Impacts of Re-Rising Groundwater Levels in Rehabilitated Opencast Mining Areas – Prediction Tools and Potential Measures of Damage Limitation

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Abstract Post-mining sites in the Central German Lignite Mining Area are characterized by filled pit lakes. In this context the groundwater re-rose to its historical level with the result of potential damages on building basements. In details, a large-scale groundwater model based on the simulation software PCGEOFIM was used to predict the potential impact on the buildings of the city of Delitzsch as well as the effect of possible measures of damage limitation. According to the modeling results, the only reasonable measure to protect the large number of affected buildings was the improvement of the bed of the local river. The objective of the planned extension measures was the re-establishment of the connectivity between aquifer and river in order to ensure stable influent flow conditions and consequently declining groundwater levels.

Keywords lignite mining, rehabilitation, re-rising groundwater levels, groundwater model, PCGEOFIM, Central German Lignite Mining Area, riverbed extension measures

Introduction

Lignite mining has shaped the region between Leipzig and Bitterfeld with the city of Delitzsch in the center (Fig. 1) for more than a century. In this northern part of the "Central German Lignite Mining Area" large-scale transformation processes took place. The installation and operation of opencast mining led to land devastation, relocation of surface waters from the operating area, lowering groundwater level and changes of groundwater quality. Thus, mining had and is still having a profound impact on the water balance and water quality of this area.

Due to the location of Delitzsch between the two opencast mines "Delitzsch Southwest" and "Goitzsche/Holzweissig/Rösa" as well as the long term groundwater use for water supply the local groundwater level was lowered significantly. As a result, the former floodplains of river Lober dried up and parts were designated as residential areas.

The rehabilitation of the opencast mines started in 1993. At first, stable embankments were constructed. Afterwards, groundwater lowering wells were turned off and the flooding of the empty lignite pits began. Against this background defining the final water levels of the pit lakes as well as predicting the rate and impact of flooding processes were required. The groundwater flow of the whole region has been modeled with the large-scaled "Groundwater Model Leipzig North" (HGMN) based on the simulation software PCGEOFIM.

Final lake water levels were reached in 2005 (mining area "Goitzsche/Holzweissig/Rösa") respectively in 2010 (Lake Werbelin in the mining area "Delitzsch Southwest"). Consequently, groundwater level was re-rising up again to its historical level closely below the surface. As a result, potential damages to building basements were likely.

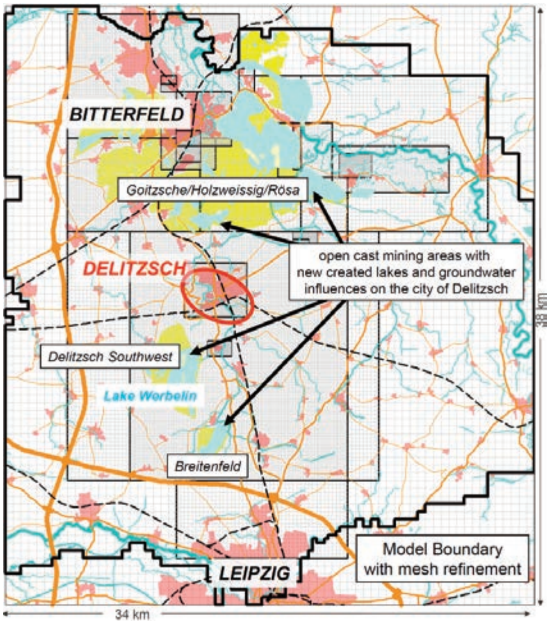

Fig. 1 Location of study area within the "Groundwater Model Leipzig North"

Prediction of the potential impact on buildings

Modeling system PCGEOFIM

PCGEOFIM (Sames *et al.* 2010) is a finite volume groundwater flow and transport model that is specifically designed for mining and post-mining areas. It provides some special features to be appropriate for the mining-specific conditions. The geological structure and subsurface parameters can be specified as time-dependent allowing for modeling the excavation of mine pits, deposition of mining dumps and creation of lakes all in one model run. The finite-volume method is characterized by a complete mass balance and provides unlimited telescopic mesh refinement. While working with a regular grid, multiple nested grid refinements that may overlap can be used to get higher resolution in areas of special interest.

