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Flooding Induced Effects from the Mining Lake Goitzsche on Groundwater and Land-use in the Bitterfeld Area

The exceptional flooding event of the river Mulde in August 2002 led to an unexpected filling of the Goitzsche, an open-pit lignite mining lake, within two days. Due to this exceptional situation, the groundwater table in the vicinity of the lake rose several meters in the area of Bitterfeld. Over the last 100 years, this region has been affected by a large-scale contaminated aquifer of the former chemical industry complex Bitterfeld/Wolfen. Consequent to the rising groundwater level, the regional hydraulic situation and the groundwater flow direction changed entirely, as proven by hydraulic modelling results. Due to the heterogeneous aquifer conditions, the hydraulic importance was shown of a small scale channel-fill at the bottom of the upper aquifer. This predominant geological structure evidently affects the groundwater flow direction indicated by the modelled path lines. The resulting pathways of the contaminants can be used for the identification of exposure routes related to areas of high ecological sensitivity. The monitoring of highly soluble groundwater contaminants (e.g. benzene, TCE, *cis*-1,2-DCE), close to the flooding event, shows (irregular patterns of increasing, as well as decreasing, concentration values of related groundwater contaminants. Until the present, no consistent regional pattern can be recorded in the shift of the distribution of the concentration induced by the flooding event. Local differences in the concentration values are obviously more related to small scale variations within the Quaternary aquifer in terms of hydraulic conductivity and higher residual concentration of the contaminated matrix sediments. The temporal effects of concentration values ca be traced back, by most of the organic compounds, to distinct observation wells within the monitored time span at the starting point before flooding.

Regionale Beschreibung der Auswirkungen von hochflutinduzierten Effekten des Bergbausees Goitzsche auf das Grundwasser und die Landnutzung in der Region Bitterfeld

Aufgrund der Auswirkungen des Jahrhunderthochwassers an der Mulde wurde der Goitzsche-Tagebausee unerwartet schnell und vollständig geflutet. Der damit verbundene Anstieg der Grundwasseroberfläche in der Region Bitterfeld führt zu einer neuen Ausrichtung der Grundwasserströmung, wie die durchgeführten hydraulischen Modellierungen zeigen. Dabei wirken sich vor allem kleinräumige Rinnenstrukturen innerhalb des quartären Grundwasserleiters signifikant aus. Die neue Ausrichtung der Strömungsverhältnisse ist damit auch unter Stoffaustrags- und Expositionsbedingungen der Schutzgüter und Landnutzung von Bedeutung. Die Konzentrationsverteilung der hier untersuchten Kontaminanten (z. B. Benzen, TCE, *cis*-1,2-DCE), besonders der mit hoher Wasserlöslichkeit, zeigt zum Teil sehr starke Anstiege nach dem Hochwasser, ergibt aber regional keinen eindeutigen Trend. Anstieg und Abfall der Konzentrationen ist unregelmäßig sowie kleinräumig wechselnd und wird offensichtlich stärker durch lokale strukturelle Eigenschaften des Aquifers und dessen Residualbelastung durch die Kontaminanten bestimmt. Neben der heterogenen und zum Teil sehr deutlichen Veränderung der Konzentrationswerte ist mit zeitlichem Abstand zur Hochflut eine Annäherung an die Ausgangssituation zu beobachten.

Keywords: Regional Assessment, Groundwater Contamination, Hydraulic Modelling, Flooding

Schlagwörter: Umweltfolgewirkung, Grundwasserkontamination, Hydraulische Modellierung, Hochwasser

Research Paper

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1 Introduction

The flooding event of the river Mulde in August 2002 led to an unexpected quick filling within two days of the Goitzsche open-pit lignite mining lake near Bitterfeld in the eastern part of Germany. The flooding-induced fill of the lake resulted in a water level rise of more than 8 m. After the temporary exceptional flooding event of the river Mulde, which affected an area of more than 25 km^2, the water level of the Goitzsche lake was retained at a level of 75.5 m above sea level by subsequent pumping activities. The position of this water level is referenced with respect to the almost natural situation of the groundwater situation before the mining activities of the Goitzsche area, started approximately 50 years ago. Due to the current remediation plan for the Goitzsche area, the flooding of the former open-pit should occur continuously during the coming years. The recent position of the groundwater table was also additionally influenced by an increasing precipitation rate over the last few years. The increase of the water table, by approximately 8 m also leads to an increasing groundwater level in the vicinity of the lake. This exceptional situation influences the hydraulic situation in the groundwater bearing strata of the Quaternary and Tertiary aquifers, and also their regional groundwater flow patterns.

Large-scale contaminated mega-sites, such as Bitterfeld, are characterized by regional pollution of groundwater due to the long and varied history of the chemical industry in this region [1]. Due to former industrial as well as lignite mining activities in the region for more than 100 years, the groundwater was significantly contaminated by different sources of dump sites of the former chemical industry and industrial areas. The whole is characterized by a complex mixture of organic compounds (chlorinated aliphatic and aromatic hydrocarbons) comprising a high variability of individual substances. Monitoring wells show a high variability of concentration values, stratified vertically as well as in their horizontally varying within the Quaternary and Tertiary aquifers [2]. A description of the complex regional groundwater contamination has been carried out recently in the field of risk assessment, groundwater remediation and environmental impact assessment, providing a set of related contributions by different authors [1−10].

2 Purpose and objectives

To describe the flooding induced impact on the regional groundwater situation and the mobility of contaminants, investigations have been carried out on a GIS-based regional assessment approach, coupled with hydraulic modelling calculations. The regional assessment of the flooding induced effects in the eastern part of Bitterfeld town integrates the:

a) modelling of the post-flooding hydraulic conditions;

b) evaluation of the flooding-induced effects on groundwater contaminants at distinct observation wells both spatially and temporally;

c) exposure point oriented pathway identification; and

d) land-use sensitivity classification and risk mapping.

