# 3-dimensional geologic and groundwater flow modelling for coal mining areas as decision support tool

## - Iterative interaction workflow to establish a reliable groundwater model -

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**Abstract** This paper describes the modelling workflow to develop a reliable geological model and a reliable hydrogeological model which were used within a cause study of a landslide in an open pit lignite mine. It is shown that interdisciplinary collaboration between field geologists, geological modellers and groundwater modellers is highly important to set up a consistent groundwater model. Thereby, the iterative interaction of the involved nature scientists and engineers is a crucial requirement to face difficulties and uncertainties in the practical modelling workflow. As shown in this paper the classic "in sequence" modelling workflow may lead to a misunderstanding of the hydrological processes and a misunderstanding of the geological setting.

**Key words** geological modelling, hydrogeological modelling, lignite mining, groundwater pressure

### Introduction

Remediation of large disused lignite mine areas and establishing structural stability are very complex and long-term projects. In several areas landslides with expansions of partly over 1 km² occurred unexpectedly although the embankments were declared as stable. One of the most dramatic landslides took place in the former lignite mine of Nachterstedt in 2009 (Fig. 1). About 4.5 million cubic metre dump slope slid into the half flooded open pit lake (Katzenbach, 2013). Thereby, three houses collapsed into the pit lake and three people lost their lives. As a consequence, several hectares of mine dumping areas were locked for public use to re-evaluate these areas and to restabilize them if necessary. In the course of the re-evaluation, but also by public and juridical demand as well as for future and exemplary assessment of other areas, the causes of the landslide had to be found.

As groundwater is one of the forcing parameters to provoke landslides (Förster, 1997), reliable geological and hydrogeological models are fundamental elements in the cause study to answer geological, geotechnical and hydrogeological questions.

Therefore, a groundwater model is an appropriate tool to understand subsurface flow processes and to predict the response of changes within these processes. The basic information of a groundwater model is the knowledge of the subsurface system. Hence, the geological model has always been recognized as a very important element in groundwater modelling (Anderson & Woessner, 1992). The accuracy of the model and the reliability of the predicted future scenarios are dominated by the geological certainty (Carrera & Neuman, 1986, Harrar et al. 2003, Troldborg, 2004, Eaton, 2006, Poeter & Anderson, 2005).

This paper discusses the development of a geological structure model starting with the basic information such as borehole data and on base of the geological model the establishment of a groundwater model. It indicates the significance of the iterative interactions between the field geologists (basic information/borehole data), the geological modellers (geological structure model) and the groundwater modeller (groundwater flow model) to face difficulties and uncertainties during the modelling workflow and to provide a consistent geological model and hydrogeological model in the cause study of the mentioned landslide. It is exemplarily shown, that this iterative modelling workflow should be considered instead of the classic "in sequence" modelling workflow especially in complex geological and hydrogeological settings with high requirements on the models.

***Figure** 1 Aerial view of the 2009 landslide Nachterstedt*

**Study area**

The lignite mine area is located nearby the village of Nachterstedt in Central Germany. Since the 19th century the area was extensively used by lignite mining both open pit and underground mining. Thus, the area is characterized by mining dumps and remaining open pits.

The geological setting is dominated by a complicated geological structure (Fig. 2) which mainly can be distinguished by an anticlinal salt dome of the Upper Permian salt. Thick estuaric tertiary sediments were deposited at the transverse basin. The syngenetic subsidence of the paralic basin of deposition led to a small scale variety in the lithological conditions in horizontal but also lateral direction. In Quaternary the study area was shaped by salt tectonics and quaternary meltwater channels, which eroded the tertiary sediments partly.

Likewise, the hydrogeological dynamics can be characterized by intense lateral and vertical variations of the groundwater level (Fig. 2). The artificial mining dump aquifer, which is an unconfined aquifer, is an extreme heterogeneous mixture of clay, silt, sand, gravel and lignite components. The natural aquifers are spatially limited with large variations in thickness and permeability. There is a connection to very permeable quaternary gravel outside the lignite basin. Thus, the groundwater flows from the quaternary gravel with its high water yield through the tertiary alternating layers and through the heterogeneous mining dump with its minor water yield into the remaining open pit. As a consequence the groundwater is flowing both in radial and ascending direction into the rising open pit lake. Depth-dependent groundwater pressure differences result partially in artesian conditions in the vicinity of the open pit lake.