The modeling system offers many ways to specify spatially varying groundwater recharge from constant in time as well as dependent on groundwater level below surface up to a sophisticate coupling with a rainfall-runoff-soil-water-budget model (Blankenburg *et al.* 2012).

PCGEOFIM provides a simple but very useful mechanism to reproduce the interactions between lakes and groundwater. The lake is represented as a water level – water volume relationship. In- and outflows such as groundwater and rivers are budgeted. Precipitation and evaporation yield a new lake water volume and hence a new water level. This water level is used as head for Cauchy boundary conditions that act jointly as "the lake". Fig. 2 shows how groundwater model elements are either vertically or horizontally coupled to the lake.

Rivers can also be represented by several time changing Cauchy boundary conditions that act jointly while the surface water level is calculated with Manning's formula based on the local discharge. Lots of special boundary conditions such as vertical and horizontal multi-level wells and defined outflow levels of lakes as well as sophisticated connections between rivers, lakes, and pipelines with control mechanisms provide a high level of representation of the natural system.

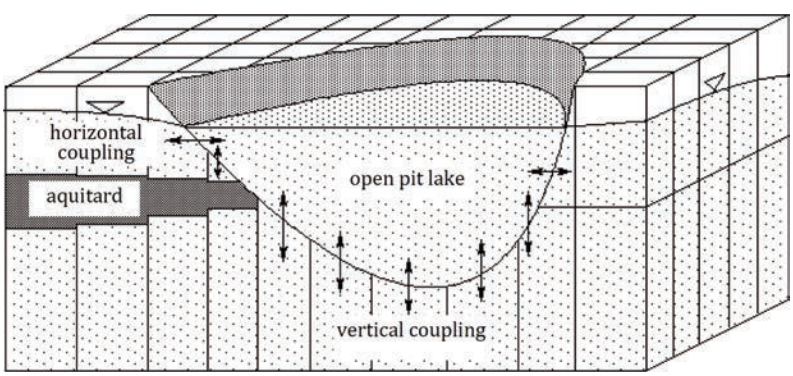

Fig. 2 Representation of boundary condition "lake" in PCGEOFIM

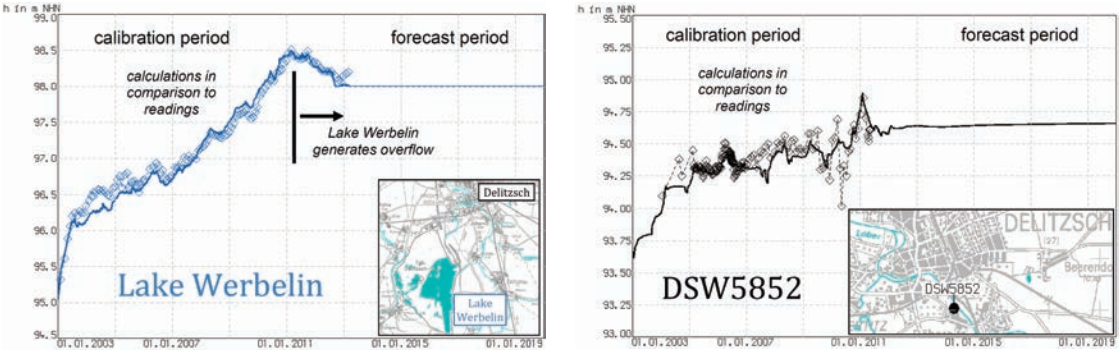

Fig. 3 Comparison of measured (rhombs) and simulated levels (solid line) at Lake Werbelin (left) and at a groundwater observation point in Delitzsch in the vicinity of river Lober (right)

Large-scale Groundwater Model Leipzig North (HGMN)

