Employment Of A Double Continuum Model To Characterize Groundwater Flow In Underground Post-Mining Setups: Case Study Of The Ibbenbüren Westfield

Diego Bedoya-Gonzalez[1,2], Timo Kessler[2], Maria-Theresia Schafmeister[2]

[1]*Department of Geography and Geology, University of Salzburg, Hellbrunner Str. 34, 5020, Salzburg, Austria, diegoalexander.bedoyagonzalez@sbg.ac.at*

[2]*Institute for Geography and Geology, University of Greifswald, Friedrich-Ludwig-Jahn Str. 17a, 17487 Greifswald, Germany, timo.kessler@uni-greifswald.de; Schaf@uni-greifswald.de*

Abstract

Underground hard coal mining usually disrupt the mechanical equilibrium of the geological media, creating fractured zones in the bedrock. The present study employs a Double-Continuum model to assess the influence of the fractured and porous media on the percolation process at the Ibbenbüren Westfield. Model results displayed good agreement with measured mine water discharges. While fractured continuum reacts readily to heavy precipitations, water is released slowly from the matrix. This behavior generates a gradual decrease in the discharge over the dry season. Findings obtained from this approach can be integrated into reactive transport models to predict long-term evolution of mine drainages.

Keywords: Hard Coal Mining, Double-Continuum Model, Mine Water Discharge, Ibbenbüren Westfield

Introduction

Underground coal mining operations tend to modify the nature of the subsurface rock structure (Kim *et al*. 1997; Newman *et al*. 2017). The employment of high-recovery methods redistribute, concentrate and/or reorientate the stress field of the rocks, generating strains (i.e., deformations) along the sequence (David *et al*. 2017). Large vertical deformations create fracture networks that provoke duality on the fundamental hydraulic processes (Qu *et al*. 2015; Zhang *et al*. 2018; Liu *et al*. 2019). This behavior is evidenced, for example, in “diffuse” or slow infiltration in pristine rocks coupled with concentrated or “rapid” fluid flow along the fracture networks (Király 1994). The contrast is even more considerable if coal mines are developed into fairly impermeable rock sequences (Morin and Hutt 2001; Wolkersdorfer 2006).

The representation of dual systems is usually complicated by requiring extensive assignment of physical and chemical properties for both media. Many of these properties are even impossible to obtain for fracture networks. It is from this dilemma where double-continuum models (DC) arose as an appropriate approach (Pruess and Narasimhan 1985). The way how fractures are treated as a network of mean characteristics solves the difficulties of obtaining detailed info for constructing discrete fractured models and the inability of equivalent porous models (EPM) for considering strong heterogeneities. DC models simulate fractured porous media as two overlapping and interacting continua, with different flow, transport and storage parameters. The interaction between both is achieved through a mass transfer function determined by the size and shape of the blocks, as well as their local difference in pressure and/or temperature potentials (Beyer and Mohrlok 2006). Over time these models have been applied to numerous subsurface geochemical processes, such as oil recovery, geothermal energy, nuclear waste repositories, and CO2 sequestration (e.g., see Azom and Javadpour 2012; Hao *et al*. 2013). For coal mining areas, this approach can potentially be extended to simulating the quantity and quality of mine drainage, including contaminant migration, characterizing the rebound process at post-mining sites, and predicting water inflows within mining-disrupted sequences.

The present study uses recent progress in the characterization of water-conducting fracture zones to set up a double-continuum model of a coal mining zone. Our purpose is to emulate the infiltration process within the disturbed shallow overburden of the Ibbenbüren Westfield. Compared to other coal mining districts in Germany, this area is sharply delineated by the topography and local geology, resulting in an easily controllable area for testing the approach. Modeling intends to determine the influence of each flow element within the time-dependent water discharge of the mining area (i.e., the temporal distribution of the rapid (fracture) and slow (matrix) flow components).

The Ibbenbüren Westfield

Mining in the Ibbenbüren Westfield was founded on the exploitation of anthracitic coal seams encountered in a shallow Carboniferous crustal block. Here, operations stopped in June 1979, with excavations as deep as 600 m below the ground level (DMT GmbH & Co. KG 2019). After its closure, the area was flooded under control up to an elevation of around 65 m above the sea level (a.s.l.). At this height, groundwater reached the Dickenberg adit, which still maintains the same phreatic level by discharging exceedance of water out of the area (Rinder *et al.* 2020).

