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• *Regional water balance – Groundwater level – Lake level – Drainage – Climate change – Global change*

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Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region – a Review

Wasserhaushaltsveränderungen und Reaktionen von Ökosystemen und Gesellschaft in der Region Berlin-Brandenburg – ein Überblick

With 8 Figures and 2 Tables

The climate change debate has increased the need for knowledge on both long- and short-term regional environmental changes. In general, these changes may often be a product of multiple causes, which complicates the separation of single driving forces. In this review we focus on current water budget changes in Germany's capital region, Berlin-Brandenburg, over the last 30 years. Available studies from a variety of disciplines (e.g. hydrology, water engineering, landscape ecology, nature conservation) were analysed in order to (1) identify both local and regional hydrological changes, (2) reveal their potential causes, and (3) discuss responses of ecosystems and society. These studies show that the Berlin-Brandenburg region is widely characterised by decreasing groundwater recharge, leading to decreasing groundwater and lake levels as well as decreasing fluvial discharge. These trends result both from complex, regional human impacts (e.g. long-term effects of hydro-melioration and changes in forest composition) and more general climate warming. The observed and assumed (future) changes of the regional water balance have been creating, and will continue to create, multifaceted impacts on existing ecosystems and society (e.g. wetland drying, decrease of biodiversity, decrease of productivity of grasslands and forests, increasing conflicts of interests). Several efforts to respond to the regional water deficit problem have already been undertaken, comprising for instance land-use optimisation, wetland restoration measures and the reestablishment of mixed deciduous forests. In general, however, the reviewed regional material on this topic reveals that the number and complexity of empirical studies are still poor. Thus, for both the identification and the explanation of current water balance changes and their effects, as well as for development and implementation of adaptive strategies, further multidisciplinary research efforts at different scales, including interregional comparisons, are required. Furthermore, both the observation of hydrological changes and the evaluation of adaptive and mitigative responses require at least continuous or, even better, extended monitoring efforts.

1. Introduction

The global integration of environmental changes has been a major focus of global change research during the past two decades. Now it is common knowledge that global warming is taking place in wide areas and may continue for some decades, even if anthropogenic emission of CO_2 and other relevant greenhouse gases could be stopped immediately (IPCC 2007a, IPCC 2007b). It is likewise known that temperature is a driver of the global water cycle and that changes in temperature will result in changes of global water cycle dynamics (*Huntington* 2006). Parallel to the global integration of environmental changes, regional assessments of change through monitoring and impact modelling are needed in support of integrated global change studies (*Easterling* 1997). Regional assessments of hydro-environmental changes have been carried out through spatial interpolation studies of measured or simulated changes in groundwater levels, percolation water or soil moisture, and the results can generally be presented through easily interpretable colour-coded maps. These studies have been based on data time series measured at or calculated for a multitude of individual sites. The spatial interpolation involved, however, entails a loss of local information that might be of great value for the process of understanding the changes taking place. One study that has attempted to overcome this problem has been presented by *Schmitz* et al. (2003) for mainly biotic ecosystem responses to climate change.

Seeking to enhance our knowledge of these processes, we have reviewed studies related to current water balance changes in order to (1) identify both local and regional hydrological changes, (2) reveal their potential causes, and (3) discuss responses of ecosystems and society. Germany's capital region of Berlin-Brandenburg is ideally suited as an area of focus for such a study, because it is marked by water scarcity, has experienced water balance changes at least over the past three decades, is affected by climate change and, at the same time, is a cultural landscape marked by significant anthropogenic influences. As outlined, for example, in general terms by *Hüttl* et al. (2000) and more specifically with a thematic and regional focus by *Wahl* et al. (2003, 2004), *Landgraf* (2005), *Kaiser* et al. (2007) and *Kirilova* et al. (2009), an understanding of the origins and consequences of past human impacts is required for understanding and management of current changes. This special issue of 'DIE ERDE' provides a broad overview of past human disturbance and environmental changes related to ground- and surface-water within the Berlin-Brandenburg region. Based on this overview and on manifold further material, our review provides a synopsis of observed and predicted impacts on ecosystems and society in the region. A concluding discussion about the causes of impacts from and possible responses to water balance changes will highlight existing gaps in knowledge and suggest avenues for future research.

