DIE ERDE **142** 2011 (1-2) | Global Change: Challenges for Regional Water Resources | pp. 21-39

• *Climate change – Water and solutes flux – Pleistocene landscape – Water management – Berlin-Brandenburg*

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Anthropogenic Changes in the Landscape Hydrology of the Berlin-Brandenburg Region

Anthropogen bedingte Veränderungen des Landschaftswasserhaushaltes in der Region Berlin-Brandenburg

With 9 Figures

For decades, water resources have been used intensively for drinking water, industry, agriculture and energy production. This paper summarises the main anthropogenic influences on the water cycle in a Pleistocene landscape and associated geochemical reactions. The results allow the identification and description of the main hydraulic and geochemical processes that control water and solute fluxes in different hydrological compartments, in particular recharge and discharge regions. Under progressive climate change, this process-based knowledge should be used to adapt land and water management to minimise negative impacts on hydrological resources and stabilise the regional water balance in the Berlin-Brandenburg Pleistocene landscape. Based on these results, a risk assessment approach for validation of future management strategies under changing climate conditions is presented.

1. Introduction

The expected changes in climate are likely to intensify pressure on water resources in North-Central Europe, strengthened by historical impacts, land-use development and complex hydrological boundary conditions in this young glacial landscape. Meanwhile, the hydrological cycle has become more and more problematic. Decreasing groundwater levels and landscape runoff have been recognised in many regions of Brandenburg for several years (*Suckow* et al. 2002, *Dreger* and *Michels* 2002). According to predictions of changing rainfall intensity, duration and spatio-temporal distribution in connection with increasing temperatures, this situation will worsen in the coming decades (*Gerstengarbe* et al. 2003). It is a challenge to manage ever-scarcer water resources, their uses/services, and their after-use disposal on the basis of process knowledge without creating environmental and economic damage.

Expected climate changes, including decreasing precipitation rates and increasing temperatures,

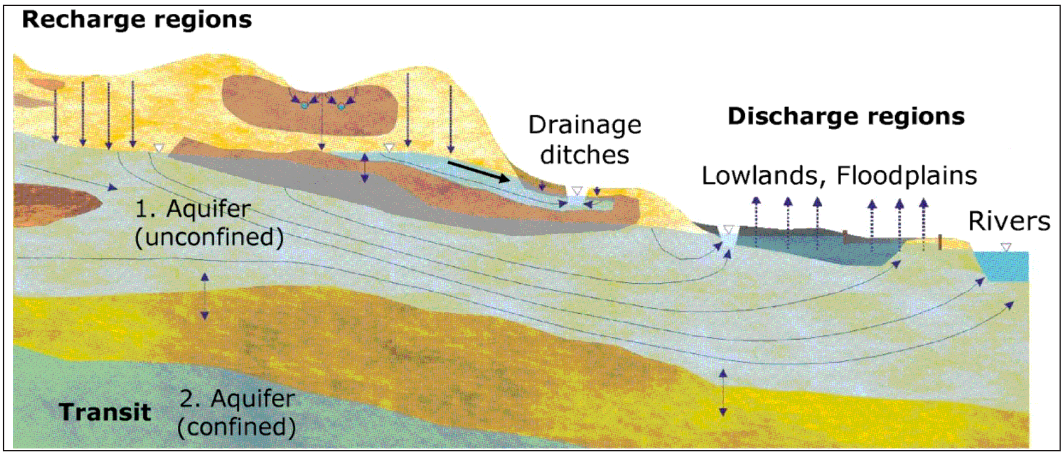


Fig. 1 Hydrogeological structures and the corresponding groundwater flow system in the glacial landscape of Berlin-Brandenburg (after *Steidl* et al. 2002) / *Hydrogeologische Strukturen der jungpleistozänen Landschaft mit regionaler Grund- und Sickerwasserdynamik (nach Steidl et al. 2002)*

will have a strong impact on water cycle properties and function (*Lahmer* et al. 2001). Therefore, the prediction of resource development requires an area-wide assessment of the impacts on water and, in particular, on substance cycles. However, the less effective description of substance migration processes reproduced by current regional model instruments, on the one hand, and the high complexity of physical models requiring a large amount of spatially distributed input data, on the other hand, will remain unsolved problems (*Kunkel* et al. 1999, *Böhlke* et al. 2002, *Huang* et al. 2009). Although the basic processes in the substance cycle have long been understood, especially for nutrients, their behaviour in complex natural systems at different scales is still of topical interest. The development of management strategies is presently lacking in validation methods that include regional hydraulic and geochemical process knowledge. The implementation of relevant subsurface substance transformation and transport processes is, therefore, essential to improve the prediction efficiency of assessment tools. Better parameterisation is needed to enhance the quality of the models used (*Schlesinger* et al. 2006).

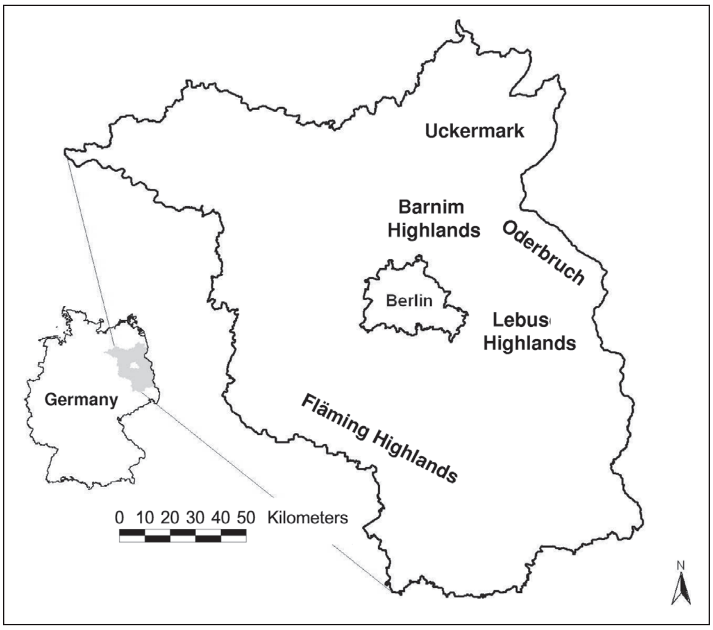
This paper summarises the main anthropogenic influences on the water cycle in the Pleistocene landscape of the Berlin-Brandenburg region. The aim is to develop a better understanding of the present and past complex hydraulic-geochemical interactions and process dynamics in regional water systems under global change, perform risk assessments, and develop management strategies for water resources in Berlin-Brandenburg accounting for expected future climate changes.