The large-scaled "Groundwater Model Leipzig North" (Mansel *et al.* 2011) covers 1079 km^2 with a maximum width of 38 km and a maximum length of 34 km (see Fig. 1). The telescopic nested mesh refinement uses widths from 500 m up to 30 m. The calculation of unsteady groundwater flow considers raising groundwater levels, emerging lakes and relocated rivers and creeks. The calibration period starts 2003 with variable groundwater recharge (monthly time step) and daily on-lake precipitation/evaporation. The main calibration parameters include soil saturated hydraulic conductivity as well as permeability of riverbed material. The forecast period begins 2012 with average climatic values corresponding to the time series 1980-2011.

Fig. 3 shows the measured and simulated rising water level at open pit lake "Werbelin" southwest of Delitzsch as well as the re-rising groundwater level at a groundwater observation point in Delitzsch with its unsteady flow conditions.

In details, the model "HGMN" was used to predict the potential impact on buildings. A building is considered, if the calculated differ-

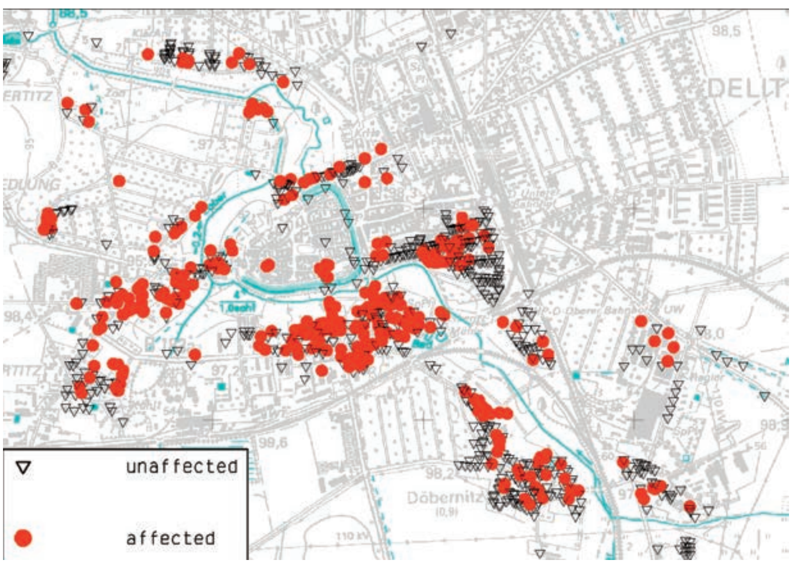

Fig. 4 *Potential affected buildings without measures according to modeling results*

ence between basement height and groundwater table is less than 0.5 m, assuming average climatic and steady flow conditions. The model predictions showed that without any limitation measures 436 buildings (by 1344) will be affected by high groundwater levels (Fig. 4).

Consequences and measures against damages on buildings

Individual measures such as sealing of basements, filling of basements with concrete or even house lifting are possible to protect buildings. If more than a few buildings are affected, large-scale measures such as horizontal filter wells, drainage systems or even improvements of conditions of water bodies may be considered as well.

According to the large number of affected buildings in Delitzsch, only integral measures appeared effective and sustainable. Due to low efficiency as well as high construction and operation costs, measures like wells and drainage systems were excluded.

In contrast, the extension of receiving waters appeared suitable. The muddy and clogged riverbed of river Lober led to a substantial reduction of the groundwater flow into the river resulting in increased groundwater levels up to the ground surface especially in the former floodplains. Differences of about 1 m were measured between ground and surface water levels in the vicinity of the river. Based on detailed hydrogeological investigations including pumping tests the permeability of the clogged riverbed material was found to be about 1×10^{-7} m s^{-1}.

The objective of the measures to be planned was the re-establishment of the connectivity between aquifer and river in order to ensure stable influent flow conditions with a minimum of maintenance costs. As part of model studies, different variations of improved riverbed permeability and optimized levels of the riverbed were examined. Riverbed permeability in the range of 1×10^{-5} m s^{-1} appeared attainable through extension measures.