The change of the groundwater flow may lead to new distributions of contaminants by induced interaction of solubility and adsorption, as well as an expected down stream shift of their local concentrations within the aquifer. Therefore, this paper is intended as a first step in describing and modelling a complex situation of highly contaminated and heterogeneous aquifer systems with the available monitored data sets. A detailed understanding of interacting processes is needed to predict the transmission, pathway direction, and resulting potential exposure routes within a regional assessment. Questions concerning the transport modelling of individual organic substances have to be addressed in the future.

The variety of organic contaminants, as well as distinctive differences of concentrations in vertical and horizontal directions, are related to the high complexity of the geological layers within the aquifer system, leading to differences in small scale hydraulic conductivity as well as to changes in the adsorption potential of the aquifer material. To verify the complex geological structure of the Quaternary and Tertiary lithostratigraphic units, a digital 3D spatial geological model of high resolution was used for hydraulic modelling [11].

3 Study area

The study area covers a region of approximately 70 km^2 west of the Goitzsche Lake and Mulde reservoir, including parts or the industrial areas and the cities of Bitterfeld and Wolfen (Saxony-Anhalt, Germany). The alluvial plain of the Mulde River defines the NE part of the studied area. Figure 1 gives an overview of the land-use setting on the basis of recent digital topographic data and land-use classification (ATKIS). The ATKIS data set has been classified in terms of its sensitivity to groundwater contaminants and their potential exposure/receptor relations to selected land-use units. The maximal extension of the high flooding event in August 2002 by the river Mulde is indicated in the map of Figure 1. This information has been provided by the ad-hoc project 2.1, D. Haase, Environmental Research Centre (UFZ Halle-Leipzig) [12].

The Bitterfeld area is located at the lower terrace and alluvial plain of the Mulde River and can be described by a generalised hydrogeological and geological cross-section, depicted

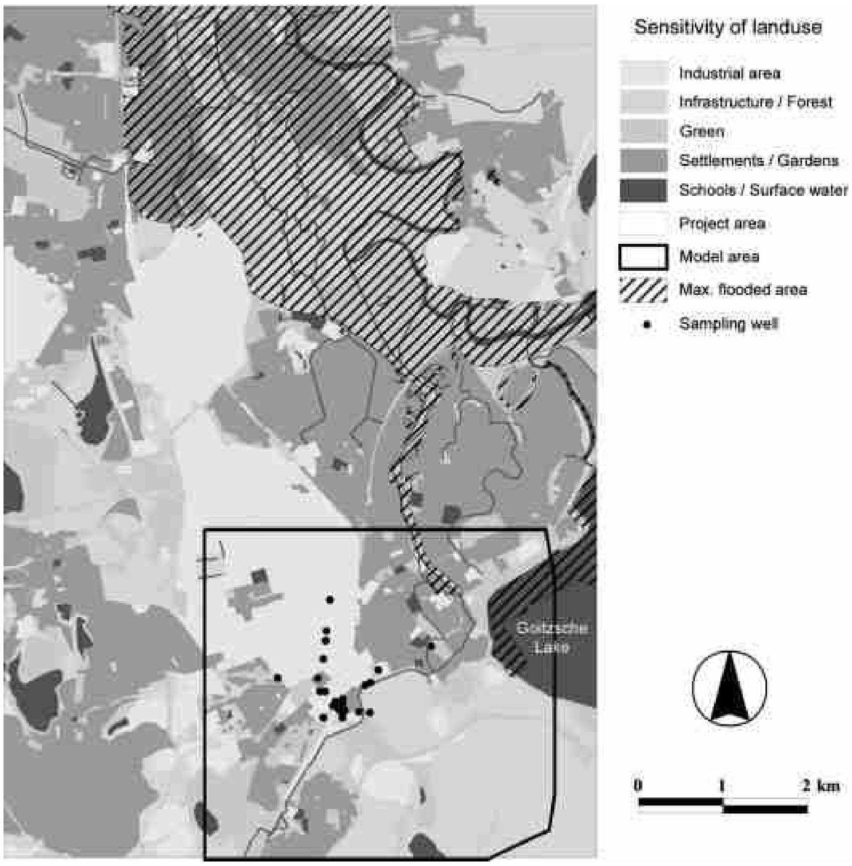

Fig. 1: Area studied with land-use sensitivity classification based on ATKIS data from 12/2002. Note the configuration of the model area in the southern part and the maximum extension of the flooding event 2002. The distribution of the available sampling wells is plotted in the modelled area.

Klassifizierte Sensitivitäten der Landnutzung im Untersuchungsraum auf Basis der ATKIS-Daten (Stand 12/2002) und Darstellung der Modellgrenzen im Südteil mit Lage der verfügbaren Beprobungsbrunnen im Modellgebiet. Als schraffierte Fläche ist die Maximalausdehnung des Hochwasserereignisses vom August 2002 zu sehen.

in Figure 2. The hydrogeological situation is characterized by the presence of two porous aquifers of different heterogeneity which are partially affected by former open-cast lignite mining activities. The upper groundwater aquifer consists of Quaternary sands and gravels. The Quaternary units can be divided into a lower part, represented by lower terrace sediments of the Weichselian Mulde deposits, and overlying sediments, composed of braided river deposits of a smaller tributary stream. Both units are partially separated by a clay layer, that provided an hydraulically effective barrier to flow [11].

The Quaternary aquifer is partially underlain by Upper Oligocene lignite seam, acting as a local aquitard. The lignite seam has been intensively mined in the southern part of Bitterfeld. The lower aquifer consists of Upper Oligocene micaceous sands of different hydraulic conductivity in its upper and lower parts. The base of this hydrogeological section is represented by middle Oligocene clays (Rupelian Clay); considered to be the aquitard of regional scale, hence corresponding to the base of groundwater pollution.

