Evaluation of mine water quality dynamics in complex large coal mine fields

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ABSTRACT

Monitoring data from historic and current mine floodings show often dramatic increase in iron and manganese concentrations. These empirical data form a fundamental and essential basis for mine water quality prognosis. Predicting the mine water quality dynamics of large mine fields with complex flow conditions is a particular challenge for which empirical approaches have to be adjusted. Experiences from Southern France and Germany give reason to adjust the exponential function normally used to take specific flow conditions into account. This approach allows direct transformation to the mass balance equation used in numeric-discrete-models. The superposition of flows in complex mine areas requires the use of the discrete transport model developed for the regional situation. The application of the model and results are demonstrated for the Lorraine/Saar coal mine region.

INTRODUCTION

Consideration of mine water chemistry is indispensable within the scope of long term planning of drainage activities during and after flooding of a mine. This applies especially for situations where parts of the mine drainage system are expected to change flow rates or flow paths due to flooding. As an example Figure 1 displays the variation in mine water levels expected when flooding the French Lorraine coal field. The development of water levels for this large interconnected complex mining area is actually has been calculated with the box model (see below).

Filling of void volumes during the flooding is in contrast to a stationary flow system with constant water levels during mine activities. Hereby the long term observed concentration levels generated by continuous reactions like pyrite oxidation and inflow of mine water are increased by dissolution of easily soluble salts from rock surfaces. In addition substances become activated which were stored in highly concentrated pore waters and in "dead water" areas experiencing previously practically no flow. This results in the well known specific intense increases of concentrations and loads.

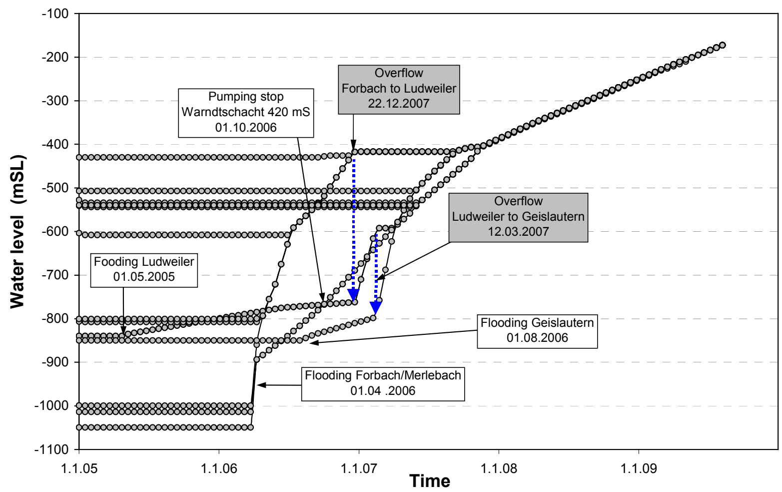


Figure 1: Calculated risings of mine water levels during flooding of the Lorraine Basin

Substance mobilisations during flooding are a consequence of geochemical processes before the flooding. Input of oxygen by ventilation accompanied by lowering of the water table is the most significant factor for changes to the geochemical environment during mining activity. The conditions prevailing and the host rock composition form the variables determining the intensity of the well known geochemical interactions having their origin mostly in pyrite oxidation (Klinger 2003). These processes shall not be further discussed in detail because the methodology applied does not deal with these primary conversions but accesses directly the mobile substance in storage (high concentration pore solutions, dead water) existing at the beginning of the mine flooding. This includes not only products of the described rock conversion processes but also building materials used for construction works in the mine (e.g. gypsum, lime) and any backfill.
During and after flooding access of atmospheric oxygen is inhibited resulting in non-oxidising to long term reducing environmental conditions. Then in addition $FeSO_4$ gains relevance as a migrant beside salts like $CaSO_4$ und $MgSO_4$ with solubility nearly unaffected by pH value and redox voltage.
Relevant sulphate und iron loads (and mostly manganese) are typically observed during the flooding of hard coal mines and are also monitored in the Lorraine Basin and the Ruhr coal mine district. Once further oxidisation and mobilisation processes cease the loads in the mine water overflow drop with time affected predominantly by flushing rate and flow dynamics. The methodology applied provides a practical basis for description of the dynamics of these processes and for prognosis of substance concentrations in mine water discharge. Reactive mass transport modelling (e.g. precipitation of barium sulphate) had to be considered also to reflect the interactions between the dissolved substances and with the loads of permanent mine water inflows.