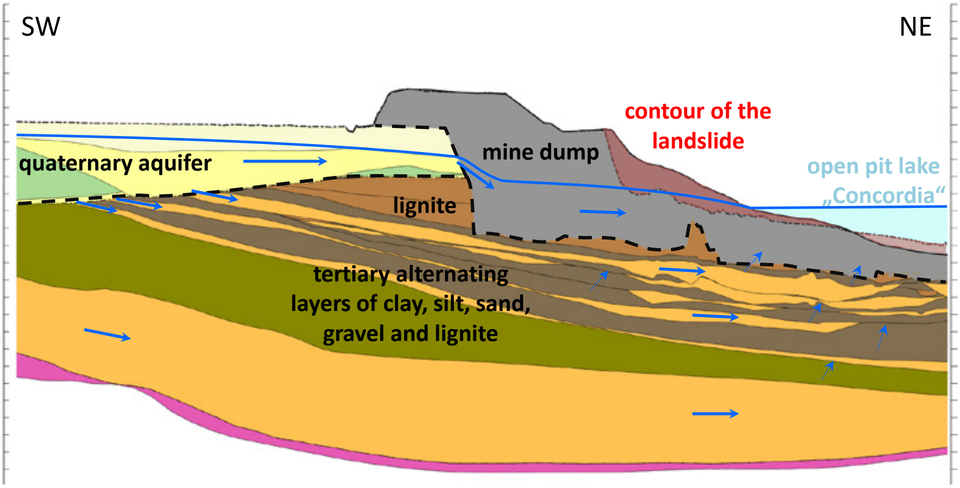


***Figure 2*** *Cross section to show the complex geological and hydrogeological situation.*

## Geological and groundwater modelling workflow

A 3-dimensional geological structure model was used to provide basic information for the cause study of the landslide. The model includes both the natural conditions of the geological structure as well as the artificial structure like mine dumps. In detail, the geological structure model was used to:

- create a database of all historical information
- create a 3-dimensional image of the complex geological conditions which helps to gain knowledge of the subsurface system
- provide the basic input data for all following model applications in the fields of hydrogeology, geotechnical engineering and remediation strategy
- provide a decision support tool for further investigations and remediation planning

About 3,900 historical soil profiles were digitalized and integrated in a borehole database. With the help of the database all soil profiles were subjected to a first stratigraphic classification. Further data input to the model was obtained by geological maps and geological cross sections from former exploration phases. On the basis of the soil profiles, the knowledge of the geological processes and the other mentioned information, a first version of the geological model could be established (Fig. 3 - “a”) with the help of the SURPAC modelling software (boundary surface model).

Altogether 39 boundary surfaces were created for the respective stratigraphic formations. With the help of a spatial review of the borehole data in the model a plausibility check of the stratigraphic classification of the soil profiles was carried out. If necessary, single layers of the soil profiles were reclassified (Fig. 3 - “b”). Though, the exchange between the geological modeller and the field geologist is essential.

The established 3-dimensional geological structure model provided a geometrical basis for the hydrogeological flow model (Fig. 3 - “c”).

The groundwater flow has been simulated with the large-scale groundwater flow model “Nachterstedt” based on the simulation software PCGEOFIM (Blankenburg et al. 2016). PCGEOFIM is a finite volume groundwater flow simulation software which is specifically designed for mining and post-mining areas. It provides particular features to be appropriate for the mining-specific conditions like time-dependent changes of geological structure and subsurface parameters – all combined in one model run.

The basis of a reliable groundwater model is the geological structure model which considers all layers in respect of relevant hydrogeological processes. The quality of the groundwater model depends strongly on the knowledge of the geology (Anderson & Woessner, 1992). Thus, the layers of the built up 3-dimensional geological structure model were transferred into the structure of the groundwater model (Fig. 3 - “c”). In the end, 26 relevant hydrogeological layers were transferred as not all 39 stratigraphic layers had to be considered for the groundwater model.

Furthermore, the knowledge and implementation of boundary conditions is necessary for groundwater modelling. Boundary conditions like drainage wells, mining pit lakes with its changing water levels as well as other relevant hydraulic parameters like regional precipitation and evapotranspiration were taken into account. By considering the mentioned data the model can be calibrated.

By comparing existing measurement data with the calculation results while the model calibration process, the past trends as well as the actual state should be simulated with the smallest possible deviation. Through specific changes of the permeability parameters or the boundary conditions the simulation results can be adapted in order to obtain a minimum deviation between the calculated and the measured water levels or flow rates by trial and error. Thus, the basis of a successful model calibration is a sufficient number of representative groundwater observation wells in all relevant hydrogeological layers (Fig. 3 - “e”). After the successful completion of the model calibration, the model can be used to predict changes or future behaviour in groundwater dynamics as well to “backcast” past situations.