In consequence of the riverbed improvement, groundwater levels will decline by approximately 0.5 to 1 m in the former floodplains and the number of buildings which are affected by high groundwater levels will decrease by 53 % (from 436 to 205 buildings), according to modeling forecasts.

Fig. 5 shows the sections with proposed riverbed improvements and the resulting affected buildings.

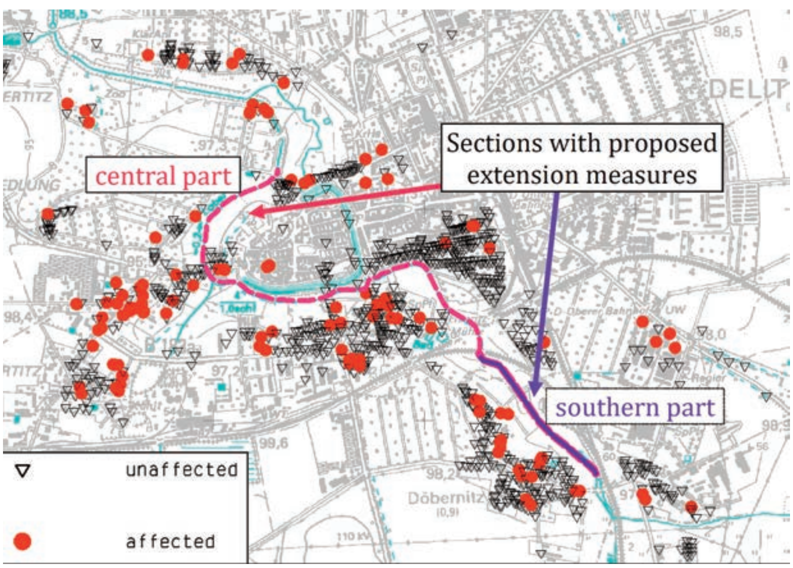

Fig. 5 *Sections with proposed riverbed improvements and resulting affected buildings according to model forecasts*

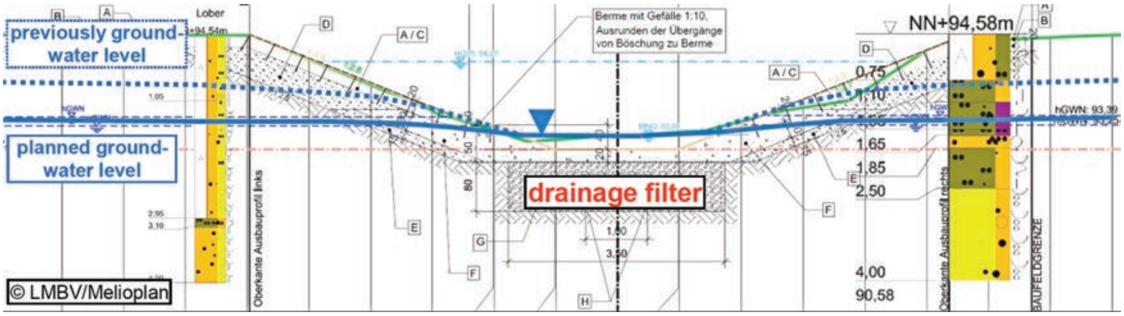

Fig. 6 *An exemplary cross section*

Fig. 7 *Before (left) and during (right) the exchange of the riverbed material*

Works carried out

Works began in 2011 with the southern section. Firstly mud deposits and the clogged riverbed were removed. Afterwards, a drainage filter was integrated and the riverbed was reshaped. The optimized riverbed shape was planned to ensure a minimum surface water flow velocity of 0.2 m s^{-1} (under average conditions) in order to prevent new mud deposits.

An exemplary cross section with the proposed drainage filter as well as the declined groundwater level (graphically-illustrated) is shown in the following Fig. 6 linked with views from the construction site in Fig. 7.

