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Modeling the Inflow and Discharge from Underground Structures within the Abandoned Hardcoal Mining Area of West Field (Ibbenbüren)

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Abstract Using the example of the abandoned and flooded hard coal mining area of West Field belonging to RAG Anthrazit Ibbenbüren GmbH, a method was developed for modeling the inflow and outflow from underground structures. The successive fractions of the water cycle such as evaporation, transpiration, surface runoff after a precipitation event, water transport in unsaturated hard rock as well as discharge from the Dickenberg-gallery were coupled in a model. The discharge from the Dickenberg-gallery was simulated with a developed hydraulic subsurface model, which describes the discharge fluctuations based on the calculated changes in the minewater level. All of the data on the geology and soils as well as the field measurements were varied using the models until good agreement was achieved between the measured and calculated discharge values. By analyzing the model results, the influence of different factors and their effects can be estimated. The methods developed in this study can be used for the further calculation of the infiltration and outflow of the East Field coal mining area.
Keywords Ibbenbüren, west field, abandoned mine, mine water transport

Introduction and objectives

Anthracite has been mined from the Ibbenbüren coal district since the 16th century. The mineral deposit stretches NNW-SSE and is divided into three parts: the West Field, the Bockradener Graben and the East Field. The natural mineral deposit is bordered by normal faults, which also enables a good demarcation of the investigated area (DROZDZEWSKI et al. 1985). While shallow mining was practiced in historical periods and also in times of need after the World Wars, actual "modern" mining in the East Field takes place at depths of up to 1,600 m since several decades. In the West Field, mining took place up to a depth of about 600 m up until the cessation of production in 1979.

After the West Field hard coal mining area in Ibbenbüren (fig. 1) was abandoned in 1979, the area was flooded. The flooding was completed when the hydraulically active transition point of the Dickenberg-gallery was reached at the Wilhelm-shaft (66 m a.s.l.). This resulted in a considerable change in the water balance, the functions of the rock body, and the demarcation of the catchment basin.

Due to the many years of mining activities, the permeability both in the upper layers of drained hard rocks and in the lower saturated rocks was strongly increased. The voids and joints created by hard coal mining resulted in a greater permeability of the rock mass and therefore to a greater groundwater recharge rate, which is significantly different from the regional average values in Münsterland.

In terms of its drainage, its relief and the tectonics, the flooded West Field can be considered as a separate geohydraulic system. Inflow from the bordering aquifers into this West Field system can be ruled out after the re-rise of the mine water up to the level of the Dickenberg-gallery. Inflow from the active East Field hard coal mining area is negligible.

The tectonic boundary faults and the hydraulically active transition point of the West Field system to the Dickenberg-gallery at 66 m a.s.l. represent the geohydraulic boundaries. The water balance is based on the precipitation less the evaporation, surface runoff and drainage outflow from the Dickenberg-gallery. In fact, the gallery as a long horizontal drain is capturing most infiltration water and discharges it out the West Field area.

The analysis of the discharge rate from the gallery (GOERKE-MALLET 2000) shows that

- Maximum discharge occurs in the time period from January to April and minimum discharge from May to September.
- After strong precipitation events - mostly in the cold season - there is a rapid reaction of the discharge after one to two weeks.
- Strong precipitation events in the summer - probably due to the greater evaporation and transpiration - do not have an effect on the discharge rate from the gallery.

However, many aspects of the abandoned West Field hard coal mining area are still unclear today. The fraction of the rainwater that does not flow into the gallery, and the zones that are drained by the Dickenberg-gallery are not fully known.

The objective of the investigation is to record and calculate the individual components of the water balance in the abandoned West Field hard coal mining area (Ibbenbüren) for different periods using inverse modeling.