Due to the phreatic level of the former coalfield is above the foreland surface (< 55 m a.s.l.), precipitation turns into the only source of groundwater recharge. The development of a water-conducting fracture zone together with a sparse Quaternary offer neither storage capacity nor great resistance for meteoric water to percolate(Lotze *et al.* 1962; Bässler 1970). Consequently, the volume and temporal distribution of the discharged mine water is directly dependent on the water dynamics through the siliciclastic overburden. This is true for the area enclosed by the Northern and Southern Carboniferous Marginal faults, Mieke Fault and Pommer-Esche Fault, which represent effective hydrogeological boundaries for the field (Figure 1) (Prof. Dr. Coldewey GmbH 2018). Furthermore, groundwater can only be extracted in areas higher than the Dickenberg

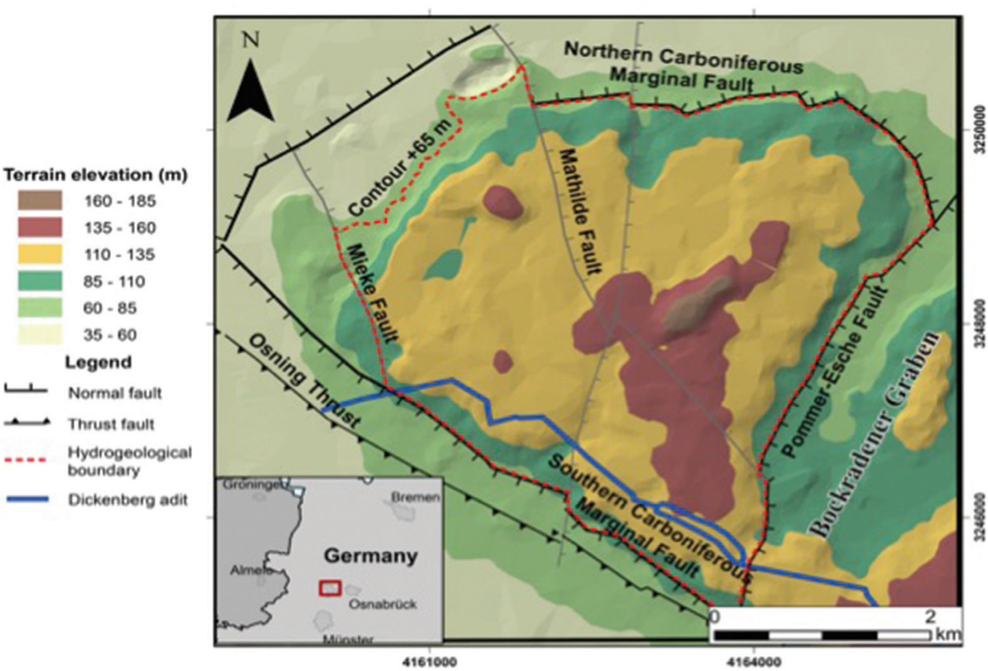

Figure 1 Location map of the Ibbenbüren Westfield. The Carboniferous blocks present some faults that turn into effective hydrogeological boundaries for the coalfield (modified after Bedoya-Gonzalez et al. 2021).

adit, turning the terrain contour +65 m into an additional hydrogeological limit

Methods

TOUGH2 (Pruess *et al.* 2012) is used to simulate the unsaturated overburden of the Ibbenbüren Westfield. The software employs Richards' equation to describe Darcy-type fluid flow in the variably saturated porous media. Space discretization is done by means of integral finite differences and fully implicit first-order finite differences in time (Xu *et al.* 2000). Modeling scenarios include isothermal flow conditions, with 2-phase and one water component

Geometry and grid construction

Conceptualization of the study area is depicted in Figure 2. The design and dimensions of the numerical model is made according to the hydrogeological limits previously described and illustrated in Figure 1. The 3D system is discretized into a number of vertical columns of 1 ha base and variable height to represent the concave shape of the area. The height difference between columns is selected equal to 5 m after considering the average thickness of the layers. The total number of columns for each height interval is, then, calculated by intersecting the DEM of the Westfield with the base boundary (65 m a.s.l.).