METHODOLOGY APPLIED

Geochemical processes as discussed above depend on the specific properties of any individual mine. Nevertheless, some common features apply to the overflow monitored during and after most mine floodings. When describing the concentration development available data imply a dominant influence of the floodable residual void volume and the inflow rate (= outflow rate) of mine water. These two parameters are the basis to describe the washing process once a mine is completely flooded and allow to calculate the time needed per exchange of the flooding volume. They provide a coordination system to characterise and compare the mine water quality developments of different mines with differing void volumes and hydraulic properties.
One of the main objectives of our ongoing joint work is to combine a hydrochemical reaction model with a quantitative mine water drainage model. For the latter we use the term “box model” which has been advanced over the last years and has become the working tool for DSK and DMT when looking at optimisation of mine water pumping systems and forecasts on changes to the underground water flow (Eckart *et al.* 2004).

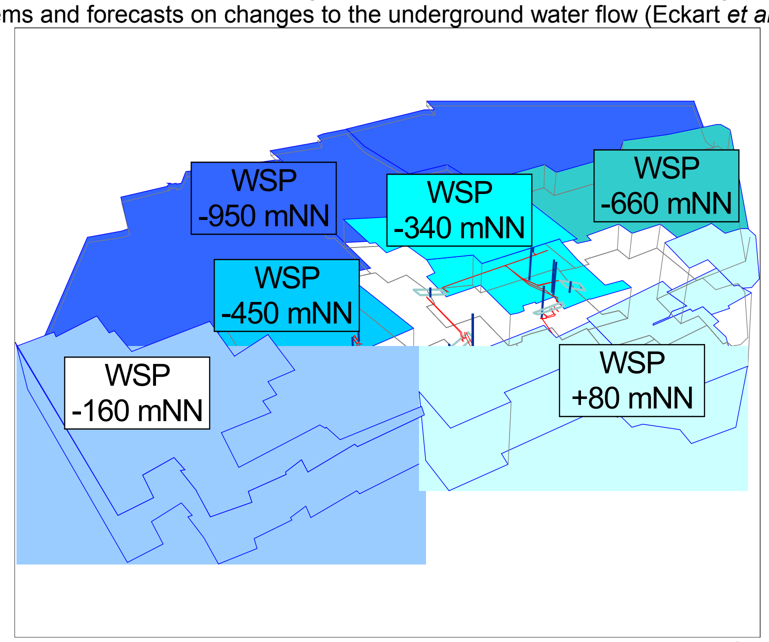


Figure 2: Typical box model with box limits coinciding with large abandoned mine fields and water levels (WSP) maintained by pumping stations

Characteristics of the hydraulic model

Numerical models have become standard in mine water management where pure assessment by experience or comparison with similar events does not suffice. From a practical point of view an appropriate numerical model has to consider a system of fairly large balance cells or compartments, the so called boxes (Paul *et al.* 1989). Figure 2 displays an example from the central part of the Ruhr coal mine district. Boxes coincide with large abandoned mine fields and water levels indicated are kept low by various pumping stations.

A box is assigned all important information and components of the mine field in the hydrogeological sense: storage volume, recharge, discharge and also information on mine-water-quality: pH, Eh, temperature, concentrations, stored contaminants, typical minerals etc..

Evaluation of mine water quality monitoring data

Monitoring data from historic and current mine floodings form the fundamental and essential basis for mine water quality prognosis. Numerous international data sets for concentration developments in mine water discharge have been normalised for statistical investigations.

Fundamental site specific data considered are floodable void volume, rate of recharge and composition of the inflowing water. This resulted in empirical exponential functions which are widely used for mine water quality prognosis and have proven their applicability at numerous sites. The basic empirical functions imply fairly non-complex sites with conditions considered more or less homogeneous.

Figure 3 shows some concentration developments in mine water discharge from three hard coal mines with clearly different residual void volumes (floodable volume) and flow rates (Klinger 2003, Blachere 2003). The flushing intensity is expressed by the flow measured divided by the floodable volume. This yields the period for one complete exchange of the floodable volume. Data corresponding to Figure 3 are listed in Table 1. Obviously, the intensity of flushing varies significantly for the three mines.