2. Study Area

The federal state of Brandenburg, together with the city of Berlin located in the eastern part of Germany, is characterised by its glacially-formed landscape that covers an area of 29,500 km^2. Geologically this area belongs to the Pleistocene unconsolidated rock region of north-central Europe.

The actual climate situation in Brandenburg is characterised by an annual precipitation ranging from more than 600 mm in the northwest (Prignitz) to less than 500 mm in the east (Oderbruch).

Fig. 2 Regions of Brandenburg representing the main aquifer types in the glacial landscape *Ausgewählte Regionen in Brandenburg, die Hauptgrundwasserleiter-Typen aufweisen*



Due to the relatively low amount of precipitation and high actual evapotranspiration rates of about 510 mm per year, the climate of NE Germany shows a semi-arid character (*Lahmer* and *Pfitzner* 2003). The water balance is negative during the summer. Therefore, groundwater recharge is limited to the winter period with a mean of 100 mm per year *(Lahmer* and *Pfützner* 2003, *Gerstengarbe* et al. 2003).

Groundwater flow and groundwater discharge into rivers and channels are the dominating hydrological components of the regional water cycle. Surface water runoff plays only a minor role, accounting for less than 5 % of total runoff. Therefore, the discharge of groundwater from Quaternary deposits is one of the main components needed to identify and quantify the water and solute flux throughout the whole region (*Fig. 1*). The geological structure of the landscape is very complex, with a high variance in hydraulic and hydrochemical parameter distributions. The different groundwater systems of Brandenburg relate to glacial structures such as glacial valleys, till uplands and end moraines. The different regions of Brandenburg representing the main aquifer types in the glacial landscape are shown in *Figure 2*. The aquifers are characterised by specific geochemical and hydraulic conditions:

1. unconfined oxic aquifers in recharge regions, dominated by till plateaus and end moraines (e.g., Fläming, Barnim/Lebus);
2. confined/unconfined aquifers in discharge regions dominated by glacial valleys and floodplains (e.g., Oderbruch and Berlin);
3. anaerobic, confined aquifers in complex moraine and till-dominated transitional regions (e.g., Uckermark).

Water resources in Pleistocene landscapes are quantitatively and qualitatively influenced by

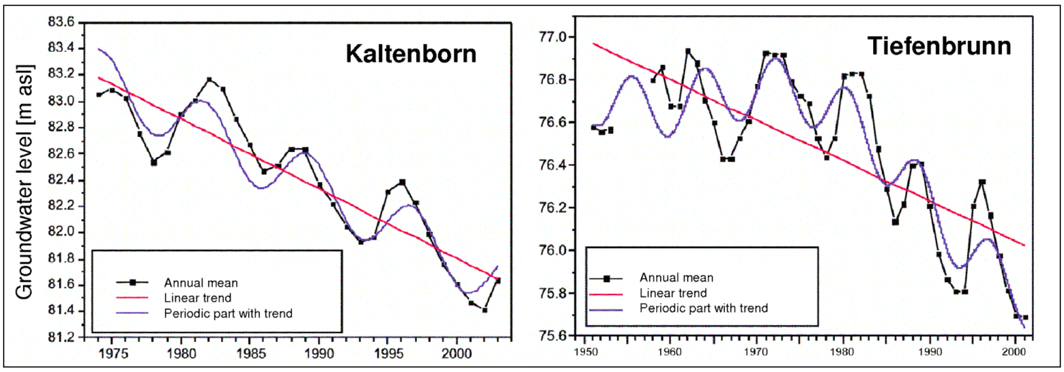


Fig. 3 Characteristic change of groundwater levels in two locations of the recharge region "Fläming uplands" (*MLUR* 2004) / *Charakteristische Entwicklung der Grundwasserstände in Neubildungsgebieten am Beispiel zweier Messstellen des „Hohen Fläming" (MLUR 2004)*

two hydrological compartments: recharge areas and discharge areas (*Merz* et al. 2009). To react to expected impacts of climate change on the regional water cycle, it is necessary to develop specific management strategies adapted for these regions, for they influence water and solute flux over time and space. Recharge regions are strongly influenced by decreasing water availability and falling groundwater levels. The water and substance budgets of floodplains and lowlands respond very sensitively to management measures due to the direct contact of groundwater and surface waters.

2.1 Actual situation of the groundwater status

Although the region is characterised by extensive groundwater resources, discharge rates are higher than recharge rates (*Wechsung* et al. 2000). For decades, decreasing groundwater levels were observed in the recharge regions of Brandenburg. The highest drawdown rates occurred in shallow uncovered aquifers. For example, in the southern parts of the Uckermark region (Schorfheide-Chorin), decreasing groundwater tables reached values between 0.7 and 2.3 m over the past two decades. This corresponds to drawdown rates between 3.3 cm per year and 11.5 cm per year (*Dreger* and *Michels* 2002). This process is still continuing. The Fläming, an important recharge region located in southern Brandenburg, also shows decreasing groundwater tables with constant rates of between 2.0 and 5.0 cm per year (MLUR 2004). This trend has been stable over the last 30 to 40 years (*Fig. 3*).

This critical development is due to a combination of different causes, such as decreasing precipitation, lengthy summer droughts, higher temperatures and, therefore, increasing evapotranspiration, an epitaxial growth of pine trees and intensive drainage. Many areas that were reforested with pine trees after World War II are now at an age when they dramatically reduce the amount of seepage (*Müller* et al. *2002*, *Fürstenau* et al. 2007). *Schindler* et al. (2008) verified a consumption of seepage down to a depth of 5 m by the pine trees which reduces the groundwater recharge nearly to zero.

In addition to such non-adapted vegetation, temperature rise plays an important role in reducing groundwater levels. Between 1906 and 2005, the global surface temperature rose by 0.74 ± 0.18°C

