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• *Water yield – Global change – Mining activities – Water transfer*

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Aspects of Integrated Water Resources Management in River Basins Influenced by Mining Activities in Lower Lusatia

Aspekte eines Integrierten Wasserressourcenmanagements in vom Bergbau beeinflussten Einzugsgebieten der Niederlausitz

With 11 Figures and 3 Tables

In Lower Lusatia, eastern Germany, the changing impacts of lignite coal mining and potential climate change have put the naturally low water yield conditions under pressure. Water resources balances describe the hydrological situation in the region and the need for action due to changing boundary conditions. Extended transfer of flood water from neighbouring catchments is considered inevitable for sustainable regional development and the establishment of a quantitatively and qualitatively self-regulated water system. Using the river basin management system WBalMo®, potential water transfer scenarios to compensate for water deficits resulting from regional and global change are analysed.

1. Water Resources Management and Water Resources Balances

1.1 Issues of Water Resources Management

Water is a renewable natural resource. Surface and subsurface waters form the water resources of a landscape, characterised by spatially and temporally changing water yields and by various water-related nature potentials. Nature potentials are benefits that come from nature and are free of costs, including self-purification, biological yield, ecological potential, energy potential, transportation and flood control potential (*Grünewald* 2003). However, global and regional examples demonstrate that overexploitation of these potentials causes negative development such as non-sustainable groundwater depletion, the degradation of rivers to waste water streams and the destruction of landscapes by urban settlements.

The aim of water resources management is to provide water in a sufficient quantity and quality for its several uses and to keep its nature potentials. Furthermore, water resources management involves the effective utilisation and protection of water bodies and aims to maintain or re-establish a good physical, chemical and biological condition of water bodies even while the intensity of ecosystem use increases (WFD 2000).

To meet these aims, water yield and water demand must be determined and compared which is most practicable by the formulation of both the state matrix Y of water yield and the state matrix D of water demand (*Fig. 1*).

Both matrices require harmonisation among the characteristics of *water quantity* and *quality* in *space* and *time* with a certain *probability*. Therefore, suitable methods, procedures, tools and operators must perform yield-oriented operations OP (Y) or demand-oriented operations OP^{-1} (D) to minimise costs and maximise sustainability. The continuous changes of natural and socio-economic boundary conditions additionally complicate finding the optimum between water yield and water demand matrices. Because the boundary conditions are randomly distributed and the users have different priorities, an exact mathematic solution does not exist. This complex task cannot be optimised directly but requires modern techniques of water resources management based on iterative approaches using scenario analyses and variant calculations.

Water resources balances are an important tool to approximate the hydrological situation of a catchment or region. However, complex boundary conditions on the catchment scale change scenarios, as described in *Figure 1*, and the sto-

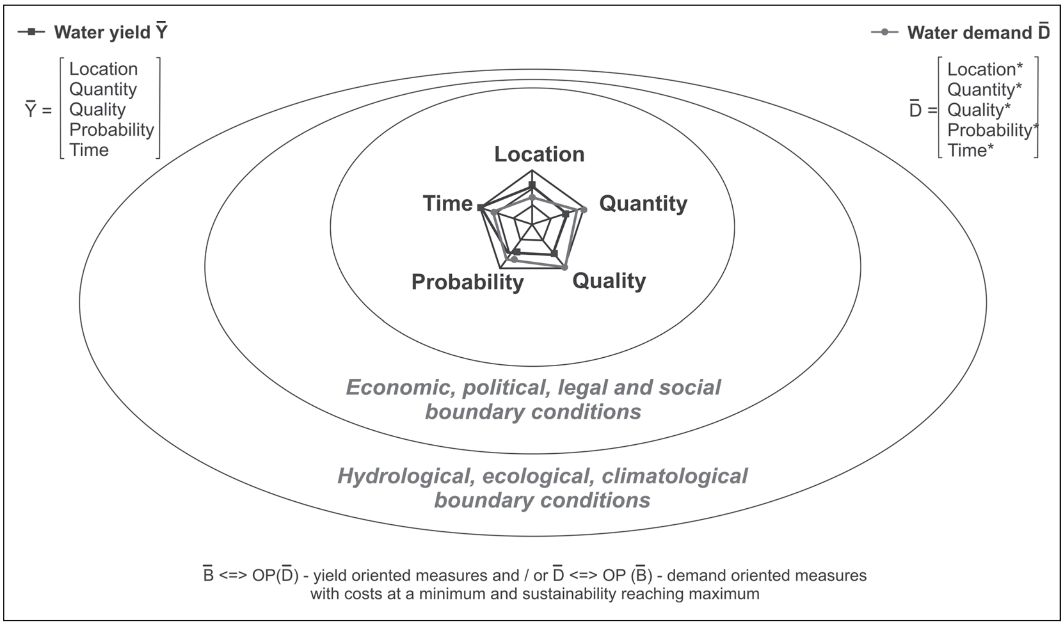

Fig. 1 Central issues of water resources management in a catchment under changing framework and boundary conditions (*Grünewald* 2001a, modified) / *Hauptprobleme integrierter Wasserbewirtschaftung im Einzugsgebiet unter sich verändernden Rahmen- und Randbedingungen (nach Grünewald 2001a)*

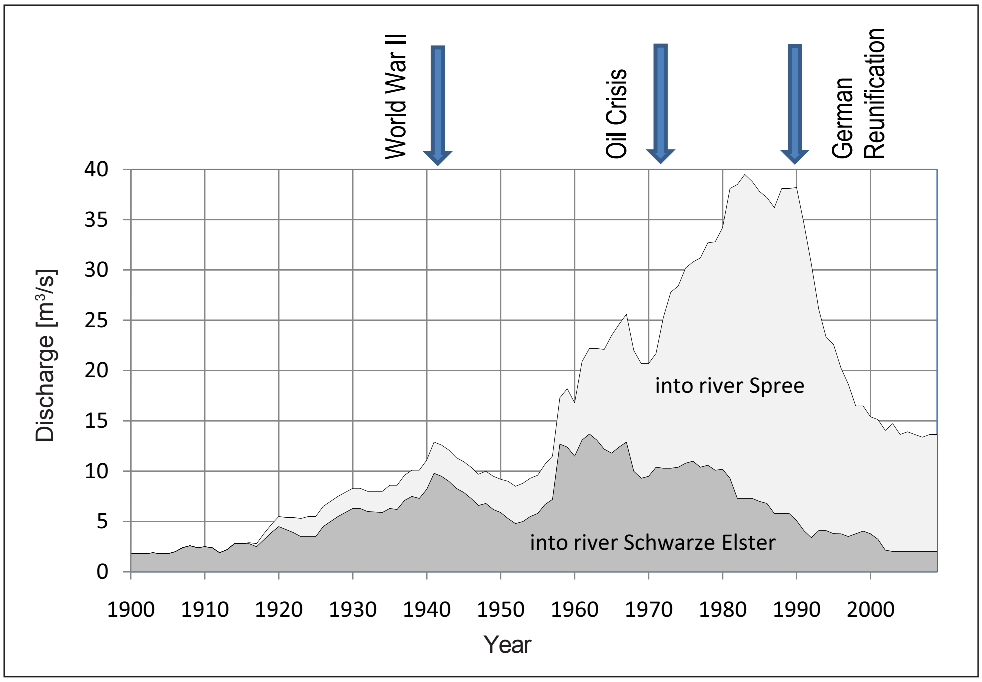

Fig. 2 Groundwater discharge into the Spree and Schwarze Elster rivers (*Grünewald* 2008, complemented)
Grundwassereinleitung in die Spree und die Schwarze Elster (nach Grünewald 2008, ergänzt)

chastic character of the input data to hydrological systems cannot be incorporated by such balances. Authorities and decision makers require complex planning systems as support tools, necessitating the continuous development of those instruments on national and international scales (*Loucks* and *van Beek* 2005).

Global change, the sum of natural (climate, biodiversity) and societal (technological, economic, demographic, land use) changes, is the transformation and modification of physical and biological components of the earth system over time. It involves those changes in nature and society that influence the livelihood of humans irreversibly and distinctively on a global scale (BMU 2009).

In Lower Lusatia, global change has repeatedly affected the lignite mining industry and thereby the region's water resources. The analysis of groundwater quantities withdrawn and discharged into surface waters to maintain dry working levels within the lignite mining pits indicates these effects (*Fig. 2*). Because the ratio between extracted lignite coal and the required groundwater pumping is approximately 1 to 7, the temporal behaviour of groundwater discharge quantities into the adjacent Spree and Schwarze Elster rivers represents the extracted lignite coal quantities.