The analysis and prediction of groundwater flow, as well as the estimation of the regional retardation potential of the matrix material, needs detailed knowledge of the complex geological structure and accurate three dimensional distributions of the Quaternary deposits and remaining lignite seams in the subsurface. The modelled area of 16 km^2 is indicated in Figure 1. The geological information is based on 125 selected boreholes and 28 networked geological cross-sections. The small-scale lithological and structural heterogeneities, in particular of the Quaternary layers, were assigned to 31 lithostratigraphic sedimentary units and depicted using a 10 m $\times$ 10 m GIS grid. An assignment of hydraulic parameters to individual sedimentary units allows a subsequent combination with flow and transport models.

The information input to the structural model was generated by well site information, networked cross-sections, additional information from validity checks of the cross-sections, and lateral information of sediment distributions from surface maps. The results of the digital 3D model are used for visualisation purposes of the complex geological structure, as well as for the assessment of the aquifer/aquitard relationship, and for volumetric calculations of distinct sedimentary units. Consequently, the detailed digital structural model from the former SAFIRA Project was used for ongoing hydraulic modelling within the ad-hoc Elbe-Mulde project [11, 13].

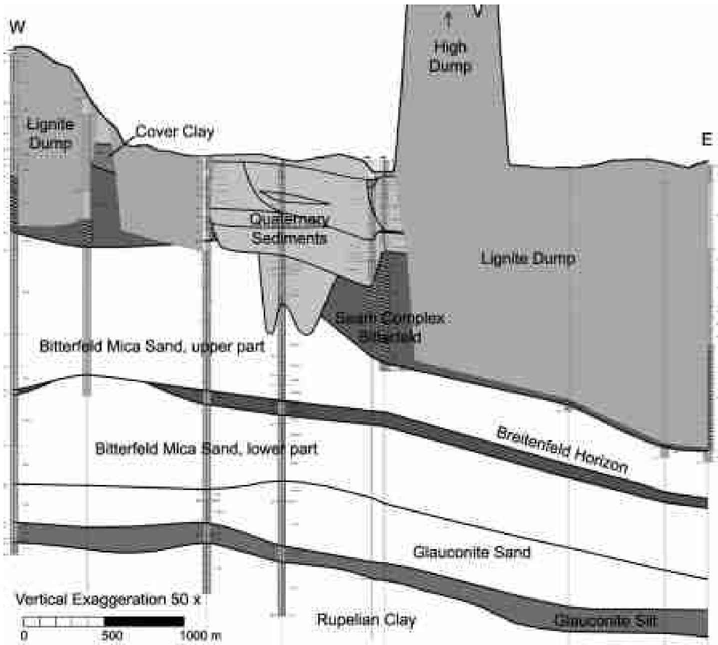

Fig. 2: Geological and hydrogeological cross-section (E-W) of the study area with the lithostratigraphic units representing the Quaternary and Tertiary aquifer.

Geologischer und hydrogeologischer Profilschnitt (E-W) des Untersuchungsgebietes mit Darstellung der lithostratigraphischen Einheiten des quartären und tertiären Aquifers.

4 Hydraulic modelling

The numerical groundwater model was carried out with two objectives:

- description of the hydraulic system prior to the flooding event of August 2002;
- predictive calculations of the changed hydraulic situation after the flooding of the Goitzsche Lake.

4.1 Methods and database

The numerical model consists of two parts: A groundwater flow model and a transport model based on the flow model. The modelling system Modflow, ModPath and MT3D [14] with the Visual Modflow 3.0 [15] pre- and postprocessors was used for modelling the southern part of the area. The modelled area of about 16 km^2 is indicated in Figure 1. The geological structure was reduced by condensing geological layers according to their hydrogeological properties, i.e. hydraulic conductivities and porosities (see Fig. 2). Most important for the numerical hydrogeological model is the completion of geological layers that peter out. The 10 layers of the numerical model have to be sustained across the whole model area. In case of petering out geological layers, the "slices" in the numerical model were given a minimum thickness of 1 m and the hydraulic conductivities of the correct geological layers were assigned. To evaluate the hydraulic conditions before and after the flooding, two steady-state groundwater flow models were calculated.

The main structure of the model is composed of Quaternary and Tertiary aquifers. Both aquifers are separated by a clay layer and also by the lignite seam, and are subdivided by several less conductive layers. The hydraulic conductivities of the Quaternary aquifers are between $2 \cdot 10^{-5}$ m/s and $1 \cdot 10^{-2}$ m/s. The Tertiary aquifer has a hydraulic conductivity of about 10^{-5} to 10^{-4} m/s. These ranges were estimated by grain size analyses and percolation tests [7, 11]. Calibration results were achieved by adjusting hydraulic conductivities within polygons.

The numerical groundwater model before August 2002 has to incorporate to two hydrological events: On the one hand a heavy rainfall with precipitation rates of more than 100 mm within 3 days led to an increased groundwater recharge in the entire catchment area; on the other hand the exceptional flooding event of the former lignite mining pit Goitzsche by the river Mulde raised the downstream boundary condition in the east of the model area by about 10 m.

Based on both steady-state flow models, two transient transport models were run as study models for ideal, non-reactive tracers. Only diffusion and dispersion were implemented, because sufficient sorption and biological degradation data are still not available. A recent research project (SAFIRA II) has been established to identify these parameters for the most important contaminants on a regional scale.