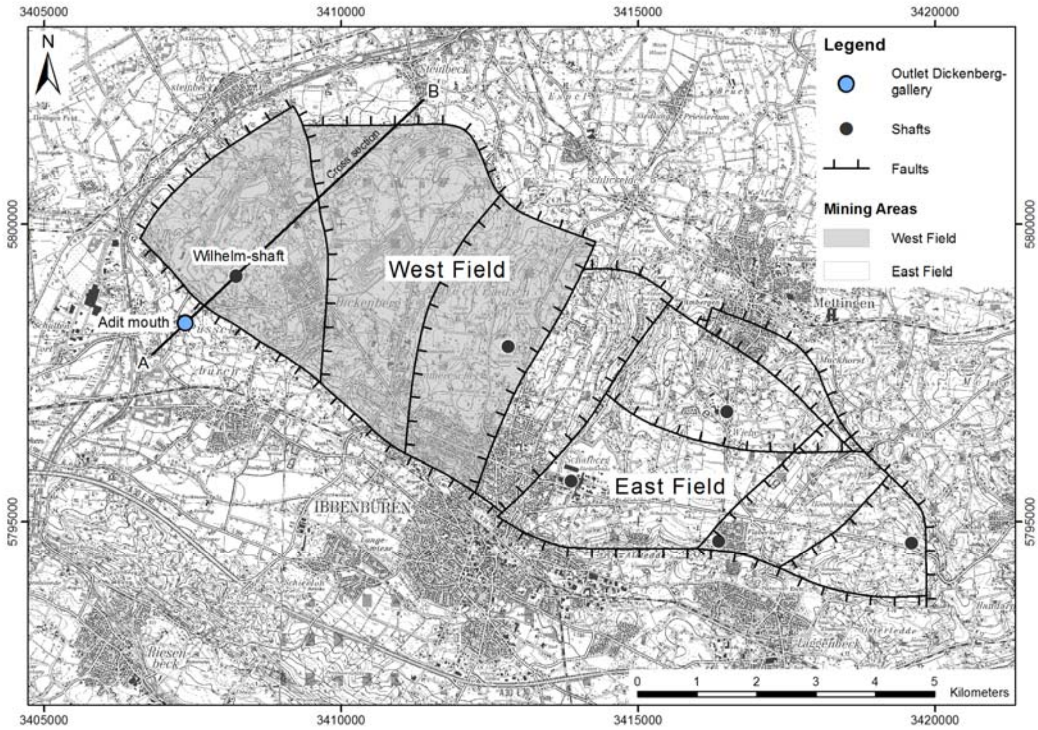

Fig. 1 *Location of the abandoned West Field hard coal mining area in Ibbenbüren*

Approaches of the flow model

To simulate the West Field system, the following methods and models were developed and coupled to each other according to the water path:

- Method for the calculation of evaporation and transpiration (interception) (chapter 3.1).

- Method for the calculation of surface runoff (chapter 3.2).
- Model for unsaturated water transport in heterogeneous rock (chapter 3.3).
- Model for temporally variable discharge from the Dickenberg-gallery (chapter 4).

The applied method for modeling the infiltration of precipitation is based on the requirements that are usually assumed for water flow in heterogeneous rocks (BEAR 1968, BARENBLATT et al. 1972, LUCKNER & SCHESTAKOW 1986). With the double porosities and different rock permeabilities, both long-term seasonal changes and short-term fluctuations in the discharge from the gallery can be mathematically described and explained. Perched groundwater occurs only in very few areas of the investigated area, so that it does not need to be considered in the large-scale observation and in terms of the water balance of the entire area. Due to the hydrogeological conditions (fig. 2), the West Field system can be calculated using a simple program, which also enables precise determination of the main parameters of the water cycle.