The continuous increase in lignite mining production and consequently groundwater pumping was interrupted the first time during World War II. At the end of the 1950s, the lignite production of the German Democratic Republic (GDR) increased immensely. Prior to the oil crisis in 1973, the GDR reduced the lignite production due to the low cost of oil imports. With increasing oil prices and other political constraints, the GDR aimed to implement an energy autarchy, resulting again in increased lignite production and groundwater pumping rates. The most drastic effects on lignite mining were the political and economic changes in Europe and particularly in Germany in 1989. Lignite exploitation in the mining districts of the former GDR dramatically declined, and the sudden cessation of many large open cast mines after 1990 resulted in a massive decrease of pumped mining water.

Currently, technological change and climate change appear to be the most relevant issues for water resources management in Lower Lusatia (*Koch* et al. 2005).

Water resources management for Lower Lusatia must compensate for the effects of decreasing mining water discharge, potential climate change and differing priorities for water demand by various users under the conditions of naturally low water yield. The river basins relevant for management measures in Lower Lusatia are those of the Spree and Schwarze Elster rivers. Because the catchments do not correspond with federal state boundaries, negotiations and agreements on management measures across political boundaries are essential.

1.2 Water resources balances

1.2.1 Summary balances

Water resources balances are the basis for the planning of water resources management. Such balances include the effect of natural and societal conditions and the consequences for water resources. The main principle is the comparison of the natural water yield and the realised and planned immediate or long-term water uses. From that comparison, the availability of surface

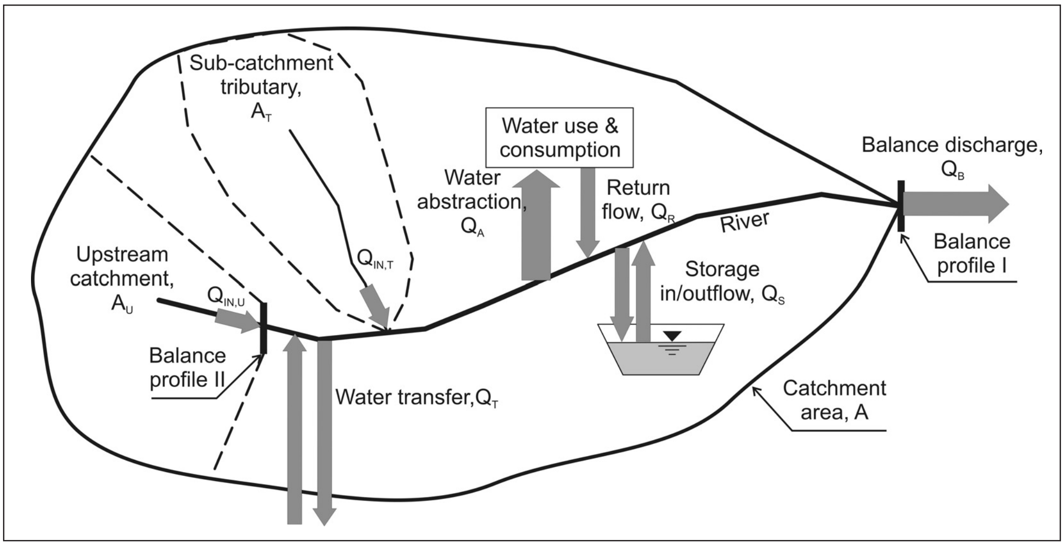

Fig. 3 Water resources balance components of a catchment (continuous line) and between two balance sections with sub-catchments (dotted lines), a simplified scheme / *Wasserbilanzkomponenten eines Einzugsgebiets (kontinuierliche Linie) und zwischen zwei Bilanzprofilen mit Teileinzugsgebieten (gestrichelte Linien), Prinzipskizze*

Calculation 1:

a)	+ Natural potential water yield (area A times runoff R)	($m^3/\Delta t$)
	– Sum of balance losses (abstraction Q_A minus return flow Q_R)	($m^3/\Delta t$)
	= Balance discharge, Q_B	**($m^3/\Delta t$)**
b)	+ Natural potential water yield, A R	($m^3/\Delta t$)
	– Sum of water abstraction, Q_A	($m^3/\Delta t$)
	+ Sum of return flow, Q_R	($m^3/\Delta t$)
	± Sum of storage inflow/outflow, Q_S	($m^3/\Delta t$)
	± Water transfer, Q_T	($m^3/\Delta t$)
	= Balance discharge, Q_B	**($m^3/\Delta t$)**
	– Ecologically required minimum discharge	($m^3/\Delta t$)
	= Available water yield	**($m^3/\Delta t$)**
c)	+ Natural potential water yield between the balance profiles I and II, reduced by the catchment of tributaries, $(A - A_U - A_T) \cdot R$	($m^3/\Delta t$)
	± Balance discharge of the upstream profile II, $Q_{IN,U}$	($m^3/\Delta t$)
	± Balance discharge of tributaries, $Q_{IN,T}$	($m^3/\Delta t$)
	– Sum of water abstraction, Q_A	($m^3/\Delta t$)
	+ Sum of return flow, Q_R ($m^3/\Delta t$)	
	± Sum of storage inflow/outflow, Q_S	($m^3/\Delta t$)
	± Water transfer, Q_T	($m^3/\Delta t$)
	– Ecologically required minimum discharge	($m^3/\Delta t$)
	= Balance discharge, Q_B	**($m^3/\Delta t$)**

and groundwater for different consumers can be determined. The simplest type of water resources balances is the summary balance which compares the natural water yield with the sum of all losses and discharges at a balance profile (*Fig. 3*), for example, at the conjunction of two rivers.

For the catchment, the calculation of the discharge at a balance profile can be formulated as given in *Calculation 1a*. The difference in water abstraction and return flow is similar to the water loss, or water consumption. Distinguishing between abstraction and return quantities and the sum of water transfers and storage water, the calculation scheme can be extended as given in *Calculation 1b*. Water deficits, surpluses and distribution issues can be analysed using this sum equation.

Relating the balance discharge, Q_B, to the ecologically required minimum discharge allows the determination of the available water yield (for positive outcomes) or the requirement of such supporting or redistribution measures as water transfer or storage management (for negative outcomes).

1.2.2 Longitudinal sectional water resources balances

Longitudinal sectional water resources balances describe the water resources situation between different balance profiles (*Fig. 3*). The calculation scheme equals the summary balance in its basic shape, but depending on the number of balance profiles along the main water course and tributaries, the single balancing steps must recur accordingly. Additionally, the balance discharges of the upstream balance profiles or of the tributary have to be included (*Both* et al. 1982), as given in *Calculation 1c.*

The longitudinal sectional water resources balance follows the principle that upstream users come first prior to downstream users. Changing the priority of users herein is not possible.

Practically, user demands compete with each other, and user priorities must be managed (based on political decisions) as a function of water yield and of numerous natural, social and economic boundary conditions (compare *Fig. 1*, *Loucks* and *van Beek* 2005). For instance, to supply a crucial power plant with cooling water is doubtless of higher importance than to provide irrigation water for agricultural use. To overcome the weakness of simple water balances, the method of detailed water resources balances was developed during the last decades.

1.2.3 Detailed water resources balances

For the elaboration of detailed water resources balances, numerous simulation models have been developed during the last years, e.g. AQUATOOL (*Andreu* et al. 1996), MIKE-BASIN (Danish Hydraulic Institute 2011), WaterWare (*Fedra* and *Jamieson* 1996), WRAP (*Wurbs* 2005), and WEAP21 (*Sieber* and *Purkey* 2007). Usually, these models were developed for regions with recurring severe water shortages due to low water availability or due to the overexploitation of water resources.

For the simulation of detailed water resources balances in the basins of the Spree and Schwarze Elster rivers, the highly sophisticated modelling system WBalMo (*Kaden* et al. 2008) is used. This modelling tool was first developed in the 1980s (*Schramm* 1995). Originally, it combined detailed longitudinal sectional water balances with the Monte-Carlo method to simulate stochastically synthetic discharge data series from existing observation data for the purpose of storage (*Fig. 4*, left) (*Grünewald* 2008). With the probability experiments, the synthetic data series provide new combinations of value and occurrence frequency. As a result, new conditions that could not be observed during the short observation period were calculated, including, for example, those of low water or flood periods. This method required the adjusting of observed discharges from water use influences. However, this separation was not possible for the discharges of the Spree and Schwarze Elster rivers strongly affected by mining activities. The indirect deterministic discharge simulation provided a solution using the stochastic simulation of causal meteorological processes such as precipitation, temperature and global radiation (*Schramm* 1995). This also incorporates global change scenarios in terms of climate or land use change (*Fig. 4*, right).