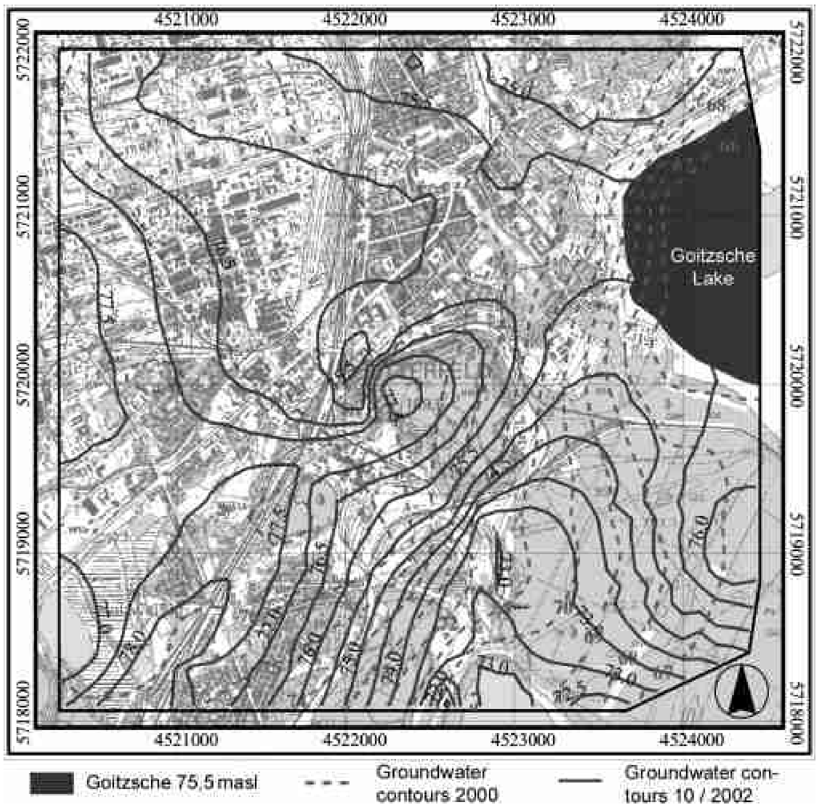

Fig. 3: Groundwater contours of the upper aquifer for the year 2000 and for October 2002 in metres above sea level. The axes show the *x,y*-coordinates in Gauss-Krueger, Germany-zone 4.

Grundwassergleichen des oberen Aquifers in m NN für das Jahr 2000 und für Oktober 2002. Die Koordinaten sind als Gauss-Krüger-Werte (Germany- Zone 4) angegeben.

4.2 Calibration of the groundwater model

The flow pattern before the flooding event has been outlined by the groundwater contour lines in the year 2000 [2]. Groundwater measurements at most of the wells were impossible during the flood so that the first reliable post-flood data are from October 2002. The groundwater flow models were calibrated to the measured water levels of the observation points and the groundwater contours.

Figure 3 shows the groundwater contours for the Quaternary aquifer of the year 2000 and October 2002 (before and after the flooding event). The data used comprise measurements of 196 observation wells. The data are nearly normally distributed so that interpolation with geostatistical methods was reliable. The information of the water levels were contributed by the Environmental Research Centre (UFZ Halle-Leipzig), the authorities of Saxony-Anhalt (Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt (LHW) and Landesamt für Altlastenfreistellung Sachsen-Anhalt (LAF)), and the former lignite mining corporation (Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH (LMBV)).

The hydraulic model results fit well to the interpolated groundwater contours. Because the measured water levels at the observation wells are the database of the interpolation, the deviation between measured data and modelled data can be calculated as the root mean square (RMS) error. The RMS error for the model 2000 compared to the measured data was about 0.15 m. For the 2002 model boundary conditions and the groundwater recharge were changed. The biggest influence came with the rising water table of the Goitzsche (from 65.6 m before the flooding to 75.5 m afterwards) but water levels also had to be changed of other constant head boundary conditions due to increased surface water levels. The calibration for the situation of October 2002 had an RMS error of 0.18 m.

The transport model could not be calibrated so far yet due to the restricted availability of field data. For future modelling balances, input and output values are important to calibrate the model. Outflow of substances from groundwater into surface water for the present models provide only a first approximation.

4.3 Results and predictive calculations

The increased recharge and the rising water levels in the Goitzsche Lake caused a pile-up in the area of Bitterfeld town and flooding with groundwater of house basements. In

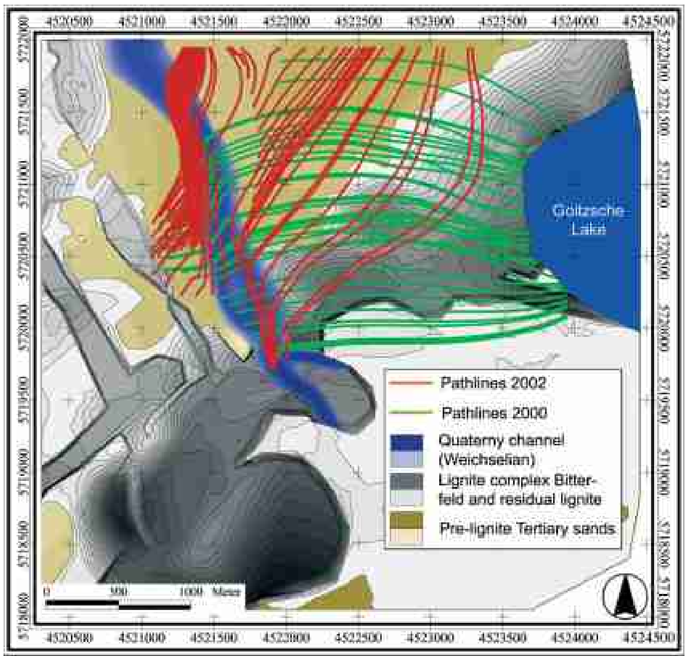

Fig. 4: Path lines of the modelled area for groundwater flow patterns in the Quaternary aquifer before flooding (2000) and after flooding (2002). Note the variation of path lines depending on different hydraulic situations and the influence of the Quaternary channel-fill with higher hydraulic conductivity. The axes show the *x*,*y*-coordinates in Gauss-Krueger, Germany-zone 4.