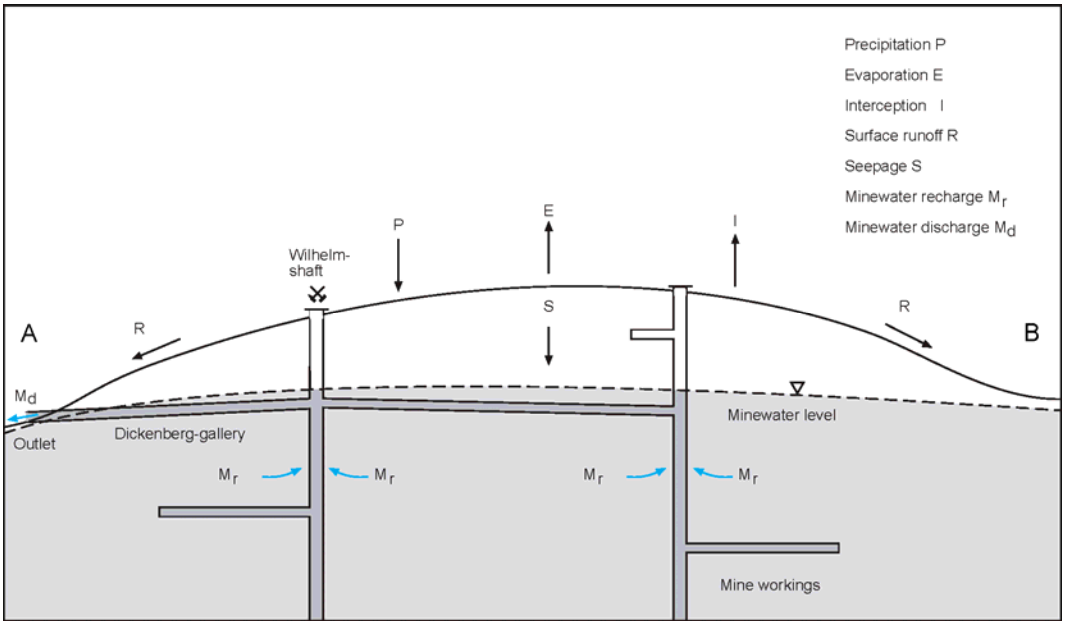

Fig. 2 *Schematic sketch of the water movement in the abandoned coal mining area West-Field (position of cross section AB is shown in fig. 1)*

Modeling of the vertical water transport

Method for the calculation of evaporation and transpiration

To simulate the course of the discharge from the Dickenberg-gallery as precisely as possible, the parameters, causes and effects that give rise both to short- and long-term hydrological changes must be taken into account. Here, "parallel" or "simultaneous" infiltration into the soil or into the rock with varying permeability is assumed. Based on the statistical interpretation of the soil permeability, a distinction can be made between individual areas. According to the classification by BREDDIN (1961), a distinction is made between soils with very low (25% of the total soil mass), low (67%) and moderate permeability (8%).

It is assumed that this distribution of permeabilities also determines the water movement in the soil and therefore the different groundwater recharge rates in various areas. Taking into account the different permeabilities in the various layers as well as the evaporation from the different surfaces (HAUDE 1955), the variability of the soil properties and the heterogeneity of the surface can be realistically simulated.

Method for the calculation of surface runoff

Regarding the surface runoff, it is assumed that it mainly occurs after very intense precipitation events. Surface runoff is high especially in the summer, because less water infiltrates into dry soil after an intense precipitation event (MONTEITH & UNSWORTH 2008). The surface runoff fraction in the water balance in 2008 was ca. 4%-5% of annual precipitation 809 mm/a, corresponding to a surface runoff rate of about 38 mm/a. As an initial approximation, precipitation rates greater than some limit ε_{max} were not included in the calculations of infiltration because of low permeability of clayey topsoil in this area not allowing all precipitation water after heavy rains to infiltrate. The value of ε_{max} was assessed by inverse modeling at 18 mm/d.

Model for unsaturated water transport in heterogeneous rock

To improve the model precision, the overall groundwater recharge rate for the investigated area $\dot{V}_{GW,\Sigma}$ was determined by integrating the groundwater recharge rates of the sub-areas. $\dot{V}_{GW}$ In doing so, the variability of the depth to water table and evaporation at the soil surface was taken into account. The unsaturated zone was discretized with rectangular 3D elements of a height Δz.

Creation of the hydraulic model for the Dickenberg-gallery

The balance equation for the "rainwater – mine water – gallery discharge" system can be approximately described for the time interval Δt as follows (1):

$$\frac{\Delta \dot{V}_{GW}}{\Delta t} = \dot{V}_{mw,\Sigma} - \dot{V}_{SD} \qquad (1)$$

with:

$\dot{V}_{GW,\Sigma}$—Total groundwater recharge rate for the catchment basin of the flooded West Field system (m^3/d);

t—Time interval (d);

$\dot{V}_{mw}$—Change in the mine water volume in the investigated area (m^3);

$\dot{V}_{SD}$—Discharge rate from the Dickenberg-gallery (m^3/d).

Results of the numerical modeling

For the analysis of the groundwater recharge rate, it is important not only to estimate the daily values and the total inflow, but also the inflow fractions from areas under different uses (forest, field, city or sealed areas), and to explain the important influencing factors quantitatively (ESCHENBACH & KAPPEN 1996, CHEN 1997, BOGENA et al. 2003).

On an annual average, the groundwater recharge rate fractions β from various surfaces $\dot{V}_h$ correspond to their groundwater recharge rate fractions from the total area $\dot{V}_{tot}$ of the West Field system (2).

$$\beta = \frac{\dot{V}_h}{\dot{V}_{tot}} \quad (2)$$

with:

β—Groundwater recharge rate fraction from a specific surface type (1);

$\dot{V}_h$—Groundwater recharge rate on the area of the surface type (m³/d);

$\dot{V}_{tot}$—Groundwater recharge rate on the total area (m³/d).