2. Regional Settings

The Berlin-Brandenburg region is situated in the glacially formed northeastern German lowlands (highest points: 201 m a.s.l., *Fig. 1*). The landscape is dominated by Pleistocene sandy and loamy sediments. Holocene organic sediments (mostly peat) are limited to riversides and peatlands where drainage and sub-irrigation systems are widely present. The major rivers are the Elbe and Oder which drain into the North and Baltic seas, respectively. Most of the Berlin-Brandenburg area is part of the Elbe catchment, whereas only a small portion in the east is part of the Oder catchment. Brandenburg receives comparatively low amounts of precipitation, with a regional average of 604 mm per year, while the climatic water demand is relatively high, with a regional average actual evapotranspiration of 511 mm per year (1951-2000, *Gerstengarbe*

Fig. 1 Map of the German federal state of Brandenburg, indicating the river gauges listed in *Table 1* and the study regions and sites listed in *Table 2* / *Karte des Bundeslandes Brandenburg mit Lage der in Tab. 1 aufgeführten Flusspegel und der in Tab. 2 genannten Untersuchungsgebiete*

et al. 2003). Although the region is characterised by an abundance of groundwater resources, wetlands and lakes, most of the precipitation evaporates and surface runoff is negligibly small (*Nützmann* and *Mey* 2007), originating mainly from agricultural land (*Schindler* et al. 2004). Considering the low quantities of annual rainfall, with high year-to-year variability, makes clear the region's high level of vulnerability in terms of water needed for agriculture, domestic and industrial uses as well as ecosystems worthy of protection.

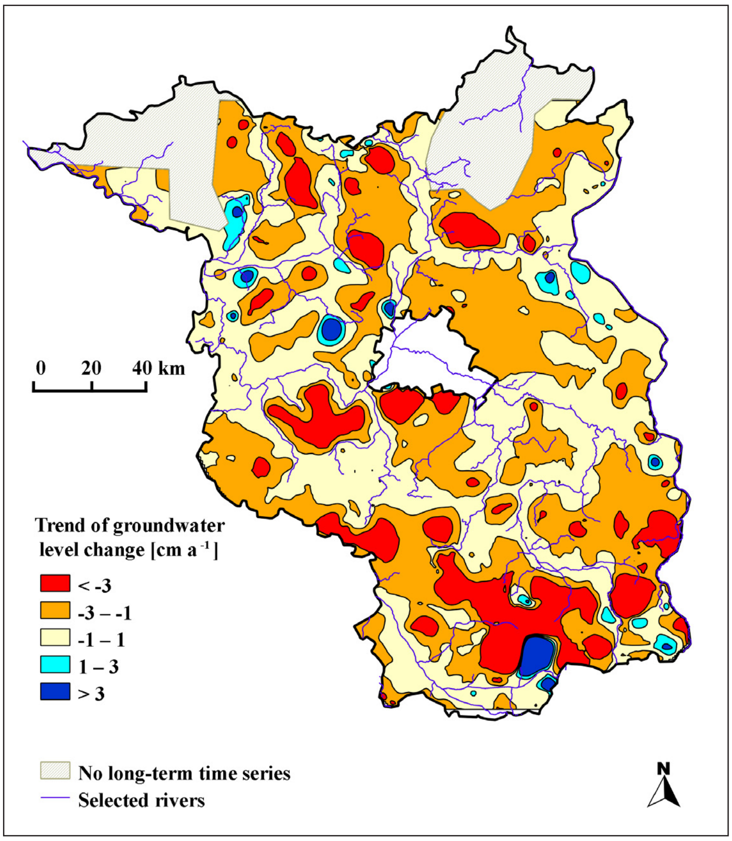

Fig. 2 Groundwater level trends in Brandenburg, interpolated from data from 1,183 groundwater wells (1976-2005, after: LUA Brandenburg 2009, *Fig. 5*, modified)
Grundwasserspiegeltrends in Brandenburg, interpoliert aus Daten von 1183 Grundwasserpegeln (1976-2005, nach LUA Brandenburg 2009, Abb. 5, verändert)