Bahnlinien der Grundwasserströmung im Modellgebiet für die Stofftransportsituation im quartären Aquifer vor dem Hochwasser (2000) und nach dem Hochwasser (2002). Zu erkennen ist die Abhängigkeit der Verteilung der Bahnlinien von den unterschiedlichen hydraulischen Verhältnissen und der Einfluss der quartären Rinnensedimente, die höhere hydraulische Durchlässigkeiten besitzen. Die Koordinaten sind als Gauss-Krüger-Werte (Germany-Zone 4) angegeben.

some parts of Bitterfeld an ongoing groundwater extraction was necessary to save the buildings [2]. The groundwater flow system changed completely because of the flooding. Before August 2002 the main groundwater flow direction was eastward, in August 2002 the flow direction turned to the north. Figure 4 shows the different traces of calculated path lines before and after the flooding event. It must be emphasized that not only the flooding of the lake Goitzsche led to these changes; the higher precipitation and therefore higher groundwater recharge induced additional higher groundwater tables in other parts of the catchment area.

Although the groundwater models can serve only as general studies, two main differences between both flow situations can to be distinguished. Both flow regimes are best shown by considering particle tracking and transport modelling results:

1. Contaminants have spread to the east during the last few decades. Since August 2002 the contaminants have trended to the north − northeast.
2. Contaminants in the Tertiary aquifer are diluted more slowly than in the Quaternary aquifer.

4.3.1 Flow models

The water balances of the flow models show that the main input to the groundwater model from recharge before the flood was about five times higher than the input from the constant head boundaries. About 900 000 m^3/a groundwater flows toward the Goitzsche Lake. The Tertiary (lower) aquifer does not contribute to the groundwater exchange. After August 2002 almost the same amount of water that flowed to the Goitzsche Lake before August 2002 now flows into the groundwater. The exchange of groundwater between Quaternary and Tertiary layers is also very low in this model and so the contamination remains in the Tertiary lithostratigraphic units over a long time. Therefore the contaminated groundwater volume therefore remains nearly constant. This behaviour is reinforced by sorption processes that could not be considered in these models.

4.3.2 Transport models

The transport model shows that the dispersion of the contaminants leads to long lasting high concentrations at obser-

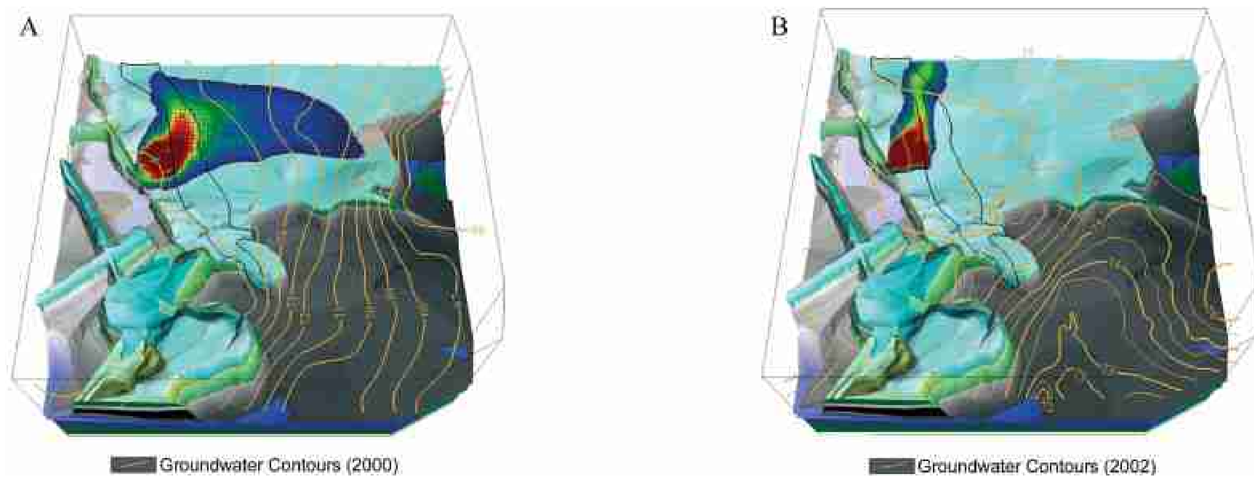

Fig. 5: The geological 3D-model shows the hydraulic relevant sediments depicted in Figure 2. Shown surface is related to the removed artificial mining dump sediments in Figure 5A and 5B, respectively. The model area represents 16 km^2, vertical exaggeration 15 $\times$. Note the strong influence of the channel-fill structure on transport effects in Figure 5B. A) Transport modelling of a non-reactive tracer after 30 years in the Quaternary aquifer before the flooding (2000). B) Transport modelling of a non-reactive tracer after 30 years in the Quaternary aquifer after the flooding (2002).

Das geologische 3D-Modell zeigt die hydraulisch relevanten Sedimentkörper, die in Bild 2 dargestellt sind. Die sichtbare Oberfläche in beiden Abbildungen ist ohne künstliche Auffüllungen durch Kippensedimente zu verstehen. Das Modellgebiet hat eine Fläche von 16 km^2, die Überhöhung ist 15-fach. Zu beachten ist der starke Einfluss der Rinnenstruktur auf den Stofftransport in Bild 5B. A) Modellierung des Transportverhaltens eines nicht-reaktiven Tracers nach 30 Jahren im quartären Aquifer für die hydraulischen Bedingungen vor dem Hochwasser (2000). B) Modellierung des Transportverhaltens eines nicht-reaktiven Tracers nach 30 Jahren im quartären Aquifer für die hydraulischen Bedingungen nach dem Hochwasser (2002).

vation points. Flow velocities are much smaller in the Tertiary aquifer than in the Quaternary aquifer. The influence of a Quaternary drainage system on the path-lines is very high; leading on the one hand to a transport of contaminants to the north, on the other hand contaminants are displaced by this drainage element into the Tertiary aquifer. Figures 5A and 5B show the results of transport modelling for the Quaternary aquifer before and after flooding. The models show that a steady-state for the contaminant transport has not been reached in the last few decades, although the flow pattern can be regarded as steady-state.