Water resources planning and management models can be characterised by

- representation of the river basin by a network of branches representing running waters and nodes (balancing profiles),
- water users (reservoirs, water transfers, withdrawals etc.) connected to these balancing profiles,
- simulation based on volume-balance accounting procedures: the procedures provide an accounting system for tracking the movement of water through a system of reservoirs and river reaches under a priority-based water allocation system,

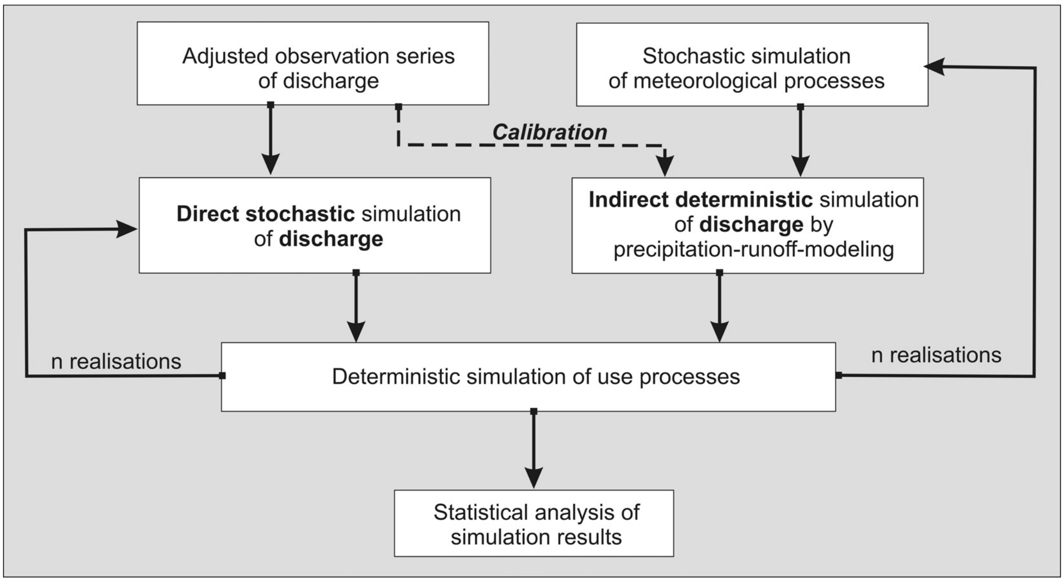

Fig. 4 Method of stochastic planning and management models
Methodik stochastischer Planungs- und Managementmodelle

- generalisation of data characterising the respective river basin: spatial configuration, hydrology, water resource practices, water use requirements etc.

For more detailed explanations as well as the ranking concept of the water users as used in the river basins of Spree and Schwarze Elster rivers, see *Kaden* et al. (2008).

2. Boundary Conditions for Water Resources Management in the Lower Lusatian Mining Area

2.1 Natural conditions

2.1.1 Physical region

The Lower Lusatian mining area covers parts of southern Brandenburg and northern Saxony (*Fig. 5*). The region was formed during several ice ages. Geologically, the area is part of the North German-Polish basin that had undergone continuous sinking processes since the Palaeozoic era. This caused repeated ocean flooding and resulted in large marine depositions, usually covered by several hundred metres of Tertiary and Quaternary material. In the Tertiary layers, vast horizontally bedded lignite coal banks occur at a depth of 40 to 100 m below the surface. In Lower Lusatia, these lignite banks reach thicknesses of more than 10 metres.

2.1.2 Hydrography

In the glacial valleys of Lower Lusatia, running water courses dominate. The high density of rivers in particular in Brandenburg results both from natural processes and the intensive melioration measures beginning in the 17th century and continuing through the 20th century. Of the

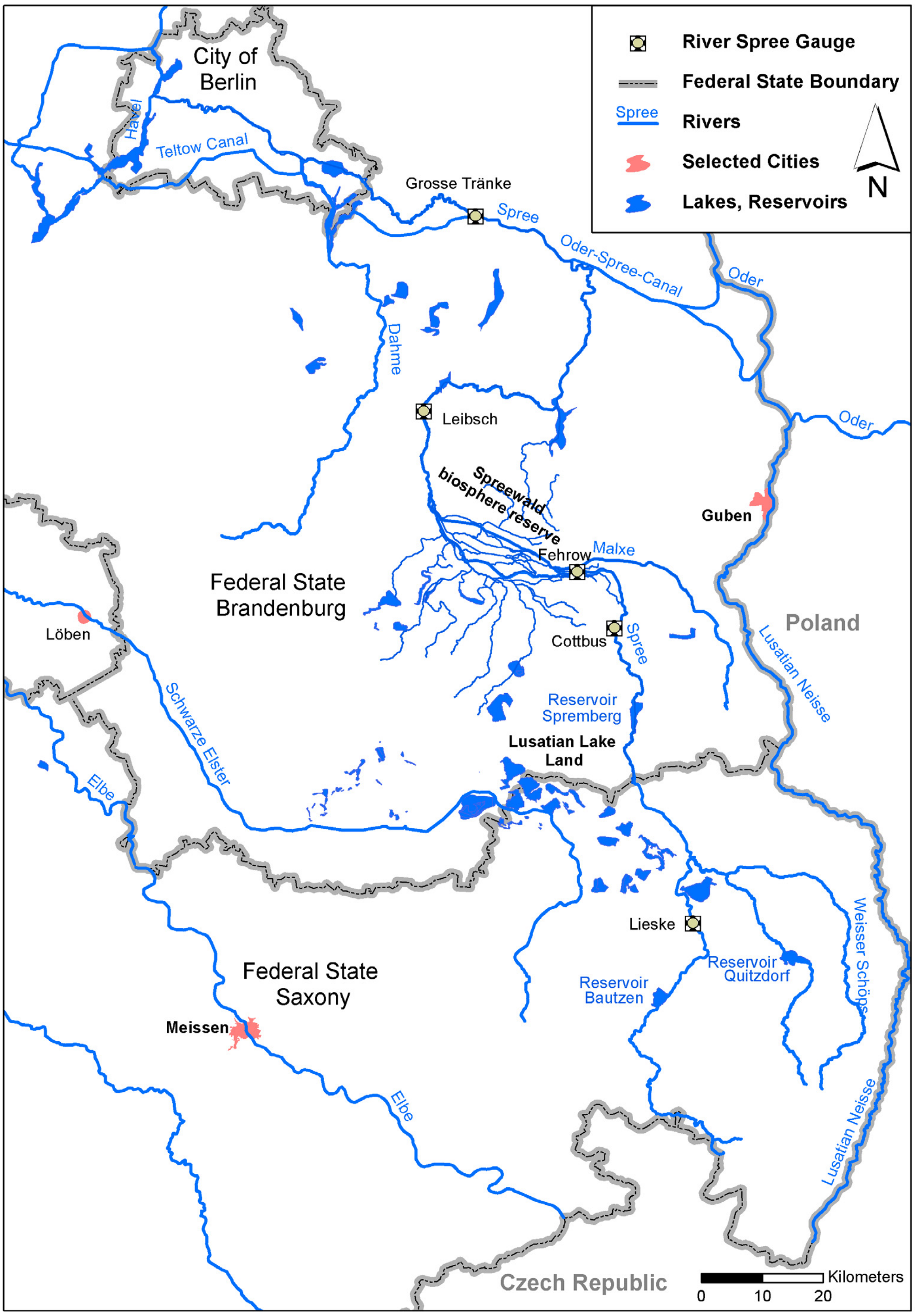

Fig. 5 Location of the study area / *Lage des Untersuchungsgebietes*

32,000 km of running waters in Brandenburg, 80 % are man-made (LUA 2004).

The largest part of Lower Lusatia lies in the Elbe River catchment, and smaller sections belong to the Lusatian Neisse River catchment which is part of the Oder River basin (*Fig. 5*). The main river basins in the region include the Schwarze Elster River and the Spree River. The sources of both are in the Upper Lusatian Uplands and are part of the Elbe River basin (*Simon* et al. 2005).

The Elbe River (*Fig. 5*) catchment, in which both the Spree-Havel and Schwarze Elster are headwaters, has a total area of 148,000 km². After a flow length of 1,094 km, the Elbe discharges into the North Sea. The mean annual discharge at the Neu Darchau gauge is 709 m³/s (observation period 1874-2000, *Simon* et al. 2005). Northwest of Meissen (*Fig. 5*), at the divide of the Upper and Lower Elbe, the mean annual discharge is 330 m³/s.

The Schwarze Elster River (*Fig. 5*) has a catchment of 5,705 km² and a flow length of 179 km and consists of 198.5 flow km at its junction with the Elbe. At the Löben gauge, 21.6 km upstream of the Elbe-Schwarze Elster confluence, the mean annual discharge is 19.6 m³/s (observation period 1974-2000, *Simon* et al. 2005). The natural discharge of the Schwarze Elster is heavily disturbed by human activities in the catchment including large open pit mines, 13 storage dams and large river diversions for mining activities and flood protection (*Simon* et al. 2005).