Berlin-Brandenburg has a total area of 30,732 km² (Amt für Statistik Berlin-Brandenburg 2008a, 2008b). Agriculture is the dominant land use, with 34 % cropland and 9 % pasture. Major crops are rye, wheat, rape and silage maize, with an area of 20 %, 13 %, 13 % and 11 % of total cropland, respectively (Amt für Statistik Berlin-Brandenburg 2008a, 2008b). Forest land use contributes to 35 % of the total area, and Scots Pine (*Pinus sylvestris*) represents the dominant tree species. Water management through indented groundwater lowering is characteristic in the large valleys of Brandenburg (former glacial spillways, *Urstromtäler* in German) consisting of peatlands and river floodplains. Large sections of the Berlin-Brandenburg area are dominated by formerly wet soils caused by high groundwater levels, which are at present mostly used as grassland (*Wattenbach* et al. 2007). Agricultural use of these areas has a long tradition, with some large-scale (hydro-)melioration projects already dating from the 18th century (e.g. *Kalweit* 1998, *Quast* 2005). Intensive melioration (*Komplexmelioration*), however, with deep drainage, pumping as well as irrigation, did not occur until the 1960s-70s (*Pollack* 1991). Eight percent of Brandenburg's territory consist of peatlands forming a total of about 2,100 km², with (riparian) fen peatlands dominating at about 74 % (*Schultz-Sternberg* et al. 2000). Remaining active peatlands which still accumulate peat have, however, only a share of 1 % (25 km²).

In 2007 Brandenburg and Berlin had populations of 2.5 and 3.4 million, respectively (Amt für Statistik Berlin-Brandenburg 2008a, 2008b). While Berlin's population has remained rather stable over the last two decades, there are significant differences in terms of demographic change in the 14 districts of Brandenburg. While the districts adjacent to Berlin experienced massive population gains due to residential and economic suburbanisation, some districts in the outer regions are facing high population losses (Amt für Statistik Berlin-Brandenburg 2008a, 2008b). Projections for population development in Brandenburg until 2020 imply that the belt around Berlin will very likely continue to benefit from its metropolitan neighbour but the rural areas situated at a greater distance from Berlin will be confronted with further depopulation. This may result in new challenges, but could also open up new opportunities for agriculture and forestry, environmental protection and compensation, as well as economic and socio-cultural planning (*Hüttl* et al. 2008).

3. Changes in Regional Water Balance and Possible Drivers

A data interpolation conducted by the state environmental groundwater observation network from 1976 to 2005 reports decreasing groundwater levels in Brandenburg: generally in the range of 1 to 3 cm per year in the groundwater recharge areas (moraine and kame plateaus, outwash plains), while for lower terrain no trends exist (1976-2005; *Fig. 2*; LUA Brandenburg 2009). According to the LUA Brandenburg report (2009), the greatest drawdown of groundwater, by 6 to 10 cm per year, can be observed near watershed divides, when excluding special settings such as mining areas or sewage fields. It should be noted that neither our *Figure 2* nor the original figure in the report contains any information about the statistical significance of these trends. *Lahmer* (2004) reports that during the time period 1961-1998 percolation decreased over almost 75 % of Brandenburg's total area. These trends, however, were significant for only 5 % of Brandenburg and, interestingly, were without exception limited to lower terrain areas with a shallow groundwater table. Despite the lack of testing for significance, the case studies suggest that substantial groundwater drawdown is indeed taking place in Brandenburg's groundwater recharge areas (see Section 3.1). In order to draw reliable conclusions on the spatial extent of this trend, further research is needed.