5 Groundwater contaminants and flooding interaction

5.1 Database

The evaluation of the flooding-induced effects on the groundwater contaminants at distinct observation wells is based on the analytical data provided by the ad-hoc subproject 8.2 (Dr. H. Weiß, Environmental Research Center, UFZ Leipzig-Halle) from several series of monitoring measurements. The data sets of 31 individual organic compounds, from 35 regional observation wells in the Quaternary aquifer were selected for three reference time spans related to the flooding event: A. pre-flooding (2002); B. post-flooding (autumn 2002), and C. post-flooding (summer 2003). The regional distribution of the observation wells is indicated in Figure 1 and does not cover the study area statistically. Therefore, changes in contaminants concentration values can be just presented and given solely as point information.

To establish comparable and consistent data sets, a reference set of contaminants, which are the most frequent, is given in Table 1. The physical and chemical parameters for tetrachloroethene (PCE), trichloroethene (TCE), *cis*-1,2-dichloroethene (*cis*-1,2-DCE), vinyl chloride (VC), 1,4-dichlorobenzene (1,4-DCB), 1,2-dichlorobenzene (1,2-DCB), monochlorobenzene (MCB), and benzene are included [16], as well as the calculated BCF (biological concentration factor) [17], and the threshold and quality targets for surface water in Saxony-Anhalt (Germany) [18], as well as the threshold values for negligible groundwater contamination [19].

5.2 Evaluation of contaminants

The appropriate and consistent analytical data from the groundwater contaminants, used for spatial and temporal

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Table 1: List of the selected organic contaminants, their relevant physicochemical properties, thresholds, and quality targets.

Darstellung der relevanten physiko-chemischen Eigenschaften, Grenzwerte und Qualitätsziele für die ausgewählten organischen Kontaminanten.

Substance	Water Solubility mg/L; 20 °C (c)	Vapour Pressure Pa; 20 °C (c)	BCF* (est) (d)	log *P** (d)	Thresholds and quality targets µg/L (a/b)
PCE	200	1 800	120.57	3.40	–/10 **
TCE	1 100	7 700	12.63	2.42	–/10**
cis-1,2-DCE	5 000	26 664	3.48	1.86	10
trans-1,2-DCE	6 300	53 000	5.90	2.09	10
VC	8 800	333 000	2.00	1.62	2/0.5
1,4-DCB	70	67	147.75	3.46	10
1,2-DCB	110	130	129.19	3.43	10
MCB	488	1 200	30.91	2.8	1
Benzene	1 800	9 300	2.13	6.47	10/1

(a) Quality target values for surface water in Saxony-Anhalt
(b) Threshold values for negligible groundwater contamination (LAWA 2004)
(c) Howard, P. H. and Meylan, W. M. (1997)
(d) CALTOX database
* BCF: bio concentration factor, log *P*: octanol-water partition coefficient
** 10 µg/L for PCE and/or TCE (single substance and total amount of both)

evaluation, originate from different monitored time periods. Based on the data from 38 observation wells, chlorinated aliphatic and aromatic hydrocarbons, listed in Table 1, are evaluated. All selected organic compounds for this evaluation show a high to very high solubility in water. Thus, a significant change in the concentrations of distinct contaminants is to be expected. High solubility values are characterized by > 10 mg/L and very high solubility by > 1000 mg/L respectively. A detailed description and comparison of the evaluation of the data sets is carried out in the ad-hoc Elbe-Mulde project report [13].

To illustrate the variability of concentration analytic values, a set of reference contaminants (TCE, *cis*-1,2-DCE, and MCB) from selected sampling points is given in Table 2. The comparison of the analytical values from the organic compounds pre- and post-flooding, as well as up to one year after the flooding event, show the great variability of concentration values; as can be observed in terms of regional and chemical aspects. The regional assessment of the changing concentrations at distinct observations wells cannot be confirmed on a regional scale. The patterns of concentrations for individual organic substances are heterogeneous and are most likely related to local presence of a higher hydraulic conductivity as well as a very different degree of residual concentration of the contaminated matrix material in the aquifer.

Figures 6A and 6B show that the spatial distribution of MCB has no systematic trend. Even close neighbouring observations indicate different concentration patterns, and are seemingly not strongly related to distinct geological structures and layers.

Comparing the post-flooding values from the summer 2003 to the flood induced values in 2002, the following tends can be observed: The majority of the analytical data reflect decreasing development of the concentrations. Most changes are recorded by the *cis*-DCE and MCB. To analyze the very complex processes of transport, adsorption/desorption relations, as well as biodegradation, a more detailed study has to be carried out, based on better statistical information.

6 Sensitivity of land-use units and changing pathways

To identify and select the potential flood-induced risk areas, a classification by land-use units has been done, depending on the effect of the rising groundwater table on the contaminated aquifer. Therefore, the most recent ATKIS-data set from December 2002 was used for the different land-use units. The individual units were ranked for their sensitivity in terms of rising groundwater, increasing contaminant concen-

Table 2: Analytical concentration values for selected organic contaminants at several sampling locations before the flood, in autumn 2002, and in summer 2003.

Analysierte Konzentrationswerte ausgewählter organischer Kontaminanten an verschiedenen Probenahmestellen vor dem Hochwasser, im Herbst 2002 und im Sommer 2003.