Horizontal layers in each column were assigned maintaining the lithological proportions and stritigraphical position as described in Bedoya-Gonzalez *et al.* (2021). Exceptions are the zones above 140 meters, which are assigned to anthropogenic waste rock deposits, and the first 5 meters of each column that correspond to highly weathered intervals. The depth at which the model splits into two continua is set at 45 meters above the deepest mined coal seam within the unsaturated zone (i.e., the nearest seam above the adit). This height was determined from empirical relationships after taking into account the thickness of the mined coal seam as well as the thickness and composition of the overburden (e.g., see Palchik 2003) However, fracture zone heights of 30 to 40 meters are also considered. Finally, fracture density per grid block is assumed to be equal to 10, resulting in a total exchange area of 10000 m^2 between the fracture continuum and the matrix.

Parameterization

Parameters used in this model are listed in Table 1. These values were extensively searched in the literature and assigned according to their correspondence with the lithological units. The calculation of relative permeability and capillary pressure values is performed according to the Van Genuchthen parametric model. However, since the Van Genuchthen parameters have been developed for porous media, their use in the fracture continuum is purely for model calibration and do not have physical meaning (e.g., see Kordilla *et al.* 2012). For the model calibration, parameters are only varied within

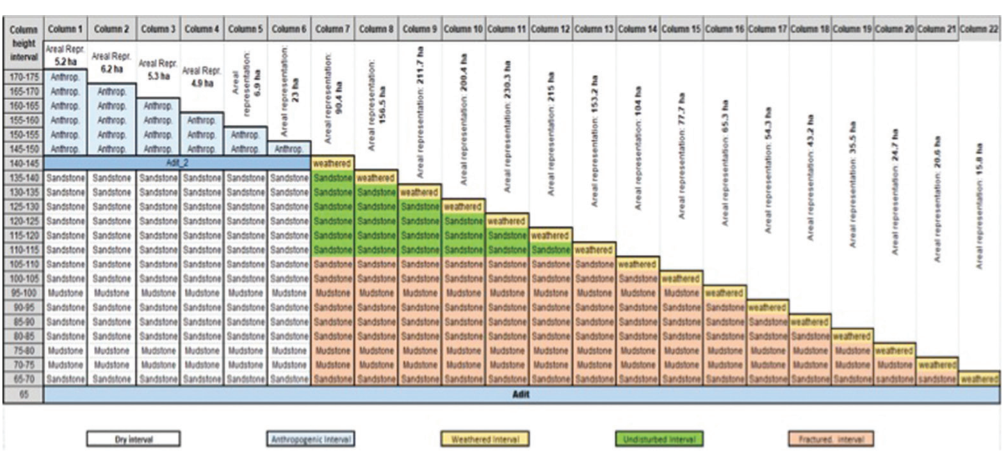

Figure 2 *Graphical representation of the 2D-grid discretization of the model.*

reasonable ranges consistent with the actual field conditions (values in parenthesis in Table 1).

Boundary conditions and initial conditions

The lateral sides of the matrix continuum, as well as the top of the model, are defined as no flow boundaries. The lower boundary is set to allow free drainage under gravity force. Lastly, a specified flux boundary is set at the top of the columns to account for diffuse recharge.

As initial conditions, Tough2 only needs the water saturations for each element. In our case, initial saturations were computed with a steady state simulation. The applied total recharge for this computation is 240 mm/y, which corresponds to the average recharge across Germany. Once the sequence reaches steady state, daily infiltration values are applied to the first element of the columns (see Figure 2). This amount varies temporarily and is estimated based on both daily precipitation and monthly average recharge for Ibbenbüren.

Model application

Fluid flow is simulated only in the vertical component of each column, only allowing lateral exchanges between fractures and matrix continua. The total discharge of the studied area is thus obtained by summing the discharge of all columns at the base (i.e., at 65 m a.s.l.). In the case of columns covered by waste rock deposits, discharge measurements are made around 145 m a.s.l., where an additional adit directs the water from these deposits to the Dickenberg adit.

