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Analyzing the Effects of Groundwater Influenced Flooding of a Large Abandoned Mining Area in Eastern Germany

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Abstract Since the end of the 19th century, parts of Eastern Germany have been characterized by large industrial zones, producing lignite and electricity. Some of the industrial activities are planned to be phased out by 2015 and a number of old pits have already been transformed and integrated in a large regionally unique lake district. One of the lakes to be developed is the Cottbuser Ostsee to the East of the city of Cottbus (mining pit Cottbus-Nord). DHI-WASY was contracted to analyze the flooding process of this lake. The flooding is strongly groundwater influenced and is modeled by a 3D groundwater FEFLOW model. The characteristics of the lake (water level dependent volume and area) are represented by a separate plug-in called IfmLake. With the modeling it was possible to develop an optimal strategy for the flooding (duration and water availability) as well as to analyze the effects of the flooding on the surroundings of the lake, especially groundwater depth in sensitive economic or ecological zones. Furthermore, the analysis of the flooding process was reproduced using the plug-in IfmMIKE11, which couples FEFLOW with the surface water model MIKE11. By integrating this surface water model additional features and analyzing possibilities could be used. Results of this comparison, advantages of this method and potential fields of application are highlighted in this study.

Keywords groundwater modeling, Cottbus-Nord, mining lakes, FEFLOW, coupling with MIKE11

Introduction

In Lusatia, a region in north-eastern Germany, Vattenfall Europe Mining AG operates several lignite opencast pits. Although mining carries on to date and three large power stations continue to produce electricity, some of the industrial activities are planned to be phased out by 2015. A number of old pits have already been transformed into a new landscape and integrated into a large lake district, previously unknown in Lusatia. One of the lakes to be developed is a pit called “Cottbus-Nord”, located 5 km to the north-east of the city Cottbus. It produces between 4 and 6 million tons of lignite yearly. The Cottbus-Nord mining pit will reach its final status in 2015 and the flooding is planned to begin in 2018 (MIL 2006). When reaching the intended maximum water level of 63.5 masl, the so called Cottbuser Ostsee will have a total area of approx. 18.4 km² and a volume of 146 Mio. m³. With the aim of investigating the flooding process and related changes in groundwater levels, DHI-WASY GmbH was contracted to build a regional groundwater model.

Fig. 1 *View at Cottbus Lake in May, 2014 (View Point North-East of the lake)*

Methodology and model set up

Details on the model components and model set up strategy are described in Monninkhoff et al. (2012). Fig. 2 shows the FEFLOW (Diersch, 2014) 3D groundwater model including the conductivity and boundary conditions. In- and outflow options of the lake were analysed in a separate MIKE11 model and the water availability for the flooding process was estimated using the model WBalMo. Optimal allocation strategies for water resources were assessed while taking into account long term water needs.

