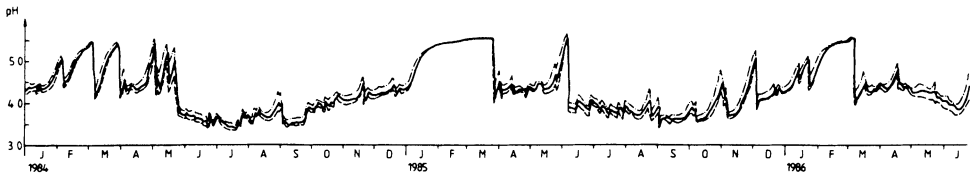


Fig. 10. Sensitivity of the model, if the areal extent of the deposit is increased or decreased by 30% respectively.

Integrated Modelling of Alkalinity and pH at the Outlet

With all previous model calibrations at hand, a simulation of runoff, alkalinity and pH was finally performed for the outlet of the basin, station Kuntebo. The results, which are shown in Fig. 8, are thus in a way an independent test as far as the hydrochemical variables are concerned, while the water balance has been subject to calibration in an earlier step. The water balance matches reasonably well, and some of the disagreement can be attributed to the long distance to the air temperature station (35 km) and the simple degree-day melt function. The systematic underestimation of pH-levels by the model could possibly be corrected by a recalibration of the chemical components of the submodels. Here, again, we have to face a compromise, because the recalibration would improve the simulation at the outlet but would undoubtedly affect the performance of the submodels in an adverse way.

Not surprisingly the hydrochemistry responds directly to the acidic waters from the deposit, which makes the correct modelling of the contribution of water from each subarea extremely important. This result is supported by the study of Sandén *et al.* (1987) in a companion paper. The effect is further illustrated by the sensitivity analyses in Fig. 9, which shows the effect on the pH simulation of a change in the upper recession coefficient of the submodel for the deposit.

Fig. 10 illustrates a sensitivity analysis of the model to the areal extent of the waste disposal site. The fact that this sensitivity is small compared to that of the recession coefficient, indicates that it is more important to determine storage characteristics of the waste than it is to determine its exact areal coverage.

Conclusions

The application of the PULSE model to the Bersbo area showed that the variation pattern of the hydrochemistry to a high degree can be explained by climatological and hydrological conditions.

A diversity of data from different subareas can be used for model calibration and support in the assessment of the various model parameters. A certain amount of compromising was necessary when trying to model the water balance and water quality of waters from the deposit. Oversimplifications in the structure of this submodel are probably the main causes of this problem. There is also a slight conflict between best fit of the submodels and the complete model. One reason for the latter could be uncertainties in the control of drainage water from the deposit, but also the generalization of hydrochemical model parameters from the area upstream the deposit to the total unaffected forested area.

The importance of a correct water balance simulation of each subbasin is emphasized in the integrated basin simulation, in particular if, like in this case, one part of the basin has a completely different and dominating hydrochemistry compared to surrounding areas.

Acknowledgements

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