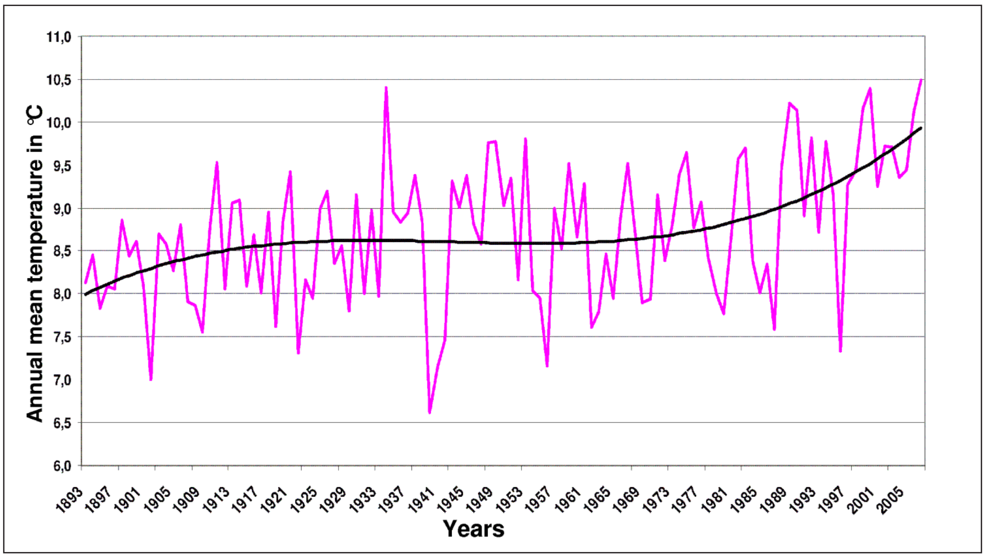


Fig. 4 Temperature change at Potsdam climate station between 1893 and 2008, with a polynomial trend line (source: DWD Germany) / *Langjähriger Temperaturverlauf an der Station Potsdam mit polynomischer Trendlinie (Quelle: DWD)*

(IPCC 2007). Temperature has been projected by the IPCC (2007) to rise by between 1.1 and 6.4°C by the year 2100. At higher air temperatures, evaporation rates and the air's capacity to hold moisture increase. In the Berlin-Brandenburg region, an increase of about 1.0°C in the past 100 years was measured (*Fig. 4*). According to calculations by *Reimer* et al. (2008), the trend will be stable for several decades.

The pressure of climate change on discharge areas is less dramatic and can even have an inverse effect. Characteristic lowlands and floodplains operate as regions with a high water and substance accumulation potential in the landscape. Recharge water from the surrounding catchment basin gathers in these regions. Their water balance is the fundamental relationship among inputs, outputs and storage that dictates the water and substance flux in the floodplains (*Richardson* et al. 2001). However, the inputs and outputs, and the entire water budget, are artificially controlled by water management measures in the lowlands (*Quast* et al. 2000). Therefore, at present, the direct influence of increasing temperature and evapotranspiration is less negative in discharge areas than in recharge areas.

3. Anthropogenic Influences on the Water Cycle of Berlin-Brandenburg

3.1 Influence of water management in brown coal mining areas

Exceptions to this climate-driven development are the rising groundwater levels in parts of southern Brandenburg. For decades, this region was intensively influenced by water management measures in connection with lignite mining in open pits. After German unification, mining activity was reduced. At the present time, there are 45 open pits with a groundwater withdrawal of 1.9 x 10^6 m^3 per year. The cone of the resulting groundwater depression reaches a depth of more than 40 m and covers an area of 2200 km^2 (*Grünewald* 2001). For several years, the majority of the open pits has been filled by groundwater with a total capacity of 4.2 x 10^6 m^3. This positive, regional, trend of rising groundwater levels is, however, combined with decreasing amounts of surface water runoff which influence the water budget of the Spree and Havel rivers.

In the past, the low discharge and seepage losses of the river system were more than compensated by the amount of groundwater pumped in the course of mining. At present, the problem of water availability is reinforced by a rapid decrease of released groundwater from 32 to 12 m^3 per second, due to the abrupt closure of a great number of mines (*Koch* et al. 2005). During drought periods, these rivers show strong water deficits in their upper reaches, and flow almost stagnates at the lower reaches. Analyses of IPCC scenarios adapted by *Kaltofen* et al. (2004) showed that by 2050 a decrease of runoff can be expected in the Spree and Schwarze Elster catchments. In springtime, particularly low runoff and high evapotranspiration in the Spreewald region aggravate this problem. To ensure the ecologically-required minimum discharge, 4 to 7 m^3 per second must be guaranteed (*Grünewald* 2001). The calculated discharges for the coming years are clearly below these values (*Kaltofen* et al. 2004). These results indicate a state of emergency for water management of the Spree River catchment and for water users along the water course in the city of Berlin.

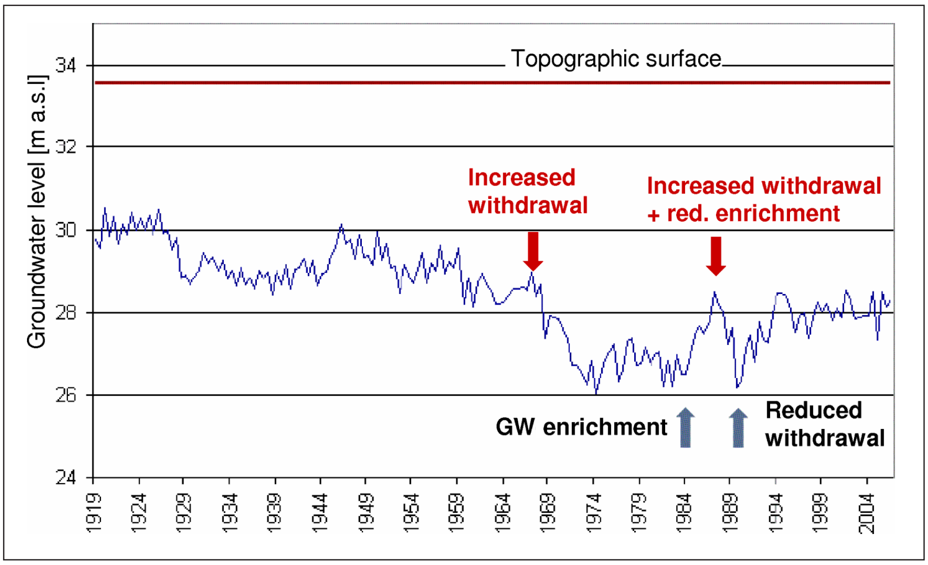
This problem will be exacerbated by sulfate contamination of surface water by the flooding of open lignite pits. A considerable accumulation of acid associated with oxidised sulfides in sediments is regarded as a severe problem in the development of the lake water and the water in the Spree River catchment (*Trettin* et al. 2007). The expected sulfate concentrations in the Spree River will reach 250 to 600 mg per litre in the next decade.

3.2 Withdrawal of groundwater to meet drinking water demand

In lowlands, water management measures, e.g., the withdrawal of groundwater for drinking water, directly influence the groundwater level. This correlation has been observed clearly in the Berlin region during the last decades. Site-specific problems such as urban land use, population growth and unsustainable abstraction practices have been posing greater threats to groundwater resources than climate change. Since the beginning of the last century, groundwater levels have been linked to the social, political and economic situation in this region. The urban development of Berlin, the dramatic political and economic changes before and after World War II, the division of Germany and its unification are clearly mirrored in the trend of groundwater levels in the glacial valley aquifers of Berlin.