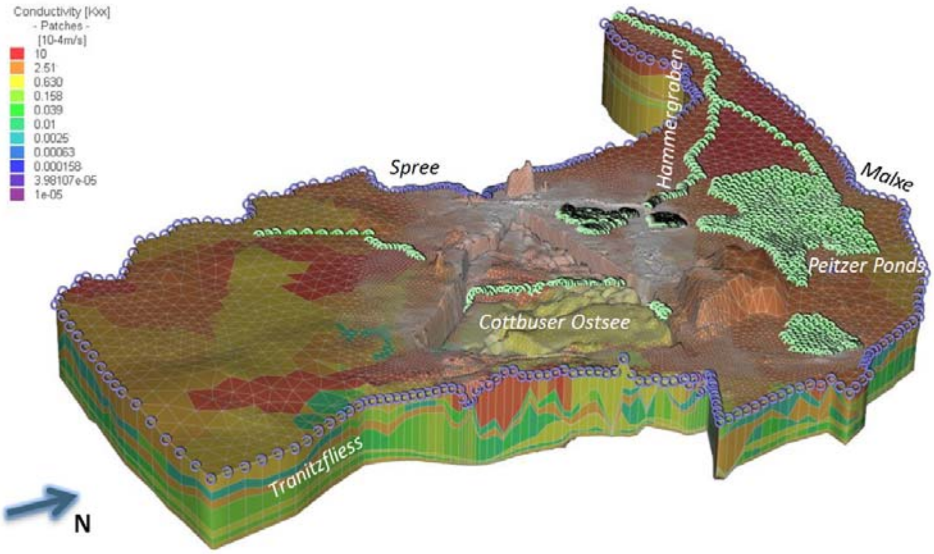

***Fig. 2** FEFLOW model with applied conductivities ad boundary conditions*

The northern and western model boundaries in the groundwater model are defined by Spree and Malxe. To the East, the boundary is defined by the subsurface water divide between the pits Cottbus-Nord and Jänschwalde to the North and Lake Klinger and Tranitzfliess to the South. The southern model boundary is located in an area unaffected by mining, and is defined by the isohypse of 80 m. The model incorporates four aquifers and three aquitards, represented by 8 model layers in total. The additional layer represents Holocene deposits at surface level. The entire model area covers 174 km², and the horizontal FEFLOW mesh consists of 79,094 triangular elements and 39,717 nodes. The model was calibrated by stationary simulations for the year 1996 (historical analyses) and for the year 2009 (present state analyses).

The water management and allocation software WBalMo has already been used in previous analyses for the utilization concept of the mining pit Cottbus-Nord (Kaltofen et al. 2008). The model WBalMo Spree / Schwarze Elster was since extended and updated and builds a good basis for long-term management analyses of the area in focus, and the lake Cottbuser See in particular.

Optimization analyses of the WBalMo model had to be restricted with respect to the maximum possible outflow discharge towards the Spree. For this reason, first hydrodynamic analyses using the 1D model MIKE11 were made for routes along the existing branch Schwarzer Graben, as well as for alternative routes directly towards the Spree. For all alternatives maximum discharges were analysed.

In the original model concept, the flooding process was integrated using the FEFLOW plug-in IfmLake. This plug-in automatically sets nodal surface water levels within the groundwater model with an active transfer boundary by retrieving the water level from a previously prescribed water-level-volume relation during each time step. This relation can for example be obtained from a digital elevation model and be implemented in the module. Depending on the water level and surface elevation the plug-in changes the horizontal lake extent. The locations of the lakes as well as surface elevation of the bottom of the lakes are defined by two nodal reference distributions. The lake was separated into 8 sub basins in accordance to the elevation model, therefore 8 separate water-level-volume and area relations were created. At each time step the module calculates the current volume by taking into account all external inflow such as surface water discharge or climate dependent gains or losses (precipitation or evaporation) and discharge resulting from groundwater flux. Once the volume at the time step is known the water level is obtained from the relation curve.

This module has proven to generate reliable results for the presented case. The time at which the desired water level is reached coincides with that of comparable calculations. An additional benefit is the low volume of required data input and related workload in pre-processing. Despite these advantages the module has some limitations. Further investigations of water quality within the flooded lake or the drainage capacity of the surface water network, e.g. at areas of critical groundwater levels, cannot be realized by this model set up. It was therefore decided to compare the previous findings with those generated by a different approach, in which the FEFLOW groundwater model is coupled with MIKE11. MIKE11 (DHI 2014) is a 1D modeling tool based on finite difference scheme, which can solve for mass transport in addition to hydraulic problems. The external coupling between this software and FEFLOW is achieved by the FEFLOW plug in IfmMIKE11, functioning as main coupling interface manager. In such external couplings each time step is calculated only once and time consuming iteration is avoided. More details to this coupling module are described by Monninkhoff & Zhijia (2009).

A MIKE11 model was set up following the same assumptions as in the IfmLake model. The same time series for surface water discharge and climate induced fluxes could be used and prescribed as inflow and global boundaries. An outflow and connection to the river network is implemented north of the lake (see fig. 2). Again, eight sub basins are delineated, being described by branches and cross sections. Regular cross sections based on the lakes' profile in the digital elevation model, as commonly applied in MIKE11, are not suitable in this case, due to the irregular topography and shape of the sub basins. A more accurate representation of volume can be obtained by making use of the known area-water-level relations. By simplifying the irregular shape of each basin area to that of a square (see fig. 2), a water-level-width relation can be formulated, from which the cross sections can be defined.