3.1 Observed hydrological changes

In addition to the regional interpolation of water balance changes, for about the past 30 years decreasing groundwater and lake levels, landscape runoff and groundwater recharge have been reported by several local case studies scattered throughout Brandenburg (e.g. *Dreger* and *Michels* 2002, *Landgraf* and *Krone* 2002, *Lahmer* 2003, *Borgwardt* et al. 2006, *Nillert* et al. 2008, *Germer* et al. 2010, *Juschus* and *Albert* 2010). Exceptions from this trend are regionally rising groundwater and lake levels in the (partly revitalised) lignite mining area of southern Brandenburg (Niederlausitz) as well as an increase of groundwater levels in parts of Berlin, due to reduced water withdrawal (Senatsverwaltung für Stadtentwicklung Berlin 2008, *Merz* and *Pekdeger* 2011, this issue). Furthermore, modelling studies dealing with the consequences of climate change on the regional water balance and water supply for the 21st century have widely predicted a worsening of the regional water balance situation (e.g. *Gerstengarbe* et al. 2003, *Werner* et al. 2005, *Rachimow* et al. 2008). Consequently, attributes such as 'problematic', 'stressed' or 'dramatic' have been used to characterise the present-day and future water balance situation in Brandenburg (e.g. *Landgraf*

Tab. 1 Mean discharge as well as absolute and relative change of discharge from 1976 to 2005 for selected rivers in Brandenburg (after LUA Brandenburg 2009) / *Mittlere Abflüsse sowie absolute und relative Abflussänderung zwischen 1976 und 2005 für ausgewählte Flüsse in Brandenburg (nach LUA Brandenburg 2009)*

Catchment (Gauge)	**Area [km²]**	**Discharge**		
		Mean [mm per year]	**Absolute change [mm per year]**	**Relative change [%]**
Nuthe (Babelsberg)	1,804	137	-55	-33
Upper Havel (Borgsdorf)	3,144	133	-63	-38
Havel (Havelberg-Stadt)	24,297	132	-85	-49
Spree (Leibsch)	4,529	131	-136	-68
Elbe (Wittenberge)	123,534	177	-38	-19
Oder (Eisenhüttenstadt)	52,189	182	-59	-28

and *Krone* 2002, *Gerstengarbe et al.* 2003, *Lahmer* 2004, *Freude* 2007). The following review is focused on case studies of regional water shortage, but excludes the special hydrologic situation of (post-)mining areas in southern Brandenburg (*Bens* and *Hüttl* 2005, *Fleischhammel* et al. 2010).

3.1.1 Fluvial discharges

The major regional rivers, Oder and Elbe, were hit by disastrous flood events in 1997 and 2002 (*Grünewald* et al. 1998, *Grünewald* 2006). For these large rivers, however, only a very weak trend of changing discharge parameters has been reported over the last decades (*Landgraf* and *Krone* 2002, *Mudelsee* et al. 2003, *Finke* and *Krause* 2005, LUA Brandenburg 2009, *Petrow* and *Merz* 2009). In contrast, the medium-scale Havel river and a multitude of small rivers as well as streams show a considerable negative trend of both mean annual and low-water discharges (*Finke* and *Krause* 2005, *Krone* 2007, *Nützmann* and *Mey* 2007). Some streams become periodically stagnant or even run dry. An analysis of 81 river and stream gauges from 1980 to 1999 revealed a significant negative trend of mean annual discharge for 54 gauges (1980-1999, t-test, α = 0.05, *Landgraf* and *Krone* 2002). A newer study, focussing on changes in the discharges of selected rivers in the region, confirmed a drastic negative trend for the period 1976 to 2005 (1976-2005, LUA Brandenburg 2009, *Tab. 1, Fig. 2*). The change in discharge from the upper reaches of the Havel river, for instance, amounts to -38 % (Borgsdorf gauge). Still higher relative changes in the lower Havel have reached -49 % at Havelberg and, along the middle course of the Spree river, -68 % at Leibsch (*Tab. 1*); these have mainly been caused by diminishing water input from the declining open-cast lignite mining in the Niederlausitz area (*Finke* and *Krause* 2005, *Grünewald* 2008) and had already been predicted a decade ago (*Arnold* and *Kuhlmann* 1993).