Quantitative management aspects, such as varying drinking water demands and artificial enrichment of groundwater, show manifest responses in the change of groundwater levels as shown in *Figure 5*. In some parts of the Berlin aquifer, even rising groundwater levels were observed, with values of more than 1 m within the 1989-2004 period. Monitoring results indicate a strong correlation between the amount of groundwater taken for water supplies and the change of the groundwater level. During the period mentioned, groundwater withdrawal decreased from 378 x 10^6 m^3 per year in 1989 to 218 x 10^6 m^3 per year in 2006 (Source: Berlin Senate Department of Urban Development). Artificial groundwater recharge by surface water, near drinking water facilities, adapted groundwater management during construction projects and taxes on groundwater withdrawal also contributed to rising groundwater levels (*Limberg* 2007).

Increasing evapotranspiration and decreasing precipitation will reduce groundwater recharge from the surrounding areas, with essential consequences for the hydraulic and geochemical



Fig, 5 Change of groundwater levels in Berlin in the last century and applied water management measures (after *Limberg* 2007, modified) / *Entwicklung der Grundwasserstände in Berlin in Verbindung mit Wasserhaltungsmaßnahmen (nach Limberg 2007, verändert)*

processes in the urban aquifer systems. Although the basic substance dynamics is well known, complex process interactions in urban water systems, e.g. during bank filtration, under changing boundary conditions and their influence on migration behaviour, are poorly understood (*Massmann* et al. 2007). In the case of decreasing recharge rates and dramatic decrease of groundwater levels, so far unexpected process interactions occur. The decreasing hydrostatic pressure favours a rise of saline tertiary groundwater with the danger for drinking water contamination in the medium term (*Tesmer* et al. 2007). Furthermore, oxygen can diffuse into anaerobic aquifer systems with negative impact on their natural reduction potential. An increasing release of sulfate and trace elements into the groundwater can be expected. In addition, ammonium contamination by industrial waste water can worsen this problem. Dissolution of oxygen gas and nitrification of ammonium initiate secondary geochemical processes such as sulfate release, acidification and hardening (*Horner* et al. 2009).

3.3 Drainage

Pleistocene landscapes are widely used for agricultural purposes. However, because of their glacial origins, the original landscapes were rich in small surface waters such as ponds, potholes and small lakes with waterlogged areas spread over till plateaus. The so-called Hummocky postglacial landscapes with internal catchment systems are widely distributed in many countries of the northern hemisphere (*Hayashi* and *van der Kamp* 2000). For centuries, intensive water management measures have influenced hydrological processes in these internal catchments. It was normal practice to drain nearly all regions to cultivate the landscape and enable an effective water discharge. Today, more than 80 % of the entire water network in Brandenburg is of artifi-

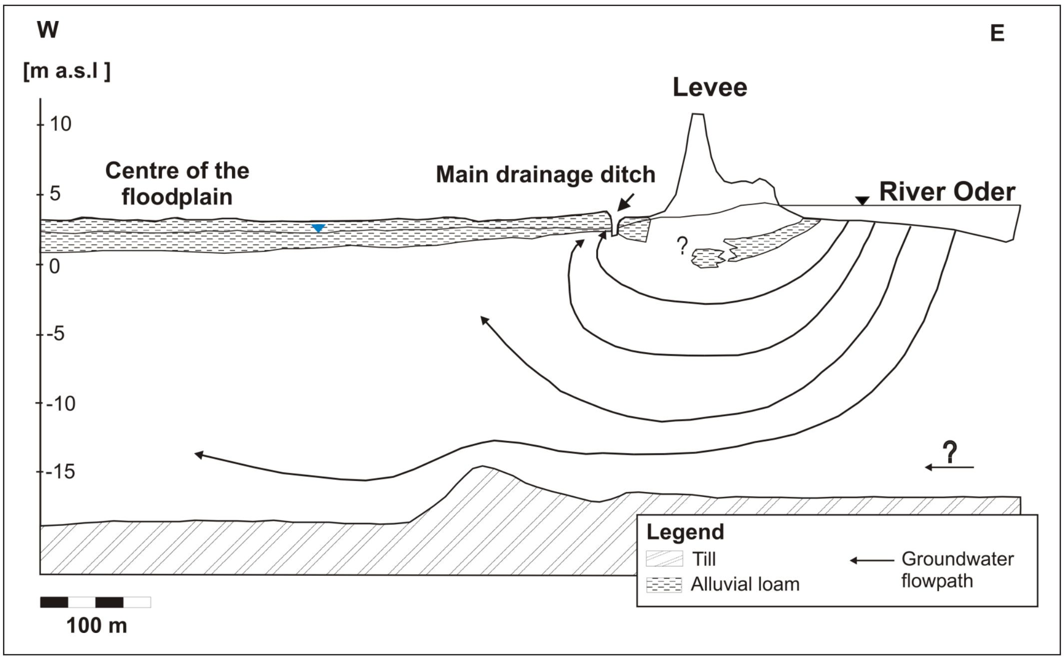


Fig. 6 Cross-section through the aquifer in the northern Oderbruch with groundwater flowpath (after *Massmann* et al. 2004, modified) / *Profilschema zur hydraulischen Situation im nördlichen Oderbruch (nach Massmann et al. 2004, verändert)*

cial origin (MLUR 2003). In the recharge areas where till dominates, drainages are used to prevent water logging. But in areas of intensive drainage, groundwater recharge is reduced, leading to higher surface discharge and solute output.

The handling of local drainage of waterlogged sites is currently a problem in Germany (*Lübbe* 2008). Tile drainage systems are a precondition for agricultural land use, but high nutrient fluxes directly from the topsoils have been observed. Nitrate and phosphate delivered by drainage have a strong eutrophying impact on downstream water bodies in all parts of the country (*Kahle* et al. 2005). The drainage water has the character of fast interflow and shows minor retention potential. Because of the mostly unknown spatial distribution of tile drain systems and the lack of concentration measurements, it is impossible to balance this substance flow. Local measurements confirm high nitrate concentrations, between 1.6 and 4.9 mmol per litre on average. This nitrate contamination is the result of agricultural land use in the last decades (e.g. *Kersebaum* et al. 2005, *Nieder* et al. 2007). Under aerobic environmental conditions, substance losses through tile drainage are critical. One way to handle this problem is to install local purification ponds that can be used to accumulate biomass and induce transformation processes under reducing biogeochemical conditions (*Steidl* et al. 2008).