For the calculation of the discharge rate from the Dickenberg-gallery, the following parameters were entered: Flow width in the gallery = 0.7 m; water level at the transition point at the Wilhelm-shaft = 65.2 m a.s.l.; water level at the gallery outlet of the Dickenberg-gallery = 62.5 m a.s.l. The water depth in the gallery was varied in the calculations from 0.2 to 0.25 m. The CHÉZY number used for calculation of hydraulic flow in the gallery and quantifying hydraulic friction was determined using the MANNING equation (SCHRÖDER & ZANKE 2003).

The simulation results are shown in fig. 3. Due to the considerable transpiration and the surface runoff in the summer and early autumn, intense precipitation does not have a significant effect on the discharge in the gallery. The calculated time series demonstrate the relatively fast reaction to large precipitation events. In this regards, the effect of water storage in the flooded mine workings smoothen the pronounced changes in the precipitation rate $\dot{h}_P$.

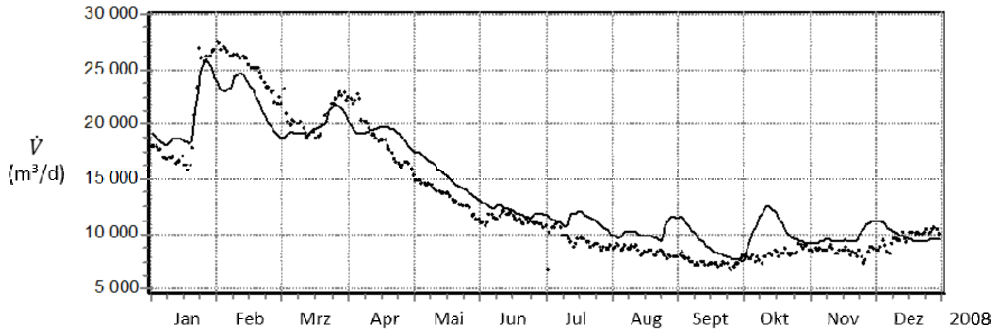

Fig. 3 *Course of the discharge rate from the Dickenberg-gallery (line – calculated, dotted – measured) for an area affected by mine water A_{mw} = 30 ha in 2008*

Overall, the calculated and measured values exhibit good agreement; the deviation is of about 10 %. The greatest differences of up to 30-40 % were generally caused by strong precipitation. Nevertheless, the calculated curve for the measured time series converges with the corresponding trend. Compared to the measured time series, the numerically analyzed curve seems smoothed, because the model for the unsaturated water transport only takes account of the macro-heterogeneity of the soil properties and surface (table 1). The short-term fluctuations in the discharge from the gallery were definitively caused by micro-heterogeneous structures such as joints and cracks.

The free mine water surface A_{mw} in the flooded mine workings causes delay in the hydraulic response. The area A_{mw} of the partly flooded pit and the voids in a horizontal section can only be estimated based on old mineplots and maps. The greater the mine water area, the longer the duration of discharge. The calculated water balance corresponds to the long-term measured values (table 1).

Conclusions

A numerical method was developed for modeling the inflow and discharge from underground structures in the abandoned and flooded West Field hard coal mining area (Ibbenbüren). It implies the coupling of a model for groundwater recharge with a model for unsaturated water transport and a hydraulic model for the discharge from the Dickenberg-gallery.

Table 1 *Water balance constituents above the mine water level for the year 2008, related to the area of the West Field system#*

Water balance constituents	Absolute values (m^3)	Fraction (%)
Precipitation	10,771,475	100.00
Surface runoff	538,574	5.00
Groundwater recharge	5,231,391	48.56
Evaporation	3,925,512	36.44
Transpiration	904,102	8.40
Change in the total water volume	171,896	1.60
Calculated gallery discharge	5,138,600	47.71
Measured gallery discharge	4,911,000	45.59

The model for water transport in the unsaturated layers takes into account the macro-heterogeneity of the surface land use and the soil permeability, evaporation and transpiration depending on the leaf area index based on daily values. This enables integrating the time-dependent contributions to the groundwater recharge from the various surface types and the estimation of the effects of water storage and retention.

The changes in the discharge rate from the Dickenberg-gallery result from fluctuations in the mine water level, which in turn depend on the groundwater recharge rate. Good agreement was reached between the calculated and measured time series for the discharge in the year 2008.

These conclusions should be considered as preliminary, because there may occur individual changes in the obtained results after increasing the level of model details, the specification of the input data and methods for the calculation of the transpiration and evaporation as well as the consideration of the micro-heterogeneity of the rocks (joints).

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