Sampling location	Screen position below surface, m	TCE, µg/L			*cis*-1,2-DCE, µg/L			MCB, µg/L		
		before flood	autumn 2002	summer 2003	before flood	autumn 2002	summer 2003	before flood	autumn 2002	summer 2003
BVV1230	8.0...11.0	2190.0	14.0	0.2	210.0	7.0	< 1	20.0	< 1	< 1
BVV1240	10.0...13.0	< 20	722.0	0.3	320.1	3340.0	6.0	56.1	17.0	< 1
BVV1250	8.0...11.0	1850.0	0.1	0.2	160.0	< 1	< 1	30.0	< 1	< 1
BVV3040	16.0...19.0	10.0	< 0.1	0.2	10.0	< 1	< 1	2217.4	5240.0	4600.0
BVV3050	6.2...9.2	660.0	4.0	2.0	35.0	< 1	560.0	10.0	< 1	< 1
SAFBIT11/97	19.0...20.0	< 20	< 0.1	2.0	< 20	20.0	4.0	9133.2	5600.0	5790.0
SAFBIT15/97	19.5...21.5	< 20	< 0.1	5.0	< 20	3.0	6.0	14051.5	16980.0	350.0
SAFBIT17/97	19.0...21.0	< 20	< 0.1	11.0	< 20	71.0	100.0	4760.8	5100.0	2280.0
SAFBIT19/97	20.0...22.0	25.5	365.0	250.0	144.3	570.0	490.0	47153.1	10930.0	4830.0
SAFBIT20/97	17.5...19.5	< 20	2.0	0.2	< 20	7.0	< 1	15871.9	25060.0	24300.0
SAFBIT21/97	13.0...15.0	< 20	< 0.1	< 0.1	< 20	2.0	< 1	31.4	< 1	< 1
SAFBIT23/98	18.3...20.3	< 20	< 0.1	64.0	61.0	< 1	190.0	4713.7	5830.0	4520.0
SAFBIT24/98	18.2...20.2	< 20	< 0.1	94.0	872.3	5.0	420.0	8848.4	6180.0	5160.0
SAFBIT25/98	13.0...15.0	< 20	4.0	1.0	< 20	6.0	47.0	200.6	211.0	17.0
SAFBIT26/98	9.0...11.0	–	< 0.1	0.3	20.0	0.7	6.0	10.0	< 1	< 1
SAFBIT27/98	19.8...21.8	< 20	< 0.1	0.2	< 20	< 1	80.0	7689.9	4080.0	2890.0
SAFBIT31/98	18.8...20.8	152.9	97.0	8.0	256.2	92.0	35.0	19611.7	12520.0	< 1
SAFBIT32/98	19.9...21.9	< 20	28.0	13.0	24.4	24.0	24.0	12263.7	10650.0	12800.0
SAFBIT33/98	15.4...16.9	< 20	< 0.1	0.4	< 20	18.0	26.0	-	< 1	< 1
SAFBIT35A/98	17.0...19.0	< 20	< 0.1	0.1	< 20	2.0	2.0	10401.8	6200.0	4440.0
SAFBIT36/98	21.2...23.2	< 20	18.0	4.0	< 20	17.0	3.0	17336.3	15380.0	13900.0
SAFBIT37/98	44.0...46.4	< 20	< 0.1	0.9	7224.4	1410.0	61.0	41.9	< 1	< 1
SAFBIT39/01	5.0...13.0	4574.5	8350.0	2630.0	276.3	21800.0	< 1	901.7	978.0	< 1
SAFBIT39Z/01	4.2...12.2	8516.1	17480.0	23100.0	354.0	36800.0	< 1	< 30	2350.0	1210.0

trations, and an exposure potential in relation to the pathway of the exposure routes to distinct land use and sensitivity.

The sensitivity ranking is, to some extent related to the normative concept of soil protection of Germany (BBodSchV). The ranking of individual units comprises areas of increasing sensitivity: industrial areas (1), forest, green land (2), meadows (3), agricultural use, open settlement (4) and schools, sensitive living areas, surface water (5) in relation to the selected objects of the ATKIS data set.

The classification of land-use sensitivity units shows that areas of low to medium sensitivity (1...3) represent 70% of the entire study area (see also Fig. 1). The major units are represented by industrial and former mining areas. The areas of high sensitivity (4 and 5) are related to housing areas, gardens and farm land and comprise 30% of the area. Particularly, the eastern part of the Bitterfeld city is affected by the rising groundwater level as well as by the flood induced hydraulic shift of the groundwater flow direction in the upper aquifer (Fig. 7). As noted earlier, the groundwater level is controlled systematically by a number of shallow extraction wells [2]. The post-flooding shift of the groundwater flow direction towards north and northeast leads, on the one hand, to an end of the exposure towards the Goitzsche, and on the other hand, to an increasing transmission to the alluvial plain of the Mulde River at further distances. As indicated in Figure 7, the remaining lignite coal in the subsurface acted as a large scale adsorbing barrier during the time of the eastward flow direction before the flooding event. After that, the path lines indicate a very strong influence of the Quaternary subsurface channel due to the higher hydraulic conductivity.