The Spree River (*Fig. 5*) has a catchment of 9,858 km² with a length of about 400 km. In Berlin-Spandau, the Spree joins the Havel river that also flows into the Elbe. The mean annual discharge of the Spree at the Grosse Tränke gauge (see *Fig. 5*), 78.1km upstream from its confluence with the Havel, is 14.9 m³/s (observation period 1971-2000, *Simon* et al. 2005). This is not the natural mean discharge because, similar to the Schware Elster, the Spree has been heavily affected by human activities including mining water discharge (see *Fig. 2*), river redirections and diversions.

The Oder River (*Fig. 5*) has a catchment of 119,000 km² and a flow length of 855 km, emptying into the Baltic Sea. At the Hohensaaten/Finow gauge, the mean annual discharge is 526 m³/s (observation period 1920-2000, *Simon* et al. 2005).

After a flow length of 255 km through a catchment of 4,400 km², the Lusatian Neisse River enters the Oder River north of Guben (*Fig. 5*). The mean annual discharge is 29.8 m³/s at gauge Guben 2 (*Fritzsche* et al. 2005).

2.1.3 Hydrological water balances at different scales

The hydrological water balance uses the equation of continuity and describes the water cycle quantitatively. The components of the water cycle numerically comprised by the water balance equation include precipitation, evapotranspiration, runoff and changes in storage. As a function of the considered space, its processes and the time segment, the different water balance types vary in their level of detail. For temporally and spatially dissolved questions, the water balance equation for a unit area and the time period *t* is as given in *Equation (1)*.

$$\int_0^t \left\{ P(t) - ET(t) - \frac{\delta}{\delta t}\left[SS(t) + SG(t)\right] \right\} dt = \int_0^t \left[QD(t) + QG(t)\right] dt = \int_0^t Q(t)\,dt$$

Eq. (1): Precipitation *P*, evapotranspiration *ET*, surface water storage *SS*, groundwater storage *SG*, direct runoff *QD*, groundwater runoff *QG* and total runoff *Q*

For Germany, the mean annual water balance was analysed and published in the Hydrological Atlas of Germany (BMU 2003). The description of the climate conditions in this section uses the numbers and definitions in this compendium (BMU 2003), unless otherwise indicated. In relation to the considered temporal scale (mean annual values of the period 1961-1990) and the spatial scale of 1 km², *Equation (1)* is simplified to

$$\overline{P_{corr}} - \overline{ET_a} = \overline{R} \qquad [\mathrm{mm/a}] \quad \textit{Eq. (2)}$$

with the long-term average of corrected precipitation P_{corr}, the long-term average of the actual evapotranspiration ET_a and the long-term average of total runoff *R*. The corrected precipitation considers the adjustment of precipitation measurements rendered too low by wind drift, wetting of the gauge funnel and evaporation losses.

Runoff is generated by the interaction of water balance components including precipitation, evapotranspiration, soil morphology, topology and land use. Runoff does not consider anthropogenic influences.

The long-term total runoff average is equivalent to the potential water yield. Reducing this value by the quickly discharged flood peaks results in a stable water yield, similar to the base flow or so-called groundwater yield. Through water storage and storage management, the stable water yield can be increased by the controlled yield released from reservoirs.

Using *Eq. 2*, the water balance for Germany is formulated as

$$\overline{P_{corr}}(859) = \overline{R}(327) + \overline{ET}_a(532) \quad [\mathrm{mm/a}] \; \textit{Eq. (3)}$$

For the Elbe River catchment, the stable water yield is much smaller. With the corrected annual precipitation of 628 mm and long-term actual evapotranspiration of 445 mm, the mean annual total runoff is only 183 mm (*Simon* et al. 2005). The catchment-related water balance in accordance to *Eq. 2* is

$$\overline{P_{corr}}(628) - \overline{ET}_a(445) = \overline{R}(183) \quad [\mathrm{mm/a}] \; \textit{Eq. (4)}$$

This low potential water yield is again smaller for the Brandenburg water balance with a mean annual runoff of 109 mm/a (LUA 2002).

$$\overline{R}(109) = \overline{P_{corr}}(617) - \overline{ET_a}(508) \quad [\mathrm{mm/a}]. \; \textit{Eq. (5)}$$

Despite the low internal runoff formation of 109 mm/a for Brandenburg-Berlin, 453 mm/a leave the area as runoff. The difference of 344 mm/a is formed mainly upstream in Saxony, indicating that only one-third of the runoff originates from Brandenburg-Berlin itself.

In comparison to the potential water yield expressed as a long-term average of total runoff, the climatic water balance *CWB* considers the difference of corrected precipitation P_{corr} and potential evapotranspiration ET_0, which reflects the evapotranspiration under conditions of unlimited water availability,

$$\overline{CWB} = \overline{P_{corr}} - \overline{ET_0} \qquad [\mathrm{mm/a}]. \; \textit{Eq. (6)}$$

For the Lusatian basin, the mean annual climatic water balance is 4 mm/a with a surplus of 105 mm in the winter half-year and a deficit of 109 mm in the summer half-year. However, from May to October, the deficit may reach values up to -300 mm.

2.2 Lignite mining activities and their consequences for water resources management

More than 10 % of the global lignite coal reserves and over 50 % of European reserves are located in Germany (Wirtschaftsvereinigung Bergbau 1994). Lignite coal plays an important role in Germany's power supply. Excessive and large-scale lignite mining activities in Lower Lusatia during the second half of the 20th century devastated the regional and inter-regional water and mass balances. Entire landscapes disappeared and were remade. The implications for water resources management were particularly significant in terms of groundwater depletion, changed river courses and discharges.

Open-pit mining operations required that the groundwater stayed beneath the deepest working level of the open-cast mine (*Fig. 6*).

Abstracting large volumes of water from interconnected aquifers in the Lusatian region achieves this requirement, and in doing so, it severely affects the water balance of a large area. The abstracted groundwater was discharged into the Schwarze Elster and Spree (see Section 1.1, *Fig. 2*). In 1989, the production of raw coal peaked with 16 open cast mines delivering almost 200 million tons per year. At that time, the Spree received more than 30 m³/s of pumped groundwater, and the Schwarze Elster received approximately 7 m³/s. Consequently, the groundwater depression cone reached its maximum area of 2,100 km² (1991) and the total water volume deficit of 13 billion m³ amounted to 9 billion m³ groundwater and 4 billion m³ volume of the remaining open pits (*Grünewald* 2001b).

By the groundwater discharge into the Spree and Schwarze Elster, the natural discharge of the two rivers was artificially elevated, and the downstream water supply management (for Berlin and the Spreewald biosphere reserve) adapted to the surplus water above the natural discharge regimes. However, due to the cessation of many large open-cast mines after 1990, the quantity of pumped mining water decreased from a total of 38.1 m³/s in 1989 to approximately 14 m³/s in 2002 (see Section 1.1, *Fig. 2*). At present, only five open cast mines still operate in Lower Lusatia.

On a large scale, the groundwater depletion cone and the formation of completely new surface and subsurface catchments and hydrological landscapes was one of the most important issues during and after the mining activities. The most obvious challenge remains the transformation of the remaining open mining pits into lakes following the end of mining-related pumping activities. As a result, completely new water and matter fluxes were formed and are accompanied

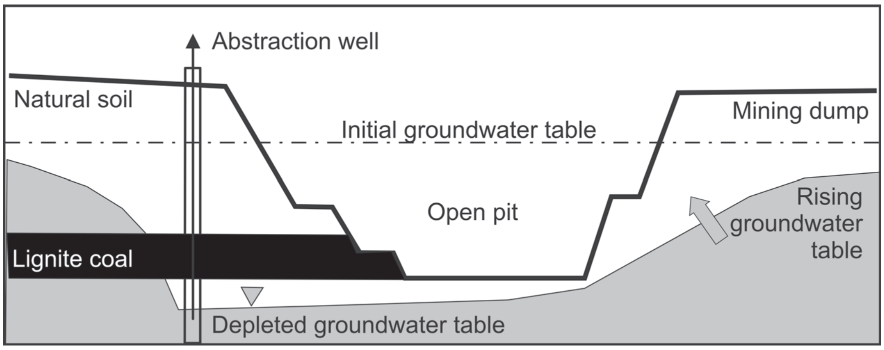

Fig. 6 Groundwater depletion during lignite mining activities
Grundwasserabsenkung während des Braunkohleabbaus

by diverse negative consequences on nature, the landscape, water consumers and water use. As an immediate consequence of the cessation of groundwater depletion, the groundwater flow follows the hydraulic gradient and enters the pits of the mining areas (*Fig. 7*).

Due to the changed redox conditions surrounding the open pits and the elution from dumped mining material by percolating water, the groundwater becomes extremely acidified and mineralised. When fed by groundwater only, the post-mining lakes contain typically highly acidified water with pH values of approximately 2.5 to 3.0, which is not acceptable for the downstream ecosystems.