Results

Results of the WBalMo simulations were used in FEFLOW to calculate the water levels in each single sub-lake and to analyse the influence of the proposed control strategy on groundwater levels in the region. An exemplary result of these simulations is shown in Fig. 4. The strategy shown in this figure involves an additional surface water inflow from the river Spree under average flow conditions. The maximum withdrawal of surface water is defined according the management rules currently established by the water authorities in the Spree river basin. The figure shows that in this case the flooding of the lake will take approximately 4,5 years (up to a level of 63.5 m). The flooding would then be finished around March 2022, which is more than 10 years earlier compared with the flooding period applying a strategy without additional surface water inflow.

The simulations with the plug-ins Ifmlake and IfmMIKE11 show an almost identical behavior with regard to the lake water level rise (see fig. 3). The entire lake is flooded in the same period of time with only two days difference (min. water level 61.8 masl at 11-Dec-

2021 [IfmMike11], 14-Dec-2021 [IfmLake]). Greater differences occur in overflow from one sub basin to the next. Though the time of intial overflow is often similar, greater differences could be observed for three of the sub basins (see Fig. 3, Sub Basin 3,6,7). After initial overflow, the discharged volume in IfmMIKE11 is often greater than simulated with IfmLake.

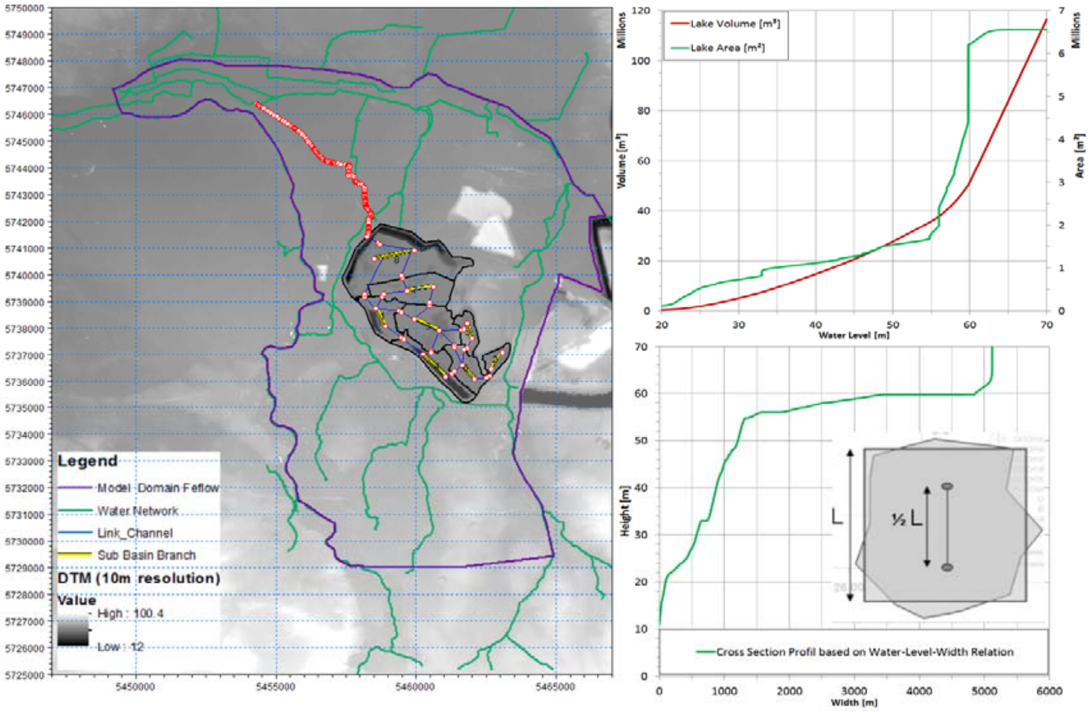

Fig. 3 *MIKE11 network and exemplary cross section based on water-level-area relation*