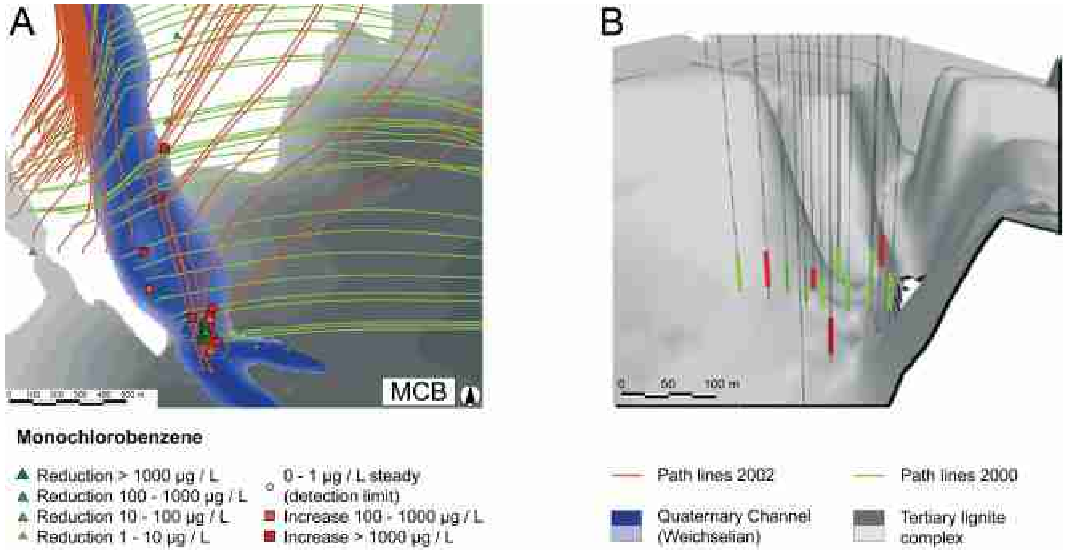

Fig. 6: A) Path line configuration of different flooding stages and classification of monochlorobenzene concentration values. B) Close up of the 3D topography of the incised channel-fill with screen positions plotted. Green colour indicates decreasing concentration values and red represents increasing concentration values.

A) Ausbildung der Bahnlinien im quartären Aquifer für die unterschiedlichen hydraulischen Bedingungen vor und nach dem Hochwasser und Klassifizierung der Konzentrationsveränderungen von Monochlorbenzen in den Beobachtungsbrunnen durch Einfluss des Hochwassers. B) Vergrößerung der 3D-Struktur der eingeschnittenen quartären Rinne mit Darstellung der Filterpositionen der Beobachtungsbrunnen. Grüne Farbe bedeutet sinkende Konzentrationen von Monochlorbenzen und rote Farbe zeigt ansteigende Konzentrationen von Monochlorbenzen.

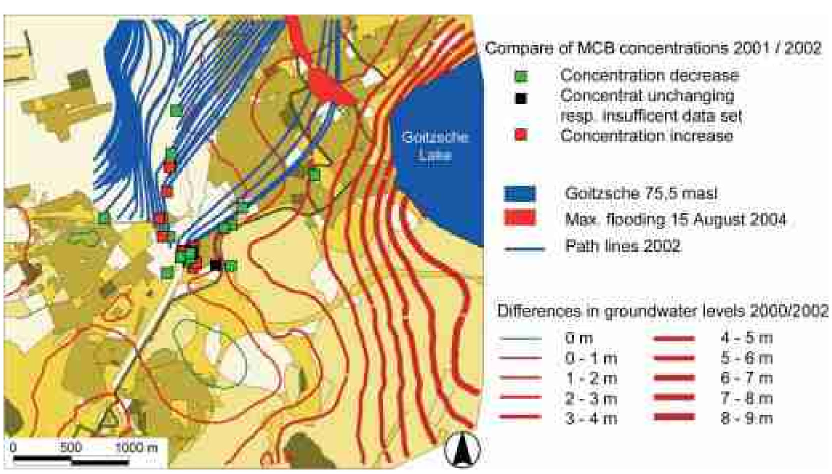

Fig. 7: GIS-based regional assessment integrating land-use sensitivity, path lines reflecting post-flooding pathways and differences in the groundwater level 2000/2002. Sensitivity classification refers to Figure 1, explanation in text.

GIS-gestützte, regionale Beurteilung der Auswirkungen des Hochwassers auf Basis der Landnutzungssensitivitäten, den Stoffaustragspfaden und des sich verringernden Grundwasserflurabstandes. Die Klassifizierung der Landnutzungssensitivitäten entspricht der in Bild 1 verwendeten und wird im Text erklärt.

The post-flooding orientation of the path lines also suggests a partially desorbing situation of the organic compounds, which had been bound on the lignite (compare Fig. 4). The presence of volatile organic compounds in combination with high groundwater levels requires ongoing monitoring and assessment concerning (i) the long-term development of the resulting hydraulic conditions, and (ii) the assessment of the exposure routes of persistent contaminants.

7 Conclusion

A widespread and very complex groundwater contamination has occurred in the study area due to the former industrial and mining activities of the last 100 years. This contamination resulted from different sources and has spread in the regional groundwater aquifer in response to heavily changing extraction conditions caused by regional lignite mining at different locations. In the southern part of the area the flow system in the Quaternary and Tertiary aquifers was oriented to the east towards the open-pit mining area of Goitzsche.

The flooding event of the Mulde River in August 2002 completed the started filling process of the open pit Goitzsche Lake and caused a completely new orientation of the groundwater flow system in the vicinity of the western part of the mining lake. In the southern part of the studied area, flow directions turned to the northeast. The major transport of groundwater contaminants also then shift to this direction. As indicated by hydraulic modelling, the influence of a Quaternary channel-fill at the base of the upper aquifer influences the groundwater flow and the pathway relation of contaminants to a large and unexpected extent. Due to the significantly higher hydraulic conductivity and the geometry of the channel-fill, the path lines are bundled and oriented to the north in the western part of the model area.

The regional assessment of the expected concentration changes at specific observation wells in the model show high values for ideal tracers. Some measurements support these modelling results but until the present day, no clear and overall regional trend can be confirmed. The effect of flooding is characterised by heterogeneous values, and the increase of concentrations for individual organic substances refer to areas of higher hydraulic conductivity.

The post-flooding development of the modelled path lines suggests a partially desorbing situation of the organic compounds, which were bound to the lignite over the years. The presence of volatile organic compounds, in combination with high groundwater levels and the new flow directions, requires an ongoing monitoring and assessment concerning the long-term development of the resulting hydraulic conditions and the assessment of the exposure routes of persistent contaminants.

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