It will be a big challenge to handle the vast drainage systems in the future under the pressure of climate change. However, a good solution is not a question of truncating all drainages or filling in ditches and channels, although a reduction of discharge into surface waters is essential. The aim must be management of drainage systems for future agricultural land use without excessive losses of water and solutes. As discussed by *Mitsch* et al. 2001 and *Youssef* et al. 2006, drainage volumes and nitrogen losses through drains can be reduced substantially by a practice called controlled drainage.

3.4 Influence of water management in floodplains

In the discharge areas where wetlands dominated originally, drained floodplains now predominate, characterised by shallow groundwater surfaces, upward flow gradients and even artesian conditions. Due to their agricultural usage, they are influenced by massive hydraulic and water management measures. The current hydraulic situation of the largest river polder in Germany, the Oderbruch region, is a typical example (*Massmann* et al. 2004). Levee construction, poldering measures and drainage with ditches and pumping stations have enabled intensive agricultural land use over the last 250 years. These measures gave the Oderbruch its current shape, with the Oder river bed located at the eastern margin influencing the present hydraulic situation, and changed the water and substance balance of the former alluvial plains and swamps intensively. Still, the danger of exceptional surge events threatens the dykes and ultimately the entire region, as seen in 1997 and May 2010.

The hydrological situation is characterised by permanent bank filtration of river water into the aquifer and intensive groundwater and substance discharge into the drainage system (*Fig. 6*). Other important examples of such regional developments in northeastern Europe are Warthebruch (Poland), Memel floodplains (Lithuania) and Wistula delta (Poland) with a total area of 1.5 x 10^6 km^2.

With respect to nutrient leaching from diffuse sources, floodplains operate as regions with high substance accumulation potential. The redox system in reducing aquifers of floodplains is mainly buffered by the Fe^{2+}/Fe^{3+}couple. The degradation of nitrate is very effective in these types of reducing aquifers. Owing to anaerobic conditions in the aquifer, groundwater is presently not affected by nitrate contamination. Relevant nitrate concentrations could be determined neither in the deeper aquifer nor in the drainage channels. Even a higher deposition of nitrate can be buffered by denitrification processes in the shallow aquifer or in the covering soils (*Kofod* et al. 1997).

Nevertheless, there is a danger: open ditches and channels are in direct contact with groundwater and show intensive exchange rates of water and contaminants. Incorrect water management measures, e.g. massive lowering of groundwater tables, disturb the natural sink function of the floodplain by creating a change from confined to unconfined aquifer conditions. Increased SO_4 and NH_4 concentrations indicate latent nitrate leaching from the soils and the alluvial loams. Under these hydraulic conditions, oxidation takes place in the unsaturated zone (*Fig. 7*). Oxygen and nitrate react with the anaerobic pore water and organic soil compounds, destroying the reducing capacity of the sediments (*Quast* et al. 2000, *Massmann* et al. 2004). The vertical distribution of NO_3 and SO_4 shows a characteristic pattern over the soil profile attributed to the redox zones. In oxidised parts of the sediment profile, there is a high concentration of nitrate. In the deeper zones of the profile and in the transition zone between the saturated and unsaturated zones, sulfate concentrations dominate, indicating progressive oxidation of further reduced areas.

Furthermore, the glacial aquifer sediment contains geogenic trace metals from weathered Scandinavian base material. Redox-sensitive trace metals such as Fe, Mn, As, Cu, Cd and Zn are mobilised from aquifer sediments under anaerobic conditions and discharged into the drainage system, a typical process leading to trace metal

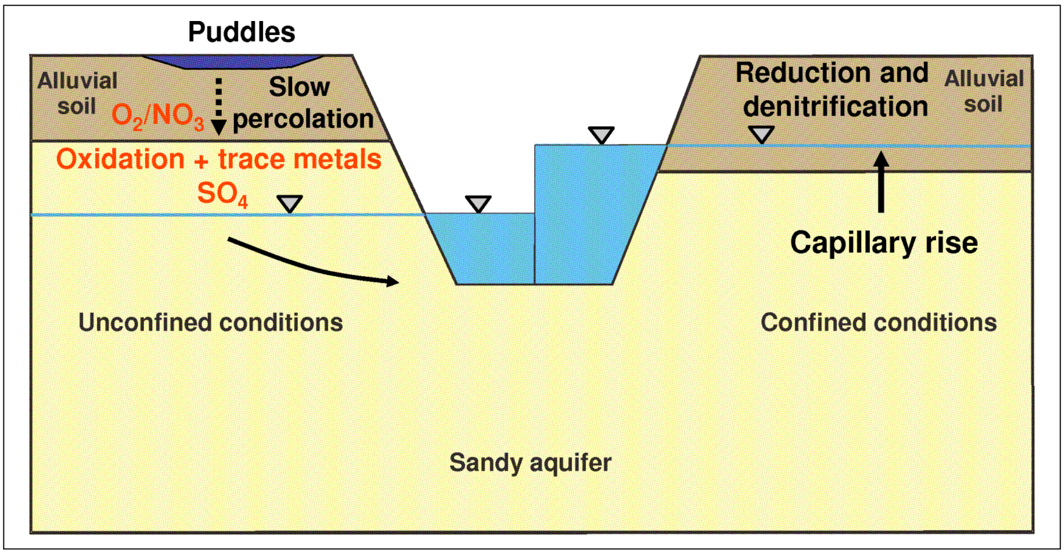


Fig. 7 Hydraulic and geochemical interactions during lowering of the groundwater table in floodplains (after *Quast* et al. 2000, modified) / *Hydraulisch-geochemische Prozesse im Auelehm während intensiver Grundwasserabsenkung in Niederungsgebieten (nach Quast et al. 2000, verändert)*

contamination of drinking water in different parts of the world (*Brown* et al. 2000, *Groffman* and *Crossey* 1999 and *McArthur* et al. 2001). In the Oderbruch, As, Cu, Zn and Cd do not pose an environmental problem. But Fe and Mn were found in drinking water at concentrations well above the threshold. *Merz* et al. (2009a) observed that under specific hydraulic conditions, trace elements can effectively accumulate in channel sediments during the discharge process. The fixation is controlled by the precipitation of hydroxides and oxides, by adsorption to Fe/Mn-hydroxide coatings or by carbonate precipitations in redox transition zones that potentially reacted as effective geochemical barriers. Therefore, water management practices should not destroy the redox transition zones but strengthen and adjust them deep in the sediment below the channel floor. The interaction of groundwater and surface water is a basic component in assessing and controlling the flow and solute transport processes in Pleistocene discharge regions (*Merz* et al. 2005).