Measuring the vertical flow of the system is valid if one considers that the overall fluid flow under unsaturated conditions is mainly driven by gravity and capillary forces in the vertical component. Also, a fairly homogeneous distribution in the horizontal plane of the zone allows this approach. Potentially, a horizontal fracture zone exists throughout the Westfield, as the Dickenberg and Buchholz coal seams were extensively mined. Also, core samples analyzed by Bedoya-Gonzalez *et al.* (2021) suggest that the proportions between sandstones and mudstones are similar throughout the shallow overburden.

Results and discussion

Figure 3 shows the actual and simulated discharge volumes of the Dickenberg adit for the year 2008. The simulated curve in the graph corresponds to the best match obtained from using the values listed outside the parentheses in Table 1. In overall, a good agreement between the two lines is observed. The greatest differences of up to 20% are associated with a small lag between the two signals from January to March. However, an advance of the simulated signal was expected because the rapid flow from the time the water reaches the adit to the point of discharge measurement was not taken into account.

According to the simulation, the system would be dominated by a high permeability

***Table 1** Hydraulic parameters used in the model. Values outside the parentheses indicate the values that showed the best agreement in our model (from *Prof. Dr. Coldewey GmbH and DMT GmbH & Co. KG 2018; ** Freeze and Cherry 1979; [¥]Bedoya-Gonzalez et al. 2021; [Ŧ]Kordilla et al. 2012; [ϕ]Parajuli et al. 2017.*

Lithology	Permeability	Effec. Porosity	Van genuchten parameters		
	(m²)	(-)	θr (-) [Ŧϕ]	Alpha (m-1) [Ŧϕ]	M [Ŧϕ]
Sandstone	1e-12 (1e-12-1e-14)*	0,15 (0,1-0,16)[¥]	0,15 (0,15–0,45)	0,1 (0,5–0,01)	0,35
Mudstone	1e-17**	0,05 **	0,65 (0.6–0.7)	0,04	0,22
Weathered interval	1e-12 (5e-11-1e-13)*	0.35 (0,15–0,4)*	0,1 (0,04–0,4)	2,6	0,65 (0,5–0,7)
Antropogenic deposit	1.0e-11 (1e-10 – 5e-12)*	0.35*	0.05	3,5	0,7
Fractured continuum	1.0e-8 (1e-7 – 1e-10)	0,99[¥]	0,05	2 (0,01- 5)	0,7 (0,4–0,75)

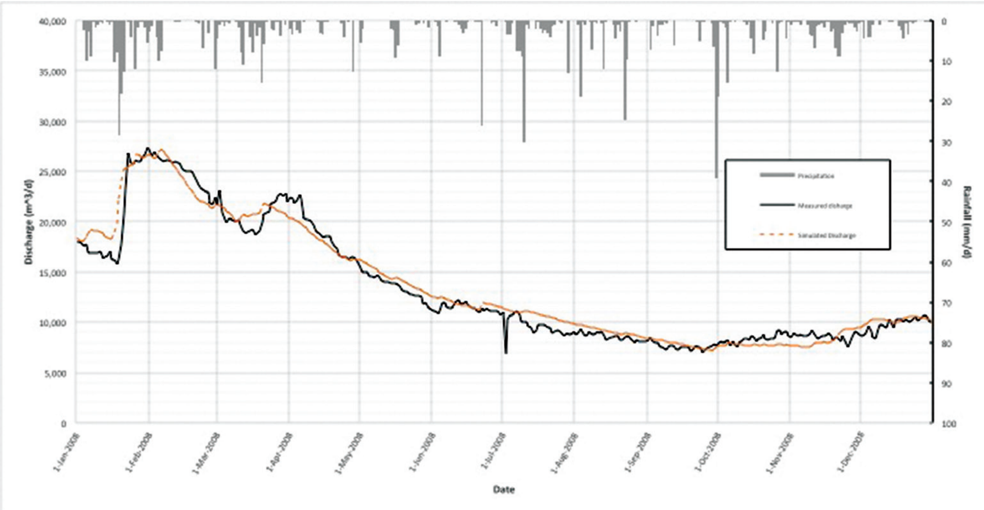

Figure 3 *Comparison between the measured and simulated discharge of the Dickenberg adit.*

media. The fractured continuum cause the system to react quickly during the months of higher precipitation generating the peaks of the discharge, while the recession of the signal is dominated by the matrix. Then, it is likely that during the summer months the saturation will slowly drop, meaning that the fractures are desaturated and the matrix has a much lower capillary pressure than the fractures (essentially holding water and slowly releasing). New water that may precipitate during summer may enter the fractures when the matrix capacity is shortly exceeded, but will mostly enter the matrix. This behavior causes that the system does not readily respond to heavy precipitation events in drier seasons, as potentially could show other types of models (e.g., see Rudakov *et al*. 2014).