3.1.2 Groundwater and lake levels

The greater part of Brandenburg comprises a young morainic area with unconsolidated sediments, often high-lying groundwater and a multitude of lakes, which largely take the form of 'hollows' located in the uppermost (unconfined) aquifer. Consequently, groundwater and lake-level dynamics in the region are closely connected. A number of local and regional case studies (*Tab. 2*) have looked at areas where different degrees of human impact on the landscape are evident. Here, three general landscape types can be distinguished: (1) the Berlin metropolitan area, which is heavily influenced by water withdrawal, waste-water processing and urbanisation; (2) large-scale drained wetlands, which comprise river floodplains and basins (partly with lakes) as well as peatlands; and (3) mostly forested lakelands of moraine and kame plateaus as well as of outwash plains.

Since the early 20th century, large areas of Berlin and its surroundings have been heavily influenced by groundwater lowering due to water withdrawal for urban and industrial use, a process which intensified in the 1960-70s. In particular, large stretches of the Grunewald area (ca. 30 km^2) have sustained a marked groundwater drop of 4-6 m (*Sukopp* 1981, *Meissner* 2004), which has caused local lake-level decreases and wetland dryings with serious environmental consequences (e.g. *Kletschke* 1977, *Sukopp* 1981, *Forner* and *Gossel* 1996, *Riek* 2001). For instance, from 1930 to 1970 the maximum lowering of Pechsee Lake in the Grunewald area was 3.5 m (*Meißner* 2004). A further example of a lake whose water balance is strongly influenced by anthropogenic impact is Großer Seddiner See, about 10 km south of Potsdam. Two thirds of its recharge area have increasingly been influenced by groundwater withdrawal since the late 1980s, contributing to lake-level fluctuations of about 1 m over the last 30 years (*Vietinghoff* 1993, *Vietinghoff* 1998, *Mietz* and *Vedder* 2010).

Using water gauge observations and dendrohydrological data for a widely forested moraine plateau southwest of Potsdam (Zauche area, ca. 100 km^2), *Landgraf* (2005, 2007a, 2007b), *Landgraf* and *Notni* (2004) and *Nillert* et al. (2008) have reported a general *regional* lowering (1.5-2.0 m) of groundwater and lake levels since the early 1970s. Through a combined analysis of both regional land-cover changes and climatic as well as hydrological data for the 20th century, the authors have provided evidence that a simple explanation of this trend by climatic effects alone is too narrow, as periods of higher water levels were observed even under periodically dry climatic conditions, when forest coverage was small. This is in line with the findings of *Mey* et al. (2008), who reported that deforestation in the 1970s-80s at Luchsee (Niederlausitz area) resulted in lower water depletion levels compared to that of the present pine forest there. *Landgraf* (2005, 2007a, 2007b), *Landgraf* and *Notni* (2004) and *Nillert* et al. (2008) concluded that it is probably the combined effects of land-cover change (increasing area and ageing of pine forests), drainage measures for agricultural purposes (e.g. melioration of the nearby Nuthe-Nieplitz river valley) and climate change (warming) that have resulted in a regional drying tendency basically caused by decreasing groundwater recharge.

Several studies have dealt with an increasing water balance deficit in the Schorfheide-Chorin Biosphere Reserve and its surroundings, north of Berlin. This area mainly consists of sandy surface substrates and is predominantly forested. A dense network of 112 groundwater gauges spread over 400 km^2 has been set up there. A subsample of 17 long-standing gauges for the period from 1981 to 2001 shows groundwater levels that generally decreased within a range of 0.7 to 2.3 m, making for a rate of about 7 cm per year (range 3.5-11.5 cm per year, *Dreger* and *Michels* 2002). Two case studies in the catchments of Großer Pinnowsee (*Borgwardt* et al. 2006) and

Tab. 2 Selected data on occurrences of groundwater drawdown and lake-level lowering in northeast Germany
Beispieldaten zur Grundwasser- und Seespiegelabsenkung in Nordostdeutschland