The calculation of exchange periods assumes an ideal and homogeneous washing of the residual void volume. This concept is easy to follow when flow through the flooded mine is intensive but in our experience this is only the exception (e.g. Victoria mine). More regularly, minor inflows in large mine systems result in areas with restricted water flow, parts of the void system experiencing practically any flow ("dead water" areas) and therefore in reduced mass exchanges.

Table 1: Principal data for flooding process evaluated at three hard coal mines

Mine	Floodable volume m³	Flow m³/h	Exchange period years
Fontanes	17.700.000	220	9,2
Rieux	1.024.800	70	1,7
Victoria	4.035.000	1.260	0,37

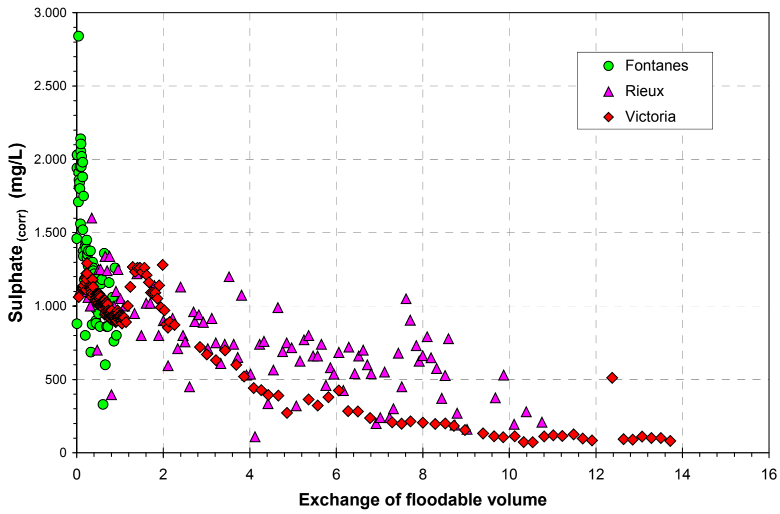


Figure 3: Sulphate concentrations measured minus sulphate concentrations of mine water inflow at three hard coal mines

Concept of mass storage and exchange

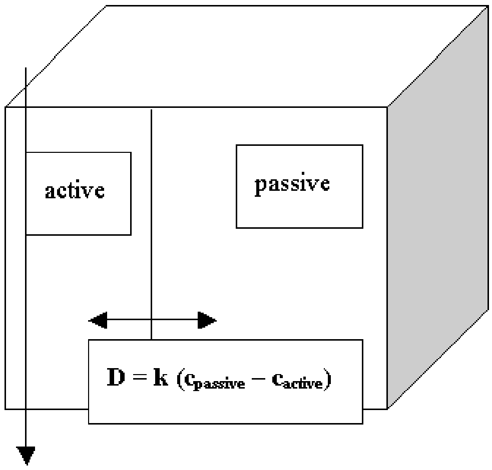
Predicting the mine water quality dynamics of large mine fields with complex flow conditions is a particular challenge for which the empirical approach has to be adjusted.

Any model to be applicable for practical purposes has to describe both the sharp initial increase in concentration levels as well as the exponential decrease as actually monitored (Figure 3). The modelling technique has to provide for an adequate mass storage to consider the long term concentration development. Assigning the maximum concentration levels observed to the void filling water volume is not sufficient. This would not comply with the mass balances encountered. Starting model runs with initial concentration levels beyond those observed would be unrealistic and not acceptable. We therefore resorted to a simplifying dual system to be incorporated into the geo-chemical model and reflecting the concentration developments actually observed. The concept provides for an active and a passive storage element (Figure 4), subsequently titled "porosity" which includes all floodable residual void volume consisting of man made voids, fractures, cleavages and rock pore space, and can be described as follows:

- the floodable volume is subdivided into an easily percolated part (active phase) and a stagnant part (passive phase)

- the easily percolated (active) volume correlates with the open mine cavities
- the stagnant (passive) part correlates with the mine workings (goaf areas) and the fracture porosity including adjacent pore spaces
- approximate spatial distribution of the residual void volume:
20 % open mine cavities + 80 % workings and fracture porosity
- the convective flow takes place only within the active porosity
- the passive porosity contains well soluble salts in high concentrations
- solution processes of weathered products take place in the passive porosity
- mass exchange between the passive and the active porosity follows the diffusion law.