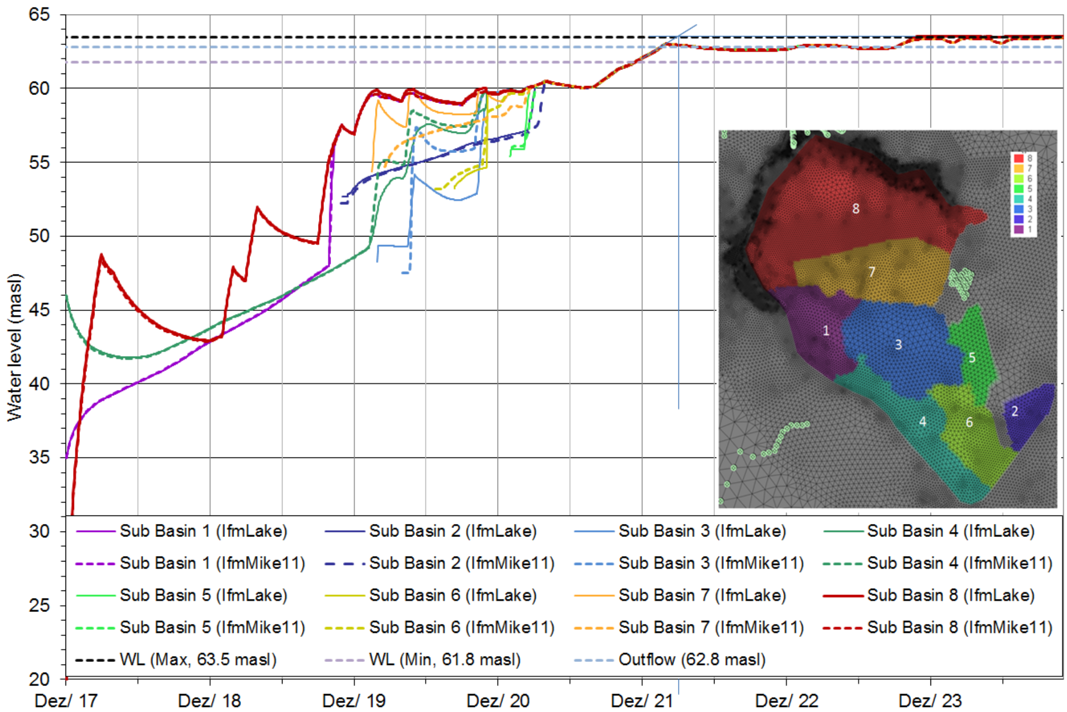

Fig. 4 *Water level of Sub Basins for IfmLake (straight line) and IfmMIKE11 (dashed line)*

A likely cause is the numerical implementation of the artificial connection between lakes. In case of IfmLake a single node is defined as link and given a width and elevation. On the basis of these data, discharge is calculated according to the simple broad crested weir equation (Poleni-equation). In IfmMIKE11 the link channels connecting the basins are of an open culvert type. Similar to an overflow weir, the discharge is calculated based on *Q/h* relations for which the nearest up- and downstream cross sections are used. Due to the utelization of water-level-area based profils, an overestimation of discharge from one lake into the other in case of IfmMIKE11 is likely. Another possible cause for differing fluxes between basins is the smaller time increment required by the surface water model compared to IfmLake, where the time step size is identical to that of FEFLOW.

A comparison of in- and outflow components between both modules has shown, that the total fluxes are of the same dimension (fig. 3, purple line), which could be expected when considering the good fit in water levels. Since fluxes due to surface water discharge and climate are prescribed per time series and are the same for both simulation, the only reason for the observed differences is the groundwater flux caclculated by both modules (fig. 3, green line).