Region	Landscape type	Gauge type (number of gauges)	Observation period (years)	Total level lowering [cm]	Mean level lowering [cm per year]	Identified / assumed cause	Reference
Brandenburg state	Entire state	Groundwater (1183)	1976-2005 (29)	48	Mainly 1-3	Hydro-melioration, land use, climate	LUA 2009
Brandenburg state	Moraine plateaus, outwash plains	Groundwater	1976-2005 (29)	76	Up to 6-10	Hydro-melioration, land use, climate	LUA 2009
Grunewald (BE)	Outwash plain	Groundwater	1915-2003 (88)	400-500	4-6	Water withdrawal for urban use	*Sukopp* 1981, *Meißner* 2004
Pechsee (BE)	Outwash plain	Lake (1)	1915-2003 (88)	350	4	Water withdrawal for urban use	*A. Meißner* (Berlin), pers. comm.
Luchsee (BB)	Moraine plateau	Groundwater	1996-2006 (10)	150	15	Land use, climate	*Mey* et al. 2008
Karower Teiche (BE)	Panke river valley	Groundwater	1985-2003 (18)	150	8	Cessation of artificial water supply (sewage farm)	*Pfützner* et al. 2006
Zauche area (BB)	Moraine plateau	Groundwater	1970-2004 (34)	150-220	4-6	Hydro melioration, land use, climate	*Landgraf* 2005, 2007a, *Nillert* et al. 2008
Moosfenn (BB)	Moraine plateau	Groundwater	1986-2003 (17)	100	6	Hydro melioration, land use	*Landgraf* and *Notni* 2003
Großer Seddiner See (BB)	Moraine plateau	Lake (1)	1992-1997 (6)	80	13	Reduced feeding by groundwater due to colmation of the lake bottom	*Vietinghoff* 1998
Schorfheide area (BB)	Outwash plain, moraine plateau	Groundwater (112)	1981-2001 (20)	70-227	4-11	-	*Dreger* and *Michels* 2002
Großer Pinnowsee (BB)	Outwash plain	Lake (1)	1983-2004 (21)	200	10	Cessation of artificial water supply, land use, climate	*Borgwardt* et al. 2006
Meelake (BB)	Outwash plain	Groundwater	1991-2004 (13)	201	15	Cessation of artificial water supply, land use, climate	*Borgwardt* et al. 2006

Region	Landscape type	Gauge type (number of gauges)	Observation period (years)	Total level lowering [cm]	Mean level lowering [cm per year]	Identified / assumed cause	Reference
Redernswalder See (BB)	Moraine plateau	Lake (1)	1976-2005 (29)	300	10	Climate	*Müller* et al. 2007
Kleiner Kronsee (BB)	Moraine plateau	Lake (1)	1999-2008 (9)	35	4	Climate, hydro-melioration	*Germer* et al. 2010
Großsee (BB)	Outwash plain	Lake (1)	1997-2006 (10)	100	10	Land use, climate	*Wichern* et al. 2010
Schwinzer Heide (MV)	Outwash plain	Groundwater	1964-2001 (37)	160	4	Hydro-melioration, land use	*Rowinsky* 2003
Nossentiner Hütte (MV)	Outwash plain	Groundwater	1969-1997 (28)	180	6	Hydro-melioration, land use	*Rowinsky* 2003
Drewitzer See (MV)	Outwash plain	Lake (1)	1982-2005 (23)	150	6	Hydro-melioration, land use	*Lorenz* et al. 2010
Müritz National Park (MV)	Outwash plain	Lake (3)	1997-2006 (9)	60-90	7-10	-	Nationalpark-amt Müritz 2006
Großer Fürstenseer See (MV)	Outwash plain	Lake (1)	1985-2007 (22)	120	5	Hydro-melioration, land use, climate	*Stüve* 2010
Drawehn area (Wendland, NI)	Moraine plateau	Groundwater	1970-2005 (35)	50-300	1-9	Land use	*Ogroske* et al. 2008