4. Risk Assessment Approach

Groundwater quality is mainly influenced by intensive reactions and processes controlled by local geological/stratigraphic conditions (*Hannappel* and *Voigt* 1997). The main geochemical processes in the hydrogeological structures are shown in *Figure 8*. Groundwater recharge areas of north-central Europe are dominated by uncovered aquifers. Their groundwater is characterised by high oxygen contents with low DOC concentrations (< 3 mg per litre). Typically, the oxygen content nearly reaches saturation level. A redox potential of > 250 mV and trace elements concentrations of Fe and Mn below the detection limits are distinct indicators of stable aerobic conditions. Therefore, there are no available electron donors such as organic material or minerals (e.g. pyrite) that can be used for a potential denitrification process (e.g. *Böttcher* et al. 1990, *Postma* et al. 1991). In uncovered aquifers, pyrite is not stable owing to the oxidising conditions in the presence of free oxygen.

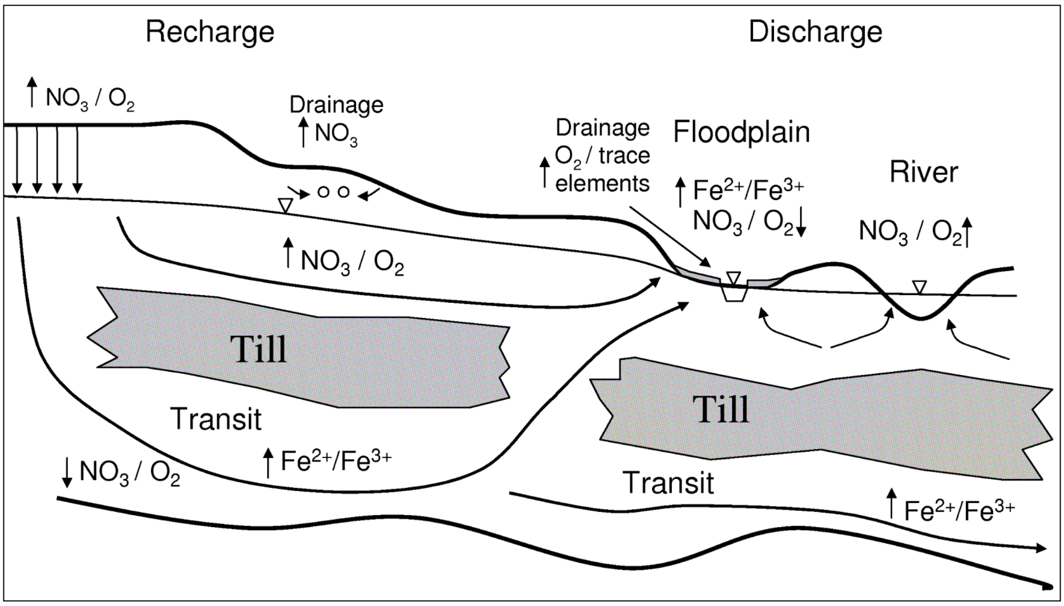


Fig. 8 Main geochemical and hydraulic processes in the hydrogeological structures of the glacial landscape in Berlin-Brandenburg / *Charakteristische geochemische und hydraulische Prozesse in den hydrogeologischen Einheiten der jungglazialen Landschaft Berlin-Brandenburgs*

In contrast, discharge areas are characterised by stable anaerobe conditions with O_2 concentration < 0.1 mg and relatively high DOC concentrations. Redox potential varied between -10 and 70 mV indicating a progressive Fe reduction. The redox systems are very constant and mainly buffered by the Fe^{2+} /Fe^{3+} couple. Therefore, floodplains operate as regions in the landscape with high substance accumulation potential. The reducing capacity of the aquifer sediments favours intensive denitrification processes and sulfidic trace metal fixation.

Adaptation of management strategies should combine knowledge of geochemical processes with knowledge of the regional water cycle. In recharge areas, water management can stabilise or even improve the water balance in the landscape. Due to climate change, water availability will be clearly limited in the future. Artificial enrichment of groundwater in areas of scant natural recharge and surface water storage (i.e. ponds and lakes during periods of water surplus) should certainly play an important role in the future. Artificial recharge is often used to improve a short cycle drinking water supply, for example, to control the local groundwater levels in Berlin as shown in *Figure 5*. But it is an inappropriate strategy for stabilising the regional water balance. In contrast, water infiltration from ponds and lakes in recharge areas far away from big streams can be a feasible method of recharging underlying regional aquifers as discussed by *Izbicki* et al. (2008). However, it is still a problem to buffer the surplus of surface water over a longer period because high evaporation rates in the semi-arid climate of NE Germany will reduce potential water stocks rapidly. In addition, artificial recharge of treated waste water can be used for the stabilisation of the regional water balance and the completion of agricultural production by irrigation.