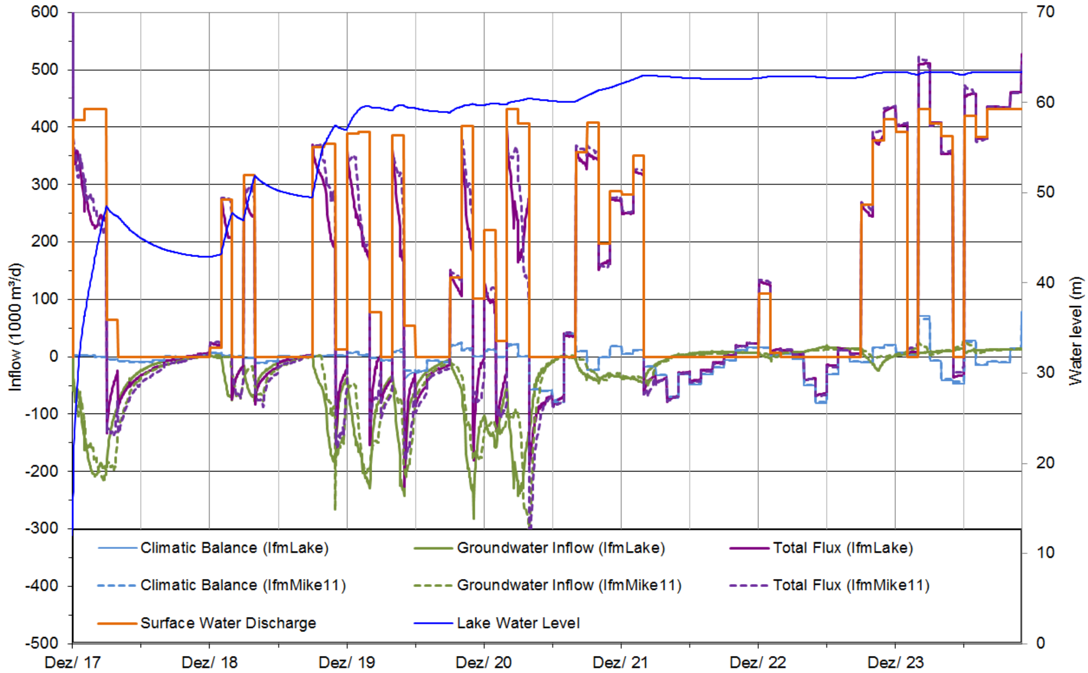

Fig. 1 *Water Level and Flux Components of IfmLake (straight line) and IfmMIKE11 (dashed line)*

Groundwater exchange is mostly driven by lake water levels and the size of the area covered by water in both modules. As discussed, due to the differences of the fluxes between the sub basins between both simulations, also the water levels within the sub basins slightly differ. Furthermore, IfmMIKE11 retrieves the sub basin water levels before each time step from only one H-Point in MIK11, the nearest H-Point of the coupled branch. Though differences between the H-Points in the simulated case can almost be neglected, the representativity of the coupled H-Point for the entire lake should preferably be confirmed in advance. Since the coupled boundary nodes are only activated after the corresponding water level exceeds a reference level (commonly surface elevation), the water covered area is the main driver of groundwater flux. Fig. 2 has already revealed differences in water level among the sub basins, which lead to the justified assumption that variations in activated boundary nodes in FEFLOW are the root cause for the observed differences in groundwater flux between both plug-ins. Minor variations may also arise as a consequence of the artificially defined cross sections in MIKE11, which have a resolution of 1 m. This is satisfactory to represent the volume of the entire basin with sufficient precision, smaller variations can occur during the flooding process, causing the number of activated boundary nodes in FEFLOW to differ.

Conclusions

Both modules are suitable to integrate a lake flooding process in the groundwater model FEFLOW and answer questions related to water level rise. Water flux between the lake and its environment, e.g. climate and groundwater induced fluxes, are well represented by both modules. Despite differences in the realization of surface and groundwater exchange, the generated volume flux and time frame of exchange are very similar, resulting in almost identical water level values.

Though IfmLake has the benefit of a lower workload related to model set up and data preprocessing as in case of MIKE11, certain limitations reduce the flexibility in application. More complex problems related to hydraulic structures, mass transport or interconnected river network systems cannot be solved by this FEFLOW plug-in.

The main advantage of IfmMIKE11 is the advanced hydrodynamic modeling tool behind it, which can be of upmost importance depending on the field of interest. A lake can be integrated in a river network composed of rivers, lakes, forelands and polder areas that may be regulated by hydraulic structures or separated by dams. Hydrodynamic problems relevant to mining, such as dam breaks, regulated hydraulic structures or shock waves (resulting in sudden change in water level and possible landslides), reallocation of a river course around a pit or even shaft flooding analyses, can be replicated. Via additional functionalities of MIKE11, mass transport and related water quality problems can be simulated as well. Also the MIKE11 interface to ECOLAB can be used by the module in order to describe biological and chemical processes.

Since both modules have proven to return results of neglectable differences, IfmLake could be the preferable option in similar case studies, considering the necessary low workload. In cases where other aspects of surface water dynamics are subject of investigation, coupling FEFLOW with IfmMIKE11 is a more suitable choice for the modeler.

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