BE = Berlin, BB = Brandenburg, MV = Mecklenburg-Vorpommern, NI = Niedersachsen

Redernswalder See (*Müller* et al. 2007, *Hoffmann* et al. 2009, *Natkhin* et al. 2009) reveal lake-level lowerings of 1.3 m (1991-2004) and 3 m (1980-2004), respectively (*Fig. 3, Fig. 4; Tab. 2*). As the main cause for the regional groundwater decline and the local lake-level lowerings in that area, DHI-WASY GmbH (2008) points to an increasing water balance deficit since the 1980s, which caused a marked reduction of groundwater recharge. This deficit, in turn, is caused by both assumed lower precipitation levels and higher potential evaporation rates following climate change. Further factors probably contributing to the water budget deficit are hydrologic effects caused by dominating pine forests (triggered by age-class changes) and by historic melioration measures taken in the 19th and 20th centuries (*Borgwardt* et al. 2006, *Reimann* 2006, *Meier-Uhlherr* et al. 2010).

In Uckermärkische Seen, a nature park in northern Brandenburg, a large-scale nature conserva-

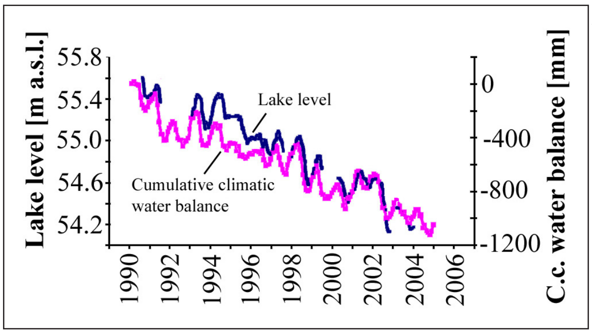

Fig. 3 Lake level and cumulative climatic water balance time series for Großer Pinnowsee, Schorfheide (after: DHI-WASY GmbH 2008) / *Seespiegel- und kumulative klimatische Wasserbilanzzeitreihe für den Großen Pinnowsee, Schorfheide (nach: DHI-WASY GmbH 2008)*

tion project was launched in the early 1990s basically aiming at the stabilisation of the water balance of lakes and peatlands (project area of ca. 250 km^2, *Mauersberger* 2010). A dense network of about 200 lake gauges was established for hydrologic monitoring, probably forming the most dense lake gauging network in northeastern Germany. Several lakes have exhibited notable level-lowering at a range of about 0.5-1 m. In some exceptional cases (e.g. Kleiner Kronsee, *Fig. 5*) the lake-level decrease during the last 25 years has been 2 m (*R. Mauersberger*, Templin, pers. comm.). Some larger but naturally shallow lakes have even disintegrated into parts.

According to a hydrologic lake classification by *Mauersberger* (2002), these lakes are so-called *groundwater lakes*, which are not influenced by surficial anthropogenic drainage measures. During the course of the 25-year observation period, there had been no drastic changes in land-use patterns or local (ground-)water withdrawal in the catchments. Even though an in-depth analysis of further potential factors (e.g. influence of past regional drainage measures, forest structure changes) does not yet exist, the lake-level lowerings in the area are assumed to be mainly caused by climatic impact, taking into consideration regional climate warming and evidence for