2.3 Climate change as additional pressure on water resources

Currently, research on potential climate change is more and more considered by water resources management. The grave potential consequences of changes in climate on water balances include higher temperatures resulting in higher rates of evapotranspiration, up to 40 % less runoff (dynamic water yield), and reduced groundwater recharge (stable water yield). This causes reduced water availability, more frequent low flow periods and decreasing water quality, e.g. due to eutrophication.

According to *Gerstengarbe* and *Werner* (2005), an average temperature increase of 2.5°C until 2050 is anticipated in the Berlin-Brandenburg region. For Lower Lusatia, the temperature may even increase by approximately 3°C in the months of October to March (*Gerstengarbe* and *Werner* 2005). The winters may become warmer with higher precipitation, occurring as rain instead of snow (UBA 2006). By contrast, precipitation in the south of Brandenburg, which is representative for Lower Lusatia, will become less by approximately 50 to 90 mm during the growing period from April to September until 2050 (*Lotze-Campen* et al. 2009). The annual climatic water balance *CWB* is expected to become negative by a decrease of up to 200 mm (*Lotze-Campen* et al. 2009), an alarming rate when accounting for the already negative *CWB* in summer months (see Section 2.1.3).

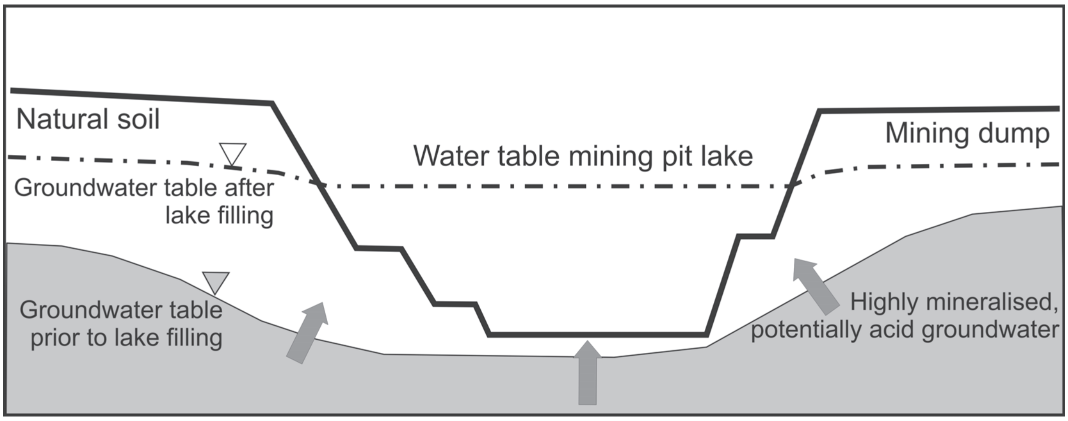

Fig. 7 Open-cast mining pit filled by rising groundwater (*Grünewald* and *Uhlmann* 2004)
Füllung des Tagebaurestlochs durch Grundwasseraufstieg (Grünewald und Uhlmann 2004)

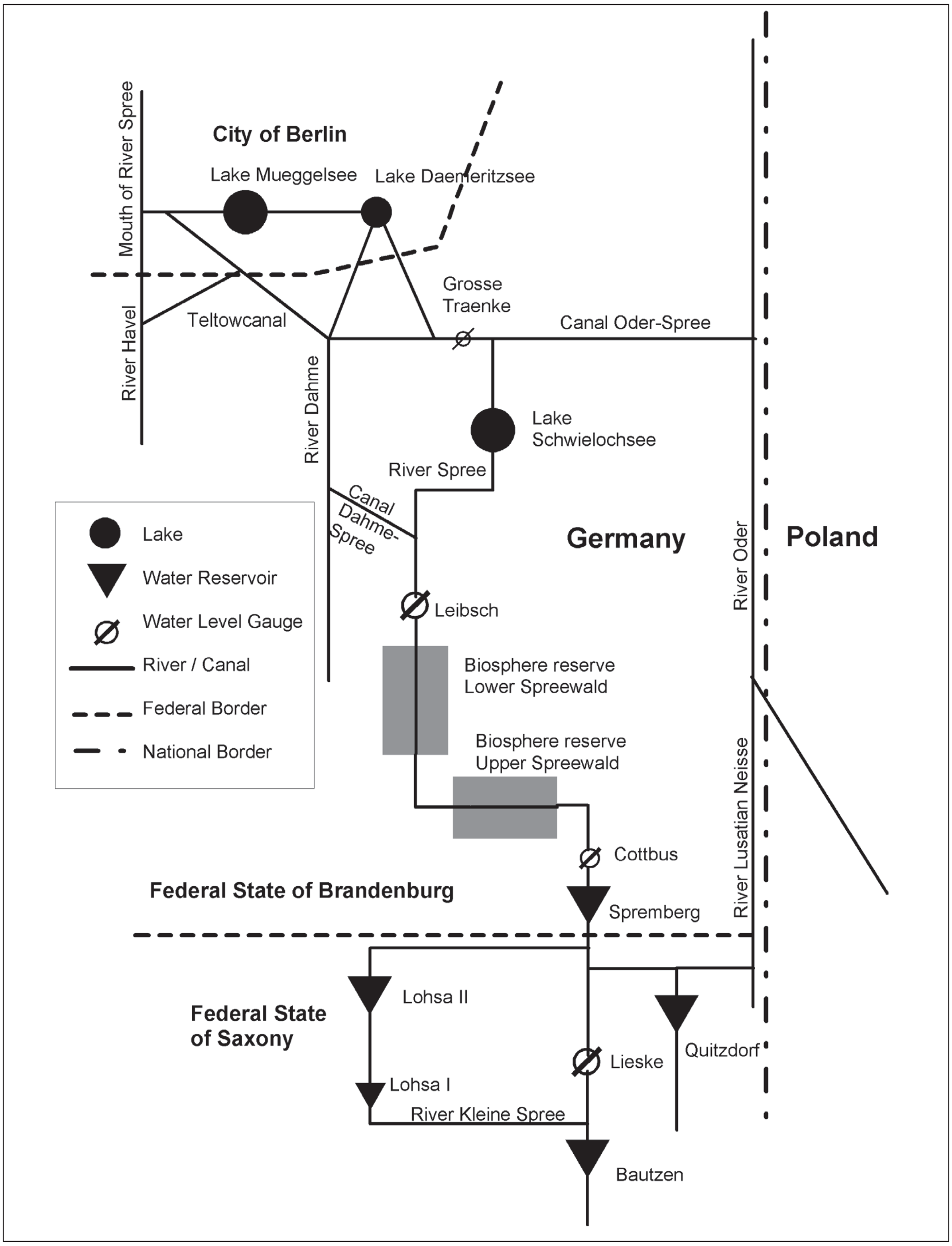

Fig. 8 Simplified water management system of the Spree
Vereinfachte Darstellung des Bewirtschaftungssystems der Spree

3 . Changing Balances in the Lower Lusatian Mining Area

3.1 Summary balances to estimate potential water deficits

Following 1989, the reduced mining water discharge into the Spree led to the awareness of potential future water scarcity with tremendous consequences for Berlin and the Spreewald biosphere reserve. To estimate the potential water deficits and form an action plan, longitudinal sectional water resources balances for distinct river sections and for critical hydrological situations in the Spree River catchment were formulated.

The longitudinal river sections between the Lieske and Leibsch gauges in the south and north Spree, respectively, hold particular importance due to the variety of users and influences, such as groundwater depletion from lignite mining, mining water discharge, abstraction for cooling of power plants, fisheries, storages, the Spreewald biosphere reserve and others. *Figure 8* defines the different potential users, the system objects and processes in an abstraction similar to that suggested by *Loucks* and *van Beek* (2005).

The natural yield of this river section supplemented by the mining water was compared to the sum of use losses. Using the algorithm presented in Section 1.2.1, the water balance was approximated for different development scenarios. In *Table 1*, an example is given for the draught month of July (LUA 1993).

The mining-related groundwater abstraction from static groundwater reserves of approximately 32 m³/s resulted in a noticeably higher discharge in the Spree at the zenith of lignite mining in 1989. The reduction of mining activities during the following 10 years resulted in pumping quantities less than half of the original groundwater abstraction. However, the groundwater discharge of about 15 m³/s was still five times higher than the discharge balance of the upper Spree catchment at the Lieske gauge for the considered month of July (*Tab. 1*).