This concept has been integrated into the geochemical reaction model. It principally allows higher mass storage in the passive porosity without resulting in high outflow concentrations. By this concept the high sulphate loadings actually observed can fairly easily be considered.



K	Kinetik coefficient	[1/s]
D	Transfer rate	[mg/L/s]

Figure 4: Separation of active and passive parts of a box

The mine water quality components are primarily released from the passive porosity and transfer is provided by the diffusion law into the active porosity with the latter being hydraulically connected to other boxes. The exchange coefficient k (see Figure 4) is controlled by a mine specific factor which is described further below (Figure 6).

General evaluation of examples following analytical and discrete methods

A well proven and straight forward method to predict development of iron and sulphate concentrations was developed by (Younger 2000) and has been further adapted by (Blachere 2003, Younger & Blachere 2003) to reflect experiences made at French hard coal mines (see equation (1)). The method is a simple statistical evaluation of numerous mine floodings and apparently works well as long as mine water hydraulics are not very complex.

According to the mine flooding events evaluated the reaction products of pyrite oxidisation (Fe and SO_4) reach typically maximum concentrations very quickly at the initial stage of flooding and decrease in an exponential mode (Figure 5). A simplifying but reasonable assumption puts the time required to drop to about 50 % of the maximum concentration level equal to the time required for flooding.

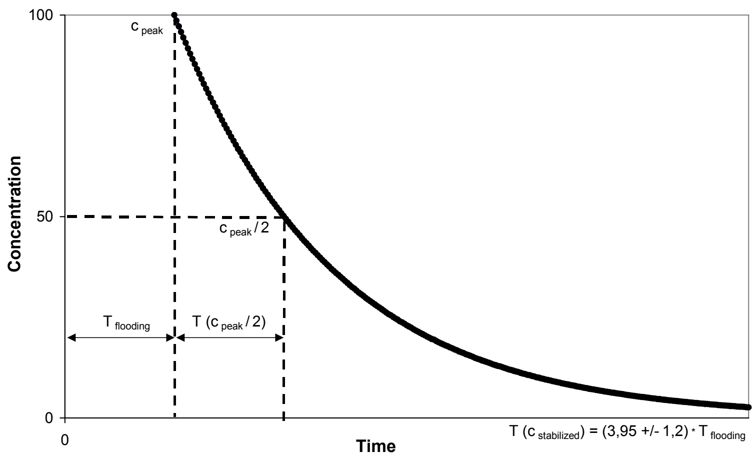


Figure 5: Exponential concentration decrease in mine water discharge after complete flooding

$C(t) = C_o * e^{-\ln 2 / t\ Flooding * (t-to)}$ *(1)*
C *Concentration* *[mg/L]*
t *Time* *[s]*

Influence of the flow rate
The aforementioned assumption is valid as long as the inflow rate during mine flooding equals the subsequent outflow rate. Under these conditions the time for one complete flush is easily determined. For non-compliant conditions a more general expression of the flushing process was developed. The concept uses a general balance equation (2) applicable to the flushing process of any known volume. This concept is also integrated into the box model calculations. The equation applied to consider the mass balance is:
$dC / dt * Volume = -Q * C$ *(2)*
Q *Flow rate* *[m^3/s]*
Equation (2) describes the decrease of a concentration in any volume V as a function of the mass carried away by the flow rate Q. The corresponding analytical solution which determines the concentration developing at a defined process time is as follows:
$C(t) = C_o * e^{-Q/V * (t-to)}$ *(3)*
V *Volume* *[m^3]*
When comparing this solution with the empirically based equation (1) it is obvious that identical mathematical solutions result for the condition
"overflow rate = flooding rate"
and substituting t by the time required for flooding.
Consequently, equation (2) represents the more generalised case considering the overflow rate immediately after flooding. This equation can also be used to compare the results of the statistical evaluations with those of the box model calculations, which should be equal - at least for simple conditions. The algorithm used for the box model calculations solves the process equation in an iterative numerically discrete mode:

$$C_{new} = C_{old} * Q * \Delta t / Volume + C_{old} \quad (4)$$

Influence of the residual void volume percolated
When evaluating actual flooding events some very different developments of concentration levels can be observed. The common explanation is that depending on the various hydraulic conditions only parts of the residual void volume are effected by the flow.
Our statistical investigations indicate a correlation of the flushing dynamics with the intensity of flushing which can be specified by the ratio "discharge volume / void volume" (Q/V). Experiences from Southern France and Germany give reason to adjust the exponential function (3) normally used by a correction factor (F) for the exponent to take specific flow conditions into account:

$$C(t) = C_o * e^{-Q/(V*\mathbf{F}) * (t-to)} \quad (5)$$

This correction factor F allowed to match calculations with concentration developments observed. Our evaluation of flooding events in large coal mines indicates that the adjusting factor F follows a regular pattern. There is apparently a strong relationship with the intensity of flushing expressed by the ratio „Q/V". In order to make our evaluation results available for prognosis calculations we had to replace the somewhat arbitrary correction factor F by a generally valid functional relationship to the Q/V ratio (Figure 6). Using this approach also allows to describe the flushing of complex mine fields with large interconnected collieries. This relationship is compatible for direct transformation to the mass balance equation used in numerically–discrete models. The site-specific factor F represents the influence of the void volume participating actually in the flushing process.

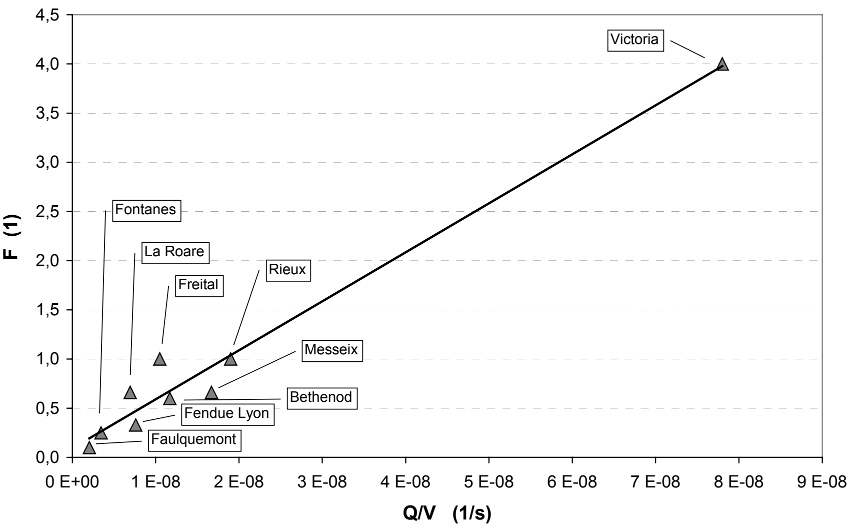


Figure 6: Relationship between Volume-Correction Factor F and ratio "Q/V"

In contrast to the above analytical solutions the box model is designed to already take complex hydraulic situations into account. When re-calculating flooding events and comparing with analytical solutions the box model renders very satisfactory results. In our view this confirms the adequacy of simplifying analytical solutions like equation (5) at mines or mine fields with a fairly straight forward flow pattern. However, large mine fields with fairly complicate hydraulics require a more demanding approach like the box model calculations.

MODEL APPLICATION

The application of the model and results are demonstrated for the Lorraine/Saar coal mine region.
The methodology described above is presently applied to forecast the mine water dynamics and quality development when flooding the Lorraine coal mines, including the adjacent Warndt coal mine across the French-German border. Experience in mine water quality developments at partial flooding of Lorraine coal mines has been used to calibrate the box model. The box model described in (Eckart *et al.* 2004) allows to calculate and evaluate various alternatives for the future mine water management. The development of mine water levels for the initial period of flooding is represented by Figure 1. The subsequent Figures 7 and 8 represent two alternatives for the development of mine water quality (parameters selected are iron, sulphate and chloride) at expected points of overflow resp. points of discharge.