Despite of the good agreement, results of the present paper should be considered as preliminary and be taken with caution. It is expected that a more extensive calibration process will bring better fits to some discrepancies, especially for the periods preceding the abundant discharges in January. Additionally, the parameters that presented the best curve adjustment corresponded to the end-members identified in the literature (e.g., the highest extension of the fracture zone and the greatest permeability for the sandstones). This could be due to the no identification, evaluation or calibration of sensitive parameters such as model geometry or conduit spacing. This latter would be, in fact, an influential parameter for the extension of the approach to modeling contaminant transport through the sequence.

Conclusions

The application of a double-continuum model positively fitted the transient discharge of the Dickenberg adit in the Ibbenbüren Westfield. The good agreement between the calculated and measured discharge for the year 2008 was possible by coupling a high permeability fracture continuum with a low permeability matrix continuum. Flow from the fractured media would derive in heavy and short discharges during the higher precipitation months, while the matrix would be responsible for a smoothed transition to the summer months, not being affected by strong precipitation events during this period. Consequently, the application of this approach to coal mining areas would add important aspects to mine water models, as they could estimate the relevance of each geological media with respect to mine drainage quality (e.g., Acid Mine Drainage generation). However, the results presented in this paper should be considered as preliminary due to the lack of study of other potentially sensitive factors, such as conduit spacing.

References

Azom PN, Javadpour F (2012) Dual-Continuum Modeling of Shale and Tight Gas Reservoirs. Soc Pet Eng. https://doi.org/doi:10.2118/159584-MS

Bässler R (1970) Hydrogeologische, chemische und Isotopen – Untersuchungen der Grubenwässer im Ibbenbürener Steinkohlenrevier. Z deutsch geol Ges 209–286

Bedoya-Gonzalez D, Hilberg S, Redhammer G, Rinder T (2021) A Petrographic Investigation of the Carboniferous Sequence from the Ibbenbüren Mine : Tracing the Origin of the Coal Mine Drainage. Minerals 11:1–19. https://doi.org/https:// doi.org/10.3390/min11050483

Beyer M, Mohrlok U (2006) Parameter estimation for a double continuum transport model for fractured porous media. In: Proceedings of ModelCARE'. IAHS Publ. 304, 2006., The Hague, The Netherlands, June 2005, pp 80–86

David K, Timms WA, Barbour SL, Mitra R (2017) .Tracking changes in the specific storage of overburden rock during longwall coal mining. J Hydrol 553:304–320. https://doi.org/10.1016/j.jhydrol.2017.07.057

DMT GmbH & Co. KG (2019) Abschluss-betriebsplan des Steinkohlen-bergwerks Ibbenbüren Anlage 17 – Prognose zur optimierten Wasserannahme nach Stilllegung des Steinkohlenbergwerkes Ibbenbüren (Ostfeld). RAG Anthrazit Ibbenbüren GmbH, Essen, Germany

Freeze R, Cherry JA (1979) Physical Properties and Principles. In: Brenn C, McNeily K (eds) Groundwater, 1st edn. Prentice-Hall Inc., Englewood Cliffs, New Jersey 07632, p 624

Hao Y, Fu P, Carrigan CR (2013) Application of a dual-continuum model for simulation of fluid flow and heat transfer in fractured geothermal reservoirs. Proceedings, 38th Work Geotherm Reserv Eng vol SGP-TR-198 Stanford Univ Stanford, Calif 462–469

Kim JM, Parizek RR, Elsworth D (1997) Evaluation of fully-coupled strata deformation and groundwater flow in response to longwall mining. Int J Rock Mech Min Sci 34:1187–1199. https://doi.org/10.1016/S1365-1609(97)80070-6