Tab. 1 Prognostic summary balances for a sub-catchment of the Spree River between the Lieske and Leibsch gauges in July 1989, 2000 and 2010, respectively (LUA, 1993) / *Summenbilanz für ein Teileinzugsgebiet der Spree zwischen den Pegeln Lieske und Leibsch, Juli 1989, 2000, 2010 (LUA, 1993)*

Balance variable [m³/s]	**Balance year**		
	1989	**2000**	**2010**
Discharge balance on the upper Spree catchment up to Lieske gauge	+2.35	+3.10	+3.10
Mining water	+31.80	+17.00	+14.00
Catchment's natural yield	+1.00	+1.35	+1.75
Storage water from Spremberg Reservoir	+0.75	+2.00	+2.00
Total use losses (industry, energy …)	–14.30	–11.90	–11.70
Infiltration losses in mining-affected area	–8.00	–6.00	–4.50
Evapotranspiration losses in the Spreewald biosphere reserve	–5.00	–5.00	–5.00
Balance at Leibsch gauge	**+8.60**	**+0.55**	**–0.35**
Ecologically required minimum discharge	***4.00***	***4.00***	***4.00***

During this period, the natural potential yield rose little due to the slow recovery of the groundwater depletion cone, losses due to water use and the mining related infiltration losses decreasing slowly. Due to the summary balance, the discharge at the Leibsch gauge on the Spree was expected to be below 1 m³/s in 2000 and even negative in 2010 compared to 8.6 m³/s in 1989. The required minimum discharge for landscape and ecological functioning equals 4 m³/s, but because the Spree supplies Berlin with drinking water, the minimum discharge demanded by water authorities at the Grosse Traenke (*Fig. 5*) gauge is 8 m³/s. Consequently, a water resources management concept was developed by Brandenburg, Berlin and Saxony to use several of the open pits as storage reservoirs after being transformed into lakes (AGFB 2000).

The observation data in *Fig. 9* and *Tab. 2* for the period between 1998 and 2006 indicate the challenge of balanced water resources management targets for the Spree. In the last 10 years, the minimum discharge requirements of 4 m³/s and 8 m³/s set by the water authorities in Brandenburg and Berlin, respectively, were not met in the month of July (*Fig. 9*).

At that stage, the artificial increase of low water discharge from 2 m³/s (*Tab. 1*) to 6 m³/s (*Tab. 2*) remains insufficient. Only 1.5 m³/s of the 10 m³/s mining water discharged from the operating mining pits remains, of which power plants used 3.5 m³/s and the groundwater depletion cone absorbed 5.0 m³/s.

The frequent water yield deficits and the potentially worsening require the utilisation of new water resources. Water transfer and storage are adaptation strategies for a more flexible water supply system to respond to demographic or climate changes (*Haakh* 2010).

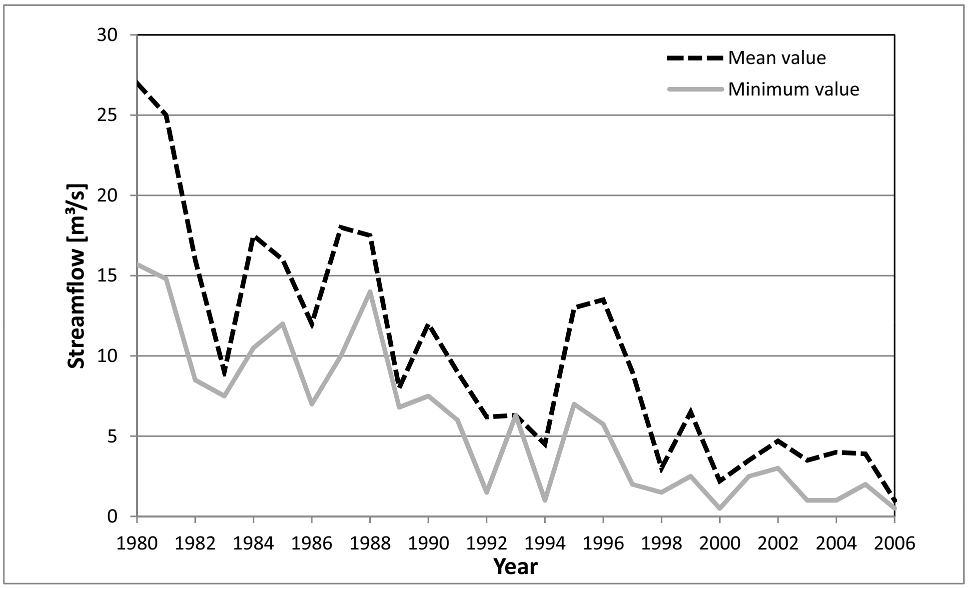

Fig. 9 Spree discharge at Leibsch gauge during the month of July, for the observation period 1980-2006 (LUA 2007) / *Durchfluss der Spree am Pegel Leibsch während des Monats Juli, Beobachtungsreihe 1980-2006 (LUA 2007)*

Tab. 2 Summary balance estimates for the Spree at the Leibsch gauge, July 2006 (according to LUA 2007)
Summenbilanz für die Spree am Pegel Leibsch, Juli 2006 (LUA, 2007)

Balance variable	**[m³/s]**
Discharge formation in the unaffected area (approx. 3,000 km²)	2.0
Mining water	10.0
Controlled increase of low water discharge by reservoirs	6.0
Use losses by large power generation plants	–3.5
Other losses, e.g. by fish farming	–3.5
Infiltration losses in the groundwater depletion cone	–5.0
Evapotranspiration losses in the Spreewald nature reserve	–5.5
Balance discharge at the Leibsch gauge	**ca. 0.5**

Water transfer increases the regional water availability and supports the establishment of appropriate water quality conditions in the post-mining lakes. The transfer of excess surface water from neighbouring catchments enables faster filling of the mining pits compared to groundwater-driven filling (*Fig. 10*). The inflow of acidified groundwater is thus pushed back and reduced, diluting the highly mineralised and acidified lake water and supporting the hydro-chemical stabilisation of the lake.

Without the availability of external flood water, many post-mining lakes undergo heavy acidification. For instance, only 66 % of the flooding water quantities estimated in 1996 existed in the flooding period between 1997 and 2001 (*Grünewald* and *Uhlmann* 2004).

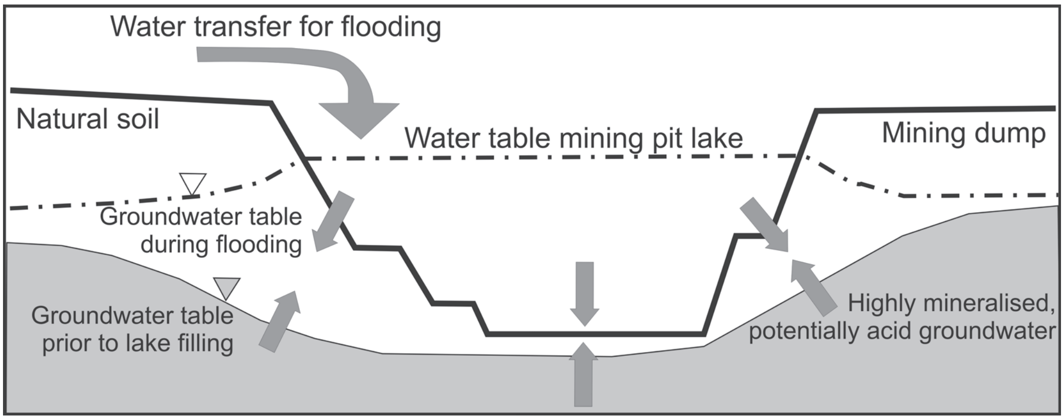

Fig. 10 Concept of groundwater displacement by flooding with surface water (*Grünewald* and *Uhlmann* 2004) / *Prinzip der Grundwasserverdrängung durch Flutung mit Oberflächenwasser (Grünewald und Uhlmann 2004)*

As a consequence, the water quality was adversely affected in several post-mining lakes (*Gröschke* et al. 2002). To prevent the uncontrolled discharge of strongly acidic and highly mineralised water from open mining pits into rivers, adjacent groundwater or the aquatic ecosystem, the utilisation of dynamic water yield to speed filling of the mining pits is a major challenge.

Because summary balances display only approximate effects of storage and corresponding water transfer, the method of detailed water resources balancing was developed and improved during the last decade (*Schramm* 1995, *Grünewald* 2008, *Kaden* et al. 2008).

3.2 Detailed water resources balances to evaluate adaptation strategies to global changes in the (post-)mining landscape of Lower Lusatia

Within the German Research Programme on Global Change in the Hydrological Cycle (see www.glowa-elbe.de), *Koch* et al. (2006) analysed alternative water resources management strategies based on the water resources management model WBalMo®. A detailed description of the model scenarios is given in *Koch* et al. (2006) and *Kaltofen* et al. (2008).

The WBalMo Spree-Schwarze Elster takes the following elements into account (*Grünewald* 2008):

- approximately 170 balance profiles and 400 water users (e.g., drinking water supply, power stations, industrial users, fishery, irrigation and waste water plants),
- 11 reservoir systems with their respective management rules,
- 50 dynamic elements for the formulation of area-specific characteristics such as models for open-pit reservoirs, rules for variable water transfer or the flooding of disused pits, and
- approximately 200 register variables to estimate the effectiveness of an adopted management strategy.