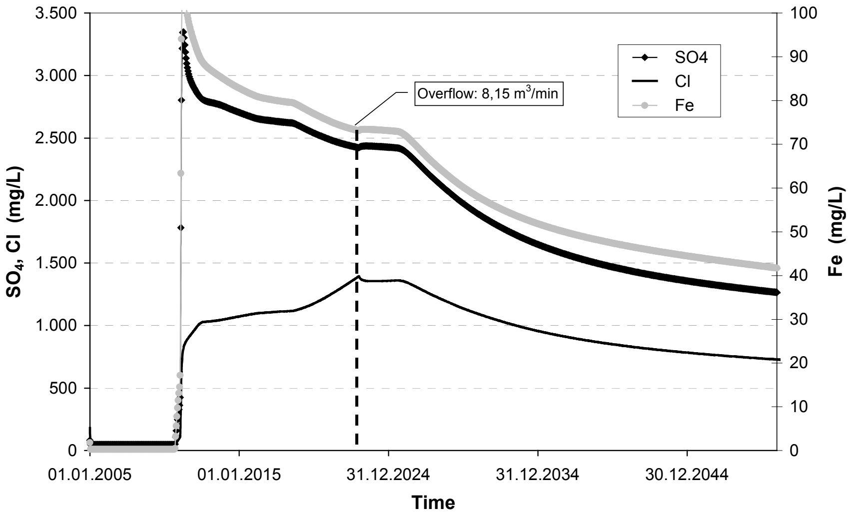


Figure 7: Development of concentrations at Gustav Schacht in case of overflow through deep mine levels into Germany (Alternative 1)

The Gustav shaft of the German Warndt mine is the decant point of the complete mine field. The development of selected mine water quality parameters are represented in Figure 7. In this Alternative 1 the mine water inflow from the French mines is not controlled by any pumping but is hydraulically forced to pass the low levels of the mines in order to rise up again and to finally overflow the decant elevation in approx. 2022. While iron and sulphate will follow more or less the expected exponential decline in concentration levels, chloride originating from deep geogenic inflow will accumulate at the deeper portion of the mines until the increasing hydraulic head will throttle the inflow.

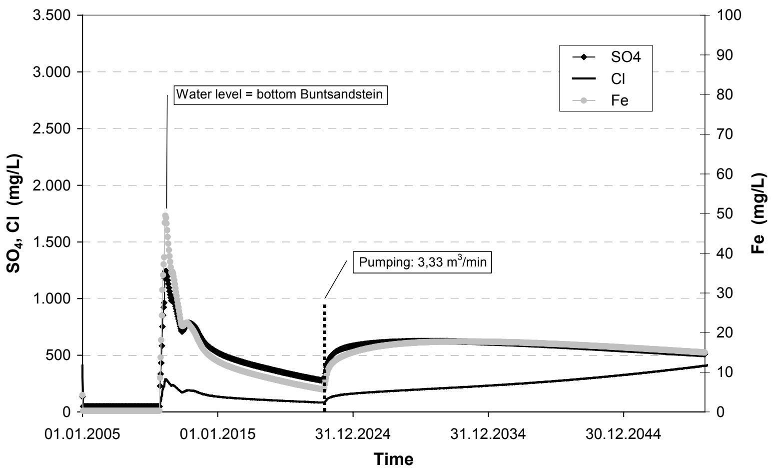


Figure 8: Development of concentrations at Simon pumping station in case of pumping in France (Alternative 2)

The Alternative 2 provides for pumping at French mine shafts controlling the mine water levels and reducing the potential overflow at the Gustav shaft to practically zero. Figure 8 shows the mine water quality development when pumping out of the Simon shaft as an example. Initial concentration levels are relatively low due to dilution of mine water from the hanging Buntsandstein aquifer. When pumping would commence in about 2022 concentration levels are expected to increase again due to upward movement of mine water with higher concentration levels. From a practical and environmental point of view Alternative 2 looks rather promising. The joint effort will be further continued to provide a sound basis for the future mine water management decisions.
Similar calculations are concurrently performed for the Saarland and the Ruhr coal mine districts.

CONCLUSIONS

Empirical analytical solutions can easily and for a number of applications adequately describe the development of mine water quality after flooding. However, large mine fields with fairly complicate hydraulics require a more demanding approach. The box model has proven its applicability and robustness in very complex mine fields when mine water flow, fate and transport of various components are to be calculated. Further developments of the box model will need to confirm the first approximation made to take also density and thermal effects into account.

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