Király L (1994) Groundwater flow in fractures rocks: models and reality. In: 14th Mintrop Seminar über Interpretationsstrategien in Exploration und Produktion. Ruhr Universität Bochum, pp 1–21

Kordilla J, Sauter M, Reimann T, Geyer T (2012) Simulation of saturated and unsaturated flow in karst systems at catchment scale using a double continuum approach. Hydrol Earth Syst Sci 16:3909–3923. https://doi.org/10.5194/hess-16-3909-2012

Liu Y, Liu Q meng, Li W ping, *et al* (2019) Height of water-conducting fractured zone in coal mining in the soil–rock composite structure overburdens. Environ Earth Sci 78:242–255. https://doi.org/10.1007/s12665-019-8239-7

Lotze F, Semmler W, Kötter K, Mausolf F (1962) Hydrogeologie des Westteils der Ibbenbürener Karbonscholle. Springer Fachmedien Wiesbaden GmbH., Wiesbaden, Germany

Morin K a, Hutt NM (2001) Environmental geochemistry of minesite drainage: practical theory and case studies. MDAG Publishing, Vancouver, British Columbia, Canada Cover

Newman C, Agioutantis Z, Boede Jimenez Leon G (2017) Assessment of potential impacts to surface and subsurface water bodies due to longwall mining. Int J Min Sci Technol 27:57–64. https://doi.org/10.1016/j.ijmst.2016.11.016

Palchik V (2003) Formation of fractured zones in overburden due to longwall mining. Environ Geol 44:28–38. https://doi.org/10.1007/s00254-002-0732-7

Parajuli K, Sadeghi M, Jones S (2017) A binary mixing model for characterizing stony-soil water retention. Agric For Meteorol 244–245:1–8

Prof. Dr. Coldewey GmbH (2018) Abschlussbetriebsplan des Steinkohlen-bergwerks Ibbenbüren Anlage 16 – Auswirkungen des Grubenwasseranstiegs im Ostfeld des Bergwerkes Ibbenbüren der RAG Anthrazit Ibbenbüren GmbH. Münster, Germany

Pruess K, Narasimhan TN (1985) A practical method for modeling fluid and heat flow in fractured porous media. Soc Pet Eng J 25:14–26. https://doi.org/doi:10.2118/10509-PA

Pruess K, Oldenburg C, Moridis G (2012) TOUGH2 user's guide , version 2. 210

Qu Q, Xu J, Wu R, *et al* (2015) Three-zone characterisation of coupled strata and gas behaviour in multi-seam mining. Int J Rock Mech Min Sci 78:91–98. https://doi.org/10.1016/j.ijrmms.2015.04.018

Rinder T, Dietzel M, Stammeier JA, *et al* (2020) Geochemistry of coal mine drainage, groundwater, and brines from the Ibbenbüren mine, Germany: A coupled elemental-isotopic approach. Appl Geochemistry 121:104693. https://doi.org/10.1016/j.apgeochem.2020.104693

Rudakov D V., Coldewey WG, Goerke-Mallet P (2014) Modeling the Inflow and Discharge from Underground Structures within the Abandoned Hardcoal Mining Area of West Field (Ibbenbüren). –. In: Sui, Wanghua; Sun, Yajun; Wang C (ed) An Interdisciplinary Response to Mine Water Challenges. 12th International Mine Water Association Congress (IMWA 2014). Xuzhou, China, 18-22 August 2014;, pp 699 – 705

Wolkersdorfer C (2006) Water Management at Abandoned Flooded Underground Mines. Springer, Freiberg, Sachsen

Xu T, White SP, Pruess K, Brimhall GH (2000) Modeling of pyrite oxidation in saturated and unsaturated subsurface flow systems. Transp Porous Media 39:25–56. https://doi.org/10.1023/A:1006518725360

Zhang Y, Cao S, Wan T, Wang J (2018) Field Measurement and Mechanical Analysis of Height of the Water Flowing Fracture Zone in Short-Wall Block Backfill Mining beneath the Aquifer: A case study in China. Geofluids 2018:. https://doi.org/10.1155/2018/7873682