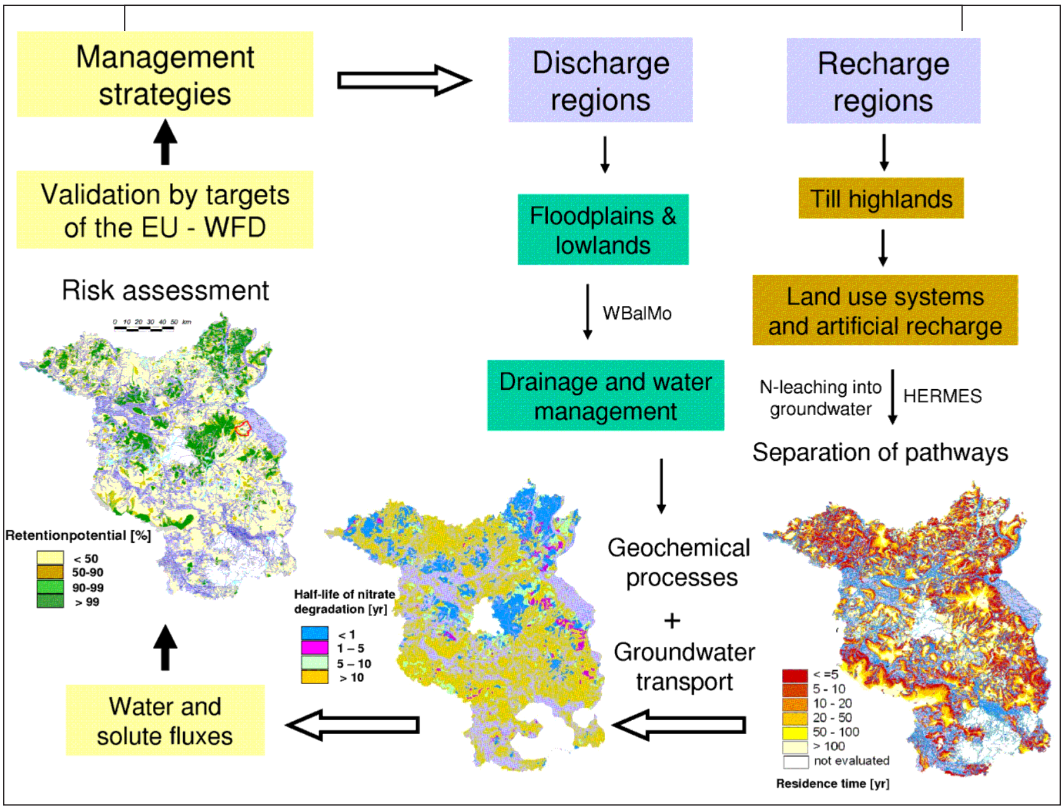


Fig. 9 Modelling approach for the evaluation of management strategies under the pressure of climate change / *Modellansatz für eine Evaluierung potenzieller Managementstrategien zur Minimierung klimabedingter Einflüsse auf den Wasser- und Stoffhaushalt*

Any management approach should consider the low protection potential against diffuse inputs by agricultural land use. An effective protection of the groundwater by regionally developed layers of till cannot be expected in these regions, and no geochemical environment for effective redox degradation processes can be assumed. There are still many open questions regarding quality maintenance in recharge regions.

Furthermore, adapted vegetation changes in different land use systems are indicated. It is well established that changes in land use and vegetation cover can significantly affect the catchment water balance (e.g. *Bari* et al. 1996, *Wegehenkel* 2002). Regional impact assessment especially emphasises the high sensitivity of natural forests in the region due to groundwater quality and quantity in recharge regions. The majority of forests in the state of Brandenburg have been managed intensively in the past. At present, large areas of forests are dominated by all-pine stands. To preserve productivity and increase groundwater recharge, current forest management practice aims at increasing the share of mixed forests (*Wattenbach* et al. 2007, *Müller* 2009).

In addition to recharge regions, floodplains and lowlands play a crucial role in the water and solute cycle of Pleistocene landscapes. Lowland catchments with shallow water table groundwater usually represent the main components of river discharge (*Hattermann* et al. 2004). Nutrient storage, denitrification and carbon fixation are the characteristic natural processes in these regions, but no management strategies are feasible without detailed knowledge about the processes that control the water and solute budget. Only proper land and water management through biogeochemistry can improve the preservation of these sensitive ecosystems. In flatlands and floodplains, most of the water pollution results from agricultural pollution in combination with inappropriate water management operations (*Böhlke* et al. 2002, *Twarakavi* and *Kaluarachchi* 2005). For example, excessive groundwater lowering and drainage mismanagement, which is still a common practice, destroy the soil properties and disrupt the sink function of the entire system (*Massmann* et al. 2004). Farmers still put strong pressure on local water authorities to intensify drainage measures in lowland regions especially in springtime and autumn, the seasons with the highest rainfall. But as shown in the Oderbruch, intensive drainage shows no positive effects on loamy alluvial soils (*Fig. 7*). It only creates high costs because there is no hydraulic connection between the groundwater and the surface water standing in the fields, and it puts additional strain on the regional water budget.

Given this knowledge, the cause-effect chain of climate and technological changes and their impacts on groundwater quality can be specifically assessed. For this approach, the GIS-based model MODEST (*Steidl* et al. 1999, *Merz* et al. 2009a is available, which allows the consideration of chemical transformation processes and the spatio-temporal differentiation of the substance transport behaviour via the complete path "soil – groundwater – surface water" at the regional scale. Adapted management strategies can be validated by this model approach calculating realistic scenarios of water and solute fluxes at regional scales under different boundary conditions (*Fig. 9*). Each iterative calculation step will end with a risk assessment and a new adaptation of management scenarios, if necessary. In the case of nutrient leaching, recharge and nutrient concentration patterns of potential land-use schemes are externally represented by specific models (e.g. HERMES, *Kersebaum* and *Richter* 1994) that take water and nutrient balances, soil cover and tillage characteristics, crop growth and potential irrigation arrangements into consideration.

Before authorisation of water management approaches in floodplains, it is necessary to apply water balance models like WBalMo (*Dietrich* et al. 2007). This model can be used for river basin management and hydraulic regulations in discharge regions, considering shallow groundwater surfaces, intensive groundwater surface water interactions and drainage by channels and ditches.

5. Conclusions

The expected climate changes intensify the pressure on water resources all over North-Central Europe. Impacts on these water resources are intensified by changed land use and water management measures like drainage, drinking water supply and re-filling open-cast mining pits, especially in the Spree basin.

Groundwater recharge is expected to decrease. In the case of decreasing groundwater levels in recharge areas and dramatic decrease of discharge during the summer, so far unexpected process interactions occur. Changing groundwater flow patterns can threaten groundwater and surface water quality as a result of changing geochemical boundary conditions in the aquifer systems. Oxygen can diffuse into the anaerobic aquifers reducing the denitrification potential and intensifying the release of sulfate and trace elements into the groundwater (*Massmann* et al. 2004). With progressive climate change occurring, the protection of hydrological resources in younger Pleistocene glacial landscapes creates the need for innovative water management strategies and risk assessments for the future.

Water management should begin with a geospatial analysis of the inputs and losses of water and solutes (*Richardson* et al. 2001). Therefore, it is important to identify the effective hydraulic flow paths, fluxes and stores to quantify the hydraulic system and the migration processes of pollutants. Typical questions involving regionalisation, identification and quantification of the linked hydrogeochemical processes, together with the prediction of system behaviour under changing boundary conditions, can be addressed with this approach.

On the basis of an excellent understanding of the complex hydraulic-geochemical interactions in Pleistocene landscapes, model-based, risk assessment calculations can predict the feedback of controlled management and local climate trends on regional water systems. Therefore, the relevant hydraulic and geochemical processes should be considered, and their complex interactions and impacts on water quality should be validated.