The simulations with WBalMo are based on various development scenarios including socio-economic trends with or without climate change and various management alternatives to adapt to the global changes. These frameworks of development are described in detail in *Messner* et al. (2008).

For the regional development, this study considered the effects of phasing out all mining activities by 2040 as a reference scenario and the inclusion of a climate change scenario with a forecasted warming of 2.1°C by 2050. The simulation covers the time from 2008 to 2052, in 9 simulation periods of 5 years each. Within a 5-year simulation period, the boundary conditions in terms of land use and climate were constant (*Kaltofen* et al. 2008).

As discussed in Section 3.1, the use of former open cast mines as storage reservoirs to support the discharge in the headwaters in the mining-affected areas is inevitable, but it is insufficient to compensate for the declining quantity of drainage water from the Lusatian lignite mines. To counterbalance the effects of potential climate change requires even more water from reservoirs (*Kaltofen* et al. 2008).

The detailed water resources balances realised in WBalMo can assess the effects of storage reservoirs and flooding duration on the discharge quantity and quality at balance profiles for the two chosen development scenarios – stable climate and climate change. The influence of the water transfer to accelerate the flooding of previous open-pit mines proved to be extremely important for quantitative and qualitative issues of water resources management in

Tab. 3 Water transfer scenarios as potential water management adaptation strategies
Wasserüberleitungsszenarien als potentielle Anpassungsstrategie im Wasserresourcenmanagement

Water transfer scenario	**(1) Elbe water**	**(2) Oder water to Brandenburg**	**(3) Oder water to Berlin**
Water transfer from:	Elbe	Oder	Oder
To (river):	Kleine Spree River, Schwarze Elster River	Malxe	Spree
Maximum transfer volume:	3 m³/s	2 m³/s	(I) 3 m³/s, (II) 6 m³/s
Potential start:	2013	2013	(I) 2013 (II) 2033
Distance:	72 km	41 km	Oder-Spree Canal
Limitations to water transfer volume:	Minimum discharge for undisturbed shipping in Elbe River	No seasonal limitations	No seasonal limitations

the region (*Grünewald* and *Uhlmann* 2004). Because the internal water yield of the region is low, neighbouring catchments with higher natural runoff are in the focus of investigation.

To date, a water transfer from the river Neisse (border river between Poland and Germany, see *Fig. 5*) is realised with a maximum quantity of 2 m³/s to fill mining pits in the Upper Lusatian Mining area. The mean quantity transferred in the last years is approximately 1 m³/s. This limited quantity is the result of restrictions agreed on in transboundary negotiations between Germany and Poland.

For the reason of limited availability of transfer water, alternative adaptation strategies such as transferring additional water from the Oder or the Elbe to the Spree were analysed. Recent studies (*Koch* et al. 2009) resulted in three potential water management adaptation strategies shown in *Table 3* and *Figure 11*.

In dry periods that occur statistically every 20 years (*Koch* et al. 2009), the Spreewald biosphere reserve benefits from the Strategies (1) and (2) in *Table 3*. Strategy (3), transferring water from the Oder directly to Berlin, is the most cost-effective but has no positive effect on the biosphere reserve and the Lower Lusatian mining region (*Fig. 11*).

For Strategy (1), the Elbe water transfer (*Fig. 11*), the potential increase for the Spree and Schwarze Elster rivers exceeds the promoted 3 m³/s in dry periods, assuming that the water transfer from the Elbe can be stored in the upstream water reservoirs during periods of high water availability. Then, the stored water can be released to the system during dry periods and thus increase low river water discharges.

All three adaptation strategies result in a higher average discharge at the Grosse Tränke gauge (for locations see *Fig. 5*) compared to the basic scenario. For the strategy ‘Oder River water to BB’, the discharge situation at the Grosse Tränke gauge accrues benefits only in the first years because additional feeding wa-

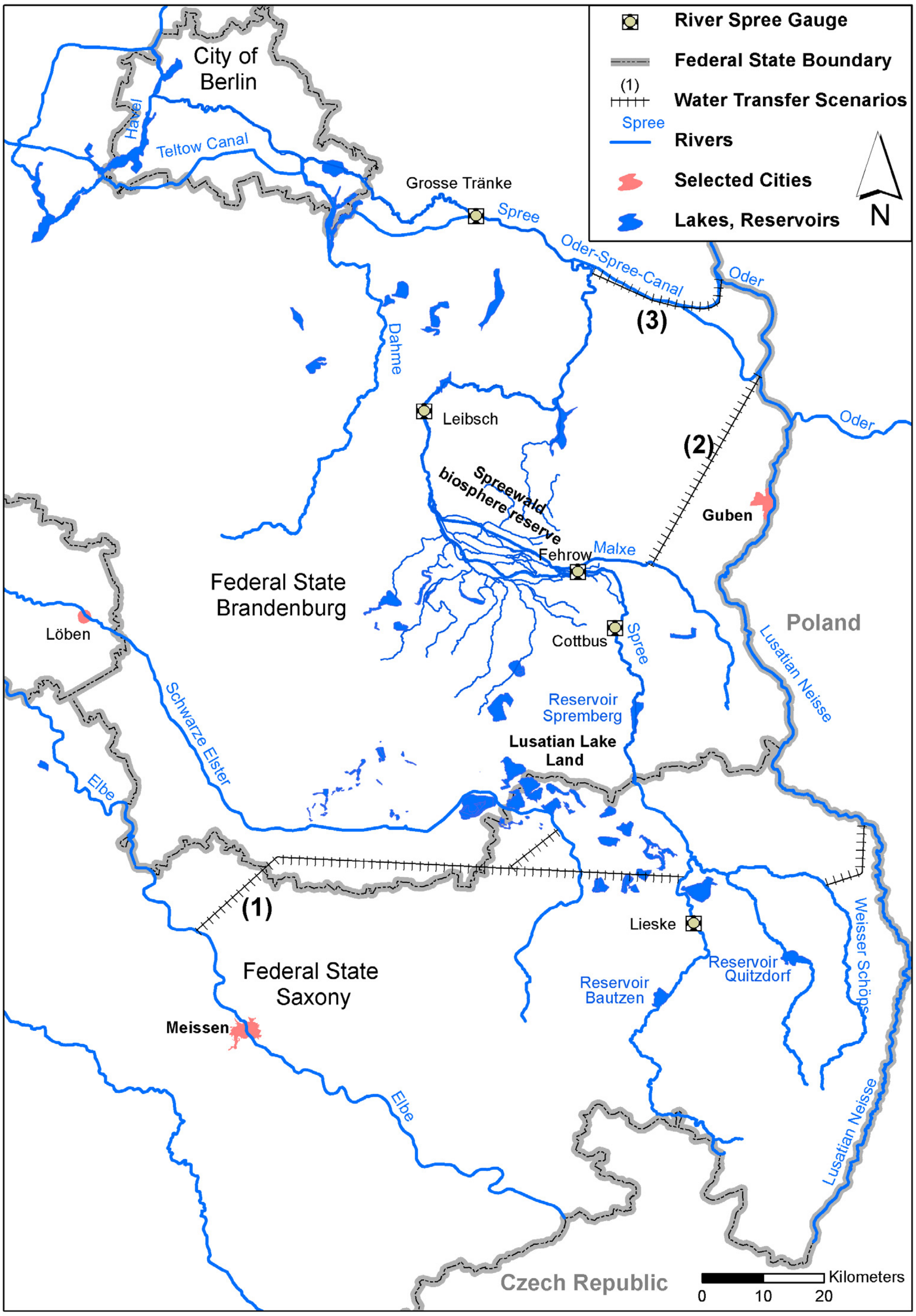

Fig. 11 Potential water transfer alternatives / *Alternativen der Wasserüberleitung*

ter quantities are consumed in the Spreewald biosphere reserve by evapotranspiration, due to the assumed climate warming.

The simulated scenario analysis demonstrates that for the whole catchment of the Spree River, the strategy 'Elbe River water transfer' has the greatest advantage despite the highest costs. Transferring water within the Elbe River catchment reduces water quality issues. Instead, the water quality of the post-mining lakes can be improved with the additional water input. Furthermore, the reservoirs in the upper Spree can be filled during high water yield seasons and equilibrate water availability in periods of water scarcity.

Although the strategy 'Oder River water to Berlin' involves minimum costs, it provides only a limited benefit for the whole Spree River catchment. The strategy 'Oder River water to BB' leads to a significant improvement of the situation in the Spreewald biosphere reserve due to the discharge just upstream of the reservation. Other users or regions in the Spree River catchment do not significantly benefit from this water transfer plan. In this strategy, the water is transferred from a different catchment. Also, the Oder River is a border river and has water quality issues, adding to the drawbacks of this strategy.