It is important to ensure that all the qualified groundwater observation wells are representative of the hydrogeological layer they were assigned to by the field geologist. Therefore, again the iterative form of modelling was applied. Based on the hydrogeological calculation results, the stratigraphic classifications were revised and adapted in some cases, e.g. if certain measured groundwater levels do not fit into the general image of the groundwater dynamics and no hydrogeological explanation of the divergent water levels can be found (Fig. 3 - “f”).

During the calibration procedure of the groundwater model and “backcast” calculations for the cause study of the landslide of Nachterstedt discrepancies appeared between the understanding of the hydrological processes and the geological structure. A rising head test indicated that certain hydrogeological layers below the slid area showed not the expected groundwater dynamics according to the constructed geological model. The rising head test was accomplished by switching off the drainage wells which were installed in the confined aquifers. A steep rising water level was observed through a tight monitoring system of groundwater observation wells and piezometers successfully installed below the lake surface. An even groundwater flow direction was expected in the aquifer for the steady state, since the aquifer was initially awaited as almost homogeneous and uniformly distributed. By analysing the data that was collected during the pumping test, a narrow defined pressure anomaly with noticeable artesian water levels could be detected, which only could be explained by a specification of the geological structure model. Finally, intensive discussions between the geologists and hydrogeologists revealed, that excessive fluctuations in thickness and permeability within the aquifer with extreme spatial variations of the parameter values be present. Therefore, the geological model had to be revised by reclassification of the original borehole data regarding the recent hydrogeological results (Fig. 3 - “d”).

During the whole workflow process, all this iterative interaction steps “a” to “f” have to be proceeded in close coordination with the engineers and natural scientists – not necessarily to establish a perfectly calibrated model but to simulate realistic possible running processes within the field of geology and hydrogeology. Thus, it is crucial that every single adjustment of the models has to be intensively discussed with all involved geologist and modellers.

## Conclusion

In applied but also in scientific groundwater modelling, often the geological model is taken as a given and unchangeable component as a consequence of an already existing geological model. Hence, e.g. the calibration and the resolution of the groundwater model are frequently called into question and need to be revised if necessary during the entire modelling workflow. But once the geological model is not sufficiently precise to challenge the issues which should be answered by the groundwater model, the results of the groundwater model

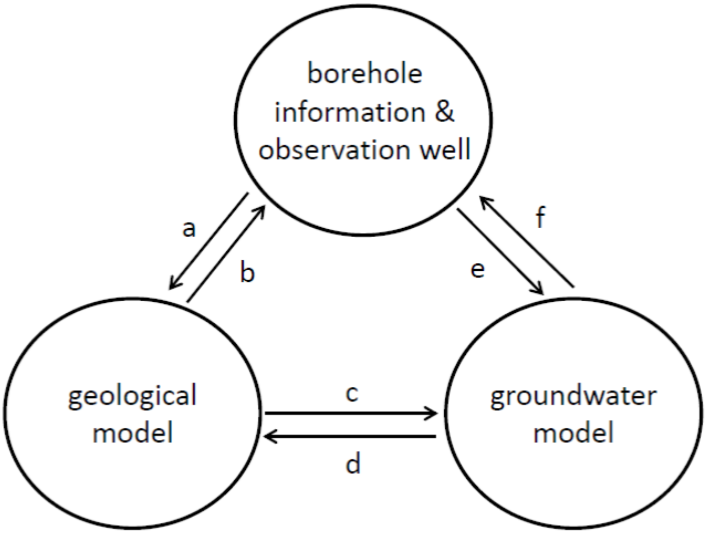


***Figure 3*** *Flow chart with the iterative interactions during the modelling workflow, explanation of the letters in the text*

cannot be reliable. As shown in this paper the classic "in sequence" modelling workflow – basic geological information to a geological structure model to a groundwater model – may lead to a misunderstanding of the hydrological processes and a misunderstanding of the geological setting. Hence, continues discussions between the involved field geologist, geological and groundwater modeller are helping to improve the understanding of the subsurface processes. Furthermore, the iterative interaction steps as shown in Fig. 3 can verify the results of the basic information like classification of stratification, the geological model and also the groundwater model. This leads to a solid understanding of the running processes and thereby to the establishment of a suitable model concept.

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