Although the Berlin-Brandenburg landscape is very complex and heterogeneous in regard to almost all parameters, Pleistocene landscapes are highly structured, and complex hydraulic and geochemical processes are influenced by these structures at larger scales (*Lischeid* et al. 2010). These regions show specific hydraulic and geochemical characteristics that control the water and solute fluxes on these scales. According to *Merz* et al. (2009) the hydraulic interpretation of different structural units, described in terms of groundwater flow direction and residence time in connection with the redox state as a geochemical proxy indicator, allows the allocation of spatially-distributed, chemical reaction pools along the calculated, regional groundwater flow path. This approach provides the complex knowledge necessary to develop protection and management measures which are adjusted to the spatially-distributed hydrological processes and geochemical water-sediment interactions in the landscape. Combined with specific local management recommendations and in close collaboration with stakeholders and local authorities to balance competition among different water and land-use demands, it can be used to adapt and validate land and water management strategies for glacial landscapes under the pressure of climate change.

Acknowledgement

Prof. Dr. Asaf Pekdeger did not live to see the publication of his paper; he died on May 17th, 2011. We deeply regret his death.

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Summary: Anthropogenic Changes in the Landscape Hydrology in the Berlin-Brandenburg Region

For decades, water resources have been used intensively by human beings for drinking water, industry, agriculture and energy. Withdrawal of groundwater, regional drainage and intensive water measures during open pit lignite mining influence the regional water balance in Berlin-Brandenburg in a variety of ways. Regional water balance is the fundamental relationship among inputs, outputs and storage that dictates the water and substance flux in the region. This relationship is disturbed by massive hydraulic water management measures, which has enabled an effective discharge of water out of the landscape for centuries. Today, more than 80 % of the entire water network in Brandenburg is of artificial origin. Regional groundwater flow is mainly controlled by hydraulic conditions in the geological/stratigraphic units of the landscape. In hydrogeologic recharge regions in particular, falling groundwater levels in connection with decreasing low level discharge during the summer have been observed. Increasing evapotranspiration and decreasing amounts of rainfall exacerbate this problem. Pressure on groundwater and surface water quantity and quality is expected to rise. Under progressive climate change, it is a challenge to manage the ever scarcer water resources, their uses/services, and their after-use disposal without creating environmental, social and/or economic damage. Changing groundwater flow patterns could threaten the status of water resources because of changing hydrological and meteorological boundary conditions in the landscape. Therefore, protection of hydrological resources and stabilisation of the regional water balance require innovative water management strategies, including risk assessment approaches to Pleistocene glacial landscapes.

Zusammenfassung: Anthropogen bedingte Veränderungen des Landschaftswasserhaushaltes in der Region Berlin-Brandenburg

Seit Jahrzehnten werden natürliche Wasserressourcen in großem Umfang für Trinkwasserversorgung, Industrie, Landwirtschaft sowie Energiegewinnung genutzt. Die lokale Entnahme von Grundwasser, großräumige Entwässerung der Landschaft und eine überregionale Absenkung der Grundwasserstände in Verbindung mit dem Braunkohletagebau beeinflussen den Wasserhaushalt in Berlin-Brandenburg in erheblicher Weise. Der regionale Wasserhaushalt ist direkt von den Wasserhaushaltsgrößen Wasserdargebot, Wasserentnahme und Speichervermögen der Landschaft abhängig. Diese Gleichgewichtsbeziehung, die die Wasser- und Stoffflüsse in der Landschaft kontrolliert, wird durch anthropogene Einflüsse seit der Industrialisierung intensiv verändert. So sind zur Zeit anthropogen geprägte Gewässer, die einen schnellen Abfluss aus der Landschaft ermöglichen, mit einem Anteil von über 80 % am Gewässernetz in Brandenburg vertreten. Der regionale Grundwasserhaushalt ist maßgeblich durch vorherrschende hydraulische Prozesse in den hydrogeologischen Einheiten der glazialen Landschaft geprägt. Insbesondere in den Grundwasserneubildungsgebieten sind fallende Grundwasserstände und sinkende Abflüsse während der Sommermonate zu beobachten. Zunehmende Verdunstung und abnehmende Niederschläge werden die Neubildungsraten weiter reduzieren, was mit weitreichenden Folgen für den Wasserhaushalt in quantitativer und qualitativer Hinsicht verbunden ist. Eine angepasste Nutzung zunehmend knapper werdender Ressourcen ohne negative Folgen für die Umwelt sowie die sozialen und ökonomischen Verhältnisse ist eine der wichtigsten zukünftigen Herausforderungen. Die in den nächsten Jahrzehnten zu erwartenden Veränderungen der meteorologischen und hydrologischen Randbedingungen werden die dynamischen Fließverhältnisse im Untergrund massiv beeinflussen. Eine Stabilisierung der regionalen Wasserhaushaltsbilanzen durch innovative Managementstrategien in Verbindung mit Risikobewertungen ist daher zum Schutz der Wasserressourcen in glazial geprägten, pleistozänen Landschaften dringend geboten.

Résumé: Changements de nature anthropogénique de l'équilibre hydraulique dans des terrains pléistocènes : l'exemple de la région Berlin-Brandebourg

Depuis des décennies, les ressources hydrauliques sont exploitées par l'homme pour satisfaire ses besoins en eau potable et en énergie, ainsi que pour combler les nécessités des industries et de l'agriculture. Le pompage de ces eaux, l'assèchement naturel à échelle régionale et leur intense utilisation par des mines à ciel ouvert influencent sévèrement l'équilibre hydraulique dans la région de Berlin-Brandebourg. L'équilibre hydraulique est une balance fondamentale entre les flux en entrée et en sortie et l'accumulation des eaux dans la région. Cette relation est perturbée par des mesures de gestion des eaux qui assurent depuis des siècles une décharge effective des eaux en dehors des limites territoriales. Aujourd'hui, plus de 80 % de tout le réseau du Brandebourg est artificiel.Le flux régional des eaux souterraines est contrôlé principalement par les conditions hydrauliques des unités stratigraphiques/géologiques du terrain. Notamment, dans les zones de recharge hydraulique, l'abaissement du niveau des eaux, du à la diminution de la décharge pendant l'été, est mesuré. La croissante évaporation et la diminution des pluies renforcent ce problème. Une hausse de la pression des eaux souterraines et des eaux de surface est désormais prévue. À cause des changements climatiques, la gestion de rares ressources hydrauliques, leur utilisation et leur élimination sans créer des problèmes sociaux/économiques à l'environnement, sont les défis à résoudre. Des changements dans les cours d'eaux souterrains pourraient menacer les ressources hydrauliques à cause des changements des conditions hydrologiques et météorologiques des régions. Ainsi, la protection de ces ressources et la stabilisation de l'équilibre hydraulique exigent des stratégies innovatrices de gestion y compris une évaluation des risques que des activités humaines peuvent engendrer dans des terrains pléistocènes.

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Manuscript submitted: 07/12/2009
Accepted for Publication: 13/02/2011