4. Conclusions

Although Lower Lusatia, particularly the part belonging to the federal state of Brandenburg, contains a wealth of bodies of water, the internal water yield is low. In the context of the projected climate change scenarios, the climatic water balance will worsen. Without comprehensive management measures, a variety of water users in the region will face severe water supply deficits.

Water resources management in the region takes advantage of the transformation of former open pits into lakes operating as storage reservoirs. Releasing stored water reduces the impact of low flow periods resulting from decreasing mining water discharge. Nevertheless, water resources summary balances indicate the insufficiency of stored water release from reservoirs under present conditions. During low flow conditions, use restrictions are expected. Wetlands including the Spreewald biosphere reserve will have an increased water demand due to the decline in the climatic water balance.

Therefore, water transfer from neighbouring catchments is considered to be most effective to counteract the present and potential future water deficits. By means of water transfer, use restrictions can be reduced, and the water availability for wetlands can increase. Additionally, the water quality of the post-mining lakes and the connected downstream rivers will improve with the water transfer quantities. Hence, the utilisation of the lakes will be facilitated, e.g. as storage reservoirs or for tourism.

Using the river basin management system WBalMo, different water transfer adaptation strategies were investigated. The most beneficial strategy transferred water from the Elbe River. In this case, the water remains within the Elbe River catchment, and no water quality problems are expected.

A continuous adaptation and advancement of the management systems and strategies in accordance with changing global and regional, natural and social boundary conditions is inevitable for future sustainable water resources management in the region.

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Summary: Aspects of Integrated Water Resources Management in River Basins Influenced by Mining Activities in Lower Lusatia

Many decades of mining activities in Lower Lusatia and the present-day changes in the post-mining landscape have long resulted in a massive hydrological transformation. Large-scale lowering of the groundwater table und subsequent recovery, the diversion of rivers and the formation of lakes in the former open-cast pits pose enormous challenges for water resources management. The situation is aggravated by the climatic water balance, which is partly negative, and the scarce overall water yield in the region. Hydrological balances are an indispensable tool for a target-oriented water resources management; they add up water demand and water availability of a catchment or a planning region and compare the two. Depending on the specific water management task, data availability and area considered, we may distinguish between summary balances, longitudinal balances and detailed water resources balances. The successful application and continuous advancement of water resources balances is shown for the example of the Lower Lusatia lignite mining area. In addition, extensive balances and projections with regard to water quality in the emerging open-cast pit lakes have been provided. Flooding of the lakes simply by rising groundwater is, inter alia, associated with a long time period of lake formation and with predominantly highly mineralised acid hydrochemical conditions in the lakes. By way of a transfer of surface water from neighbouring catchments a more rapid replenishing and improved lake water quality can be achieved. Using detailed water resources balances, various alternatives for water transfer from the Elbe and Oder rivers are examined, considering potential climate change, socio-economic trends and regional change. While water transfer from the Oder river into the Spree catchment is less expensive, transfer of Elbe water appears to be more advantageous with regard to the duration of the replenishment process, lake water quality change and the potential to store water for periods of water scarcity, e.g. to feed the ecosystems of the Spreewald biosphere reserve.

Zusammenfassung: Aspekte eines Integrierten Wasserressourcenmanagements in vom Bergbau beeinflussten Einzugsgebieten in der Niederlausitz

Die über viele Jahrzehnte andauernde Bergbautätigkeit sowie die derzeitige Entwicklung der Bergbaufolgelandschaft in der Niederlausitz waren und sind unter anderem auch durch extreme hydrologische Veränderungen gekennzeichnet. Die großflächige Absenkung und der Wiederanstieg des Grundwasserspiegels, die Umleitung von Flüssen und die Ausbildung von Seen in den ehemaligen Bergbaugruben stellen große Herausforderungen an die Wasserbewirtschaftung dar. Sie werden durch die teilweise negativen klimatischen Wasserbilanzen sowie das geringe Wasserdargebot in der Region zusätzlich kompliziert. Wasserwirtschaftliche Bilanzen sind ein unverzichtbares Werkzeug für zielorientiertes Wasserressourcenmanagement. Dabei werden Wasserbedarf und Wasserdargebot eines Einzugs- oder Planungsgebietes einander gegenübergestellt und analysiert. Je nach wasserwirtschaftlicher Fragestellung, Datenverfügbarkeit und betrachtetem Bilanzraum werden Summenbilanzen, Längsschnittbilanzen und detaillierte wasserwirtschaftliche Bilanzen unterschieden. Die erfolgreiche Anwendung und kontinuierliche Weiterentwicklung wasserwirtschaftlicher Bilanzen wurde am Beispiel des Niederlausitzer Braunkohlereviers gezeigt. Daneben werden umfangreiche wassergütewirtschaftliche Bilanzen und Wasserbeschaffenheitsprognosen für die entstehenden Tagebauseen erstellt.Die Flutung der Seen allein durch Grundwasseraufgang ist unter anderem mit langen Flutungsdauern und der Einstellung überwiegend hochmineralisierter, saurer Verhältnisse in den Seen verbunden. Mittels Fremdflutung durch Oberflächenwasser aus benachbarten Flussgebieten ist eine schnellere Füllung und bessere Seewasserbeschaffenheit möglich. Anhand detaillierter wasserwirtschaftlicher Bilanzen wurden verschiedene Konzepte zur Wasserüberleitung aus der Elbe und der Oder unter Berücksichtigung potentiellen Klimawandels, sozioökonomischer Trends und regionaler Entwicklung untersucht. Während die Überleitungen von der Oder in das Spreegebiet kostengünstiger sind, erweist sich die Überleitung von Elbewasser in das Spreegebiet hinsichtlich der Dauer des Füllprozesses, der Beschaffenheitsentwicklung in den Seen und der Bereitstellung von Reservewasser für Wassermangelperioden u.a. für die Ökosysteme des Biosphärenreservates Spreewald als vorteilhafter.

Résumé: Aspects d'une gestion intégrée des ressources en eau dans les bassins de réception sous l'influence de l'exploitation minière dans la région de la Basse-Lusace

L'activité minière qui s'est étendue sur de nombreuses décennies ainsi que l'évolution actuelle du paysage post-minier dans la région de la Basse-Lusace ont été caractérisés et sont marqués entre autres également par les changements extrêmes sur le plan hydrologique. La baisse du niveau des eaux souterraines sur de grandes surfaces ainsi que la remontée de la nappe phréatique, la déviation de fleuves et la formation de lacs sur le site des anciennes mines lancent de grands défis à la gestion des eaux. Des derniers se voient par ailleurs renforcés par le bilan climatique sur les eaux en partie négatif ainsi que par les faibles ressources en eau disponibles dans la région. Les bilans de gestion des eaux constituent un outil indispensable pour pouvoir procéder à une gestion bien ciblée des ressources en eau. Dans ces bilans, les besoins et la disponibilité en eau de la région du bassin de réception ou de la zone de planification en question font l'objet de comparaisons et d'analyses. En fonction des questions sur la gestion des eaux, de la disponibilité des données et de la période de bilan considérée, on fera une distinction entre les bilans totaux, les bilans longitudinaux et les bilans détaillés de gestion des eaux. L'exemple du site d'extraction de lignite de la Basse-Lusace a permis de montrer que les bilans de la gestion des eaux ont été utilisés avec succès et qu'ils ont été continuellement développés. En outre, d'autres bilans importants sur la gestion de la qualité de l'eau ainsi que des pronostiques sur la qualité de l'eau ont été également établis pour les lacs de mines issus des anciennes exploitations à ciel ouvert. La mise en eau des lacs, ne serait-ce que par l'arrivée des eaux souterraines dans le lac, est liée entre autres à une longue période de mise en eau et à l'installation de conditions caractérisées principalement par une haute minéralisation et une acidité dans les lacs. La mise en eau effectuée par intervention externe et par prélèvement d'eau de surface en provenance des régions fluviales avoisinantes permet un remplissage plus rapide et l'obtention de meilleures propriétés pour l'eau du lac. A l'aide de bilans détaillés de gestion de l'eau, plusieurs concepts de transfert d'eau de l'Elbe et de l'Oder ont été examinés du point de vue d'un changement climatique potentiel, des tendances socio-économiques et du développement régional. Alors que les déviations de l'eau de l'Oder vers la région de la Spree sont de moindre coût, la déviation de l'eau de l'Elbe vers la région de la Spree se sont révélées être plus avantageuses en ce qui concerne la durée du remplissage, l'évolution de la qualité de l'eau dans les lacs et de la mise à disposition d'eau de réserve pour les périodes de manque d'eau, entre autres pour les écosystèmes de la réserve de biosphère de la « Forêt de la Spree ».

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