Results and future works

The groundwater monitoring showed that the predicted decline of groundwater levels occurred after completing the first construction stage. Fig. 8 shows the readings of the exemplary groundwater observation point "DSW5852" in comparison to the calculated levels with and without extension measures.

The decline of the groundwater level will remain on the basis of a regular maintenance. Hence, the protection of numerous buildings can be ensured permanently. So the construction of the second part in the center of Delitzsch started in 2013.

The most remaining affected buildings will be saved with special maintenance measures on small tributaries and trenches. The other few buildings can only be protected with individual measures in connection with special case examinations.

Conclusions

In consequence of the rehabilitation of the opencast mines in the vicinity of the city of Delitzsch, groundwater level rose up again to its historical level closely below the surface with the result of potential damages on buildings.

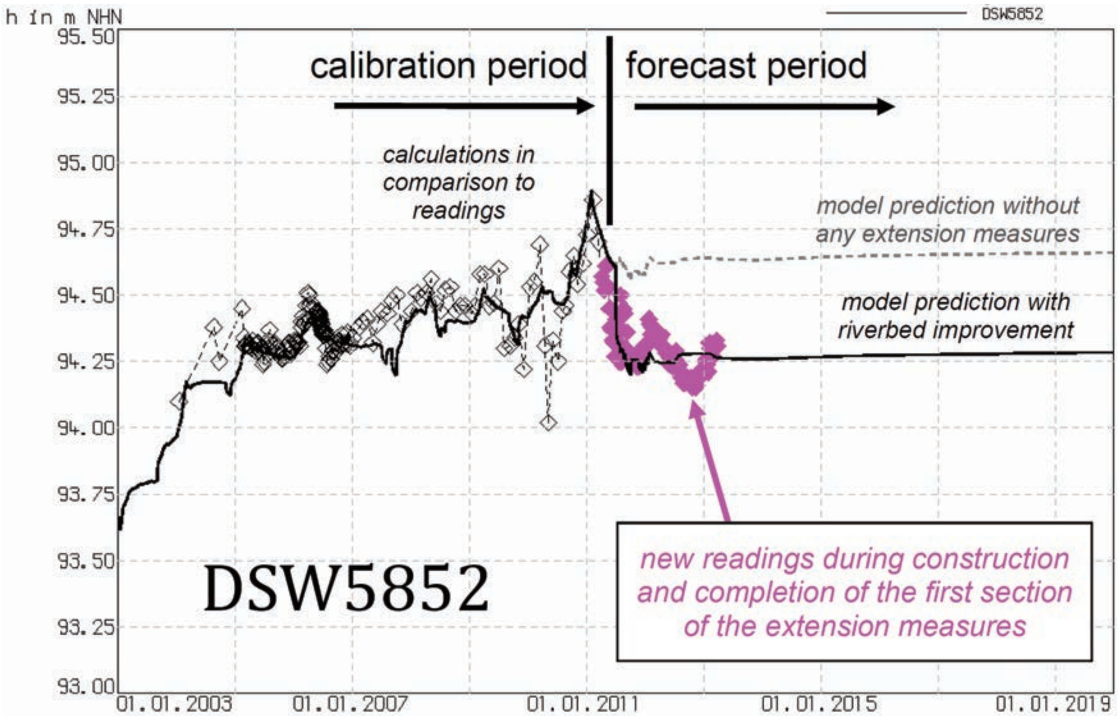

Fig. 8 *Comparison of measured (rhombs) and simulated groundwater levels (with and without riverbed improvement) at the groundwater observation point "DSW5852"*

According to the modeling results at average climatic conditions, the only reasonable measure to protect the large number of affected buildings was to improve the bed of the local river. The muddy and clogged riverbed led to a substantial reduction of the groundwater flow into the receiving waters resulting in increased groundwater levels up to the ground surface.

The objective of the river development was the re-establishment of the connectivity between aquifer and river in order to ensure stable influent flow conditions with a minimum of maintenance costs. The model prediction of the declined groundwater levels was confirmed by the groundwater monitoring during the first construction period.

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