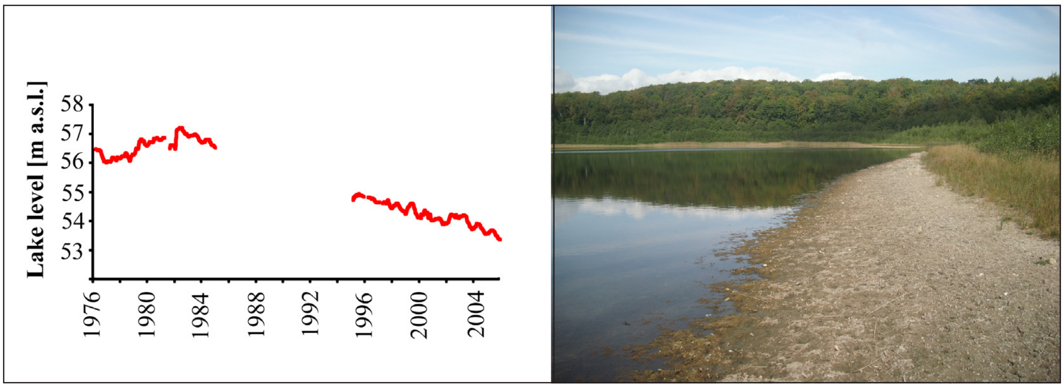

Fig. 4 Lake level time series for Rederns walder See, Schorfheide, and a photograph of the lake (graph: *Müller* et al. 2007, photo: *K. Kaiser,* September 2009) / *Seespiegelzeitreihe und Foto des Rederns walder Sees, Schorfheide (Grafik: Müller et al. 2007, Photo: K. Kaiser, September 2009)*

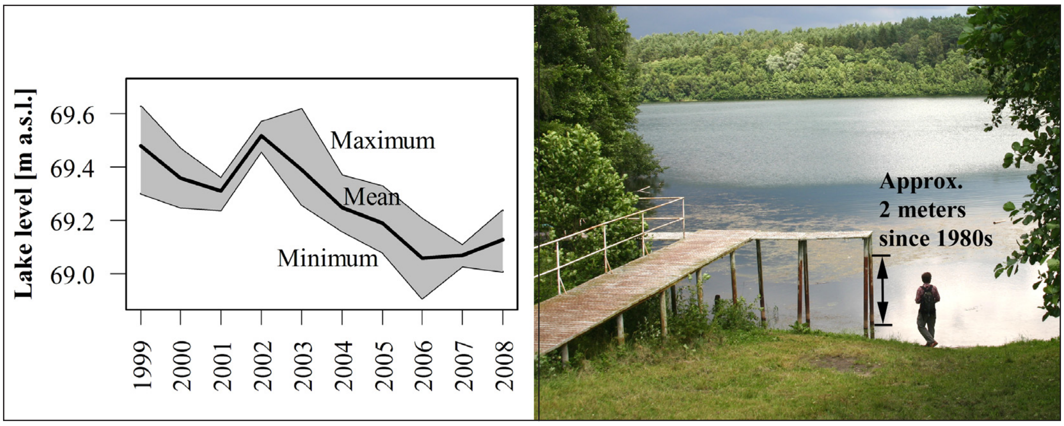

Fig. 5 Mean, maximum and minimum lake level time series for Kleiner Kronsee, Uckermark, and a photograph of the lake showing a jetty built in the 1980s, revealing a lake level lowering of approximately 2 m since then (graph: unpublished data from *R. Mauersberger*, photo: *S. Germer,* July 2009) / *Zeitreihen des mittleren, höchsten und niedrigsten Seespiegels des Kleinen Kronsees, Uckermark sowie ein Foto des Sees mit Bootssteg aus den 1980er Jahren, der auf eine Seespiegelsenkung von annähernd 2 m seit dieser Zeit hindeutet (Graphik: unveröffentlichte Daten von R. Mauersberger, Photo: S. Germer, Juli 2009)*

parallel decreases of groundwater recharge in northern Brandenburg (e.g. *Lahmer* 2003, *Werner* et al. 2005, *Borgwardt* et al. 2006, DHI-WASY GmbH 2008).

3.2 Interregional comparison

As in Brandenburg, observations on a regional decrease of discharge in medium- and small-sized rivers have been reported from the adjacent federal state of Mecklenburg-Vorpommern. Between 1971 and 2000, 12 of 17 analysed river gauges revealed a negative trend of mean annual discharge (*Mehl* et al. 2004). Even with respect to the negative groundwater and lake level trends, similar data have been reported from the southern parts of the state, revealing for example in the Nossentiner/Schwinzer Heide Nature Park (365 km^2) a groundwater level lowering of about 1-2 m from 1964 to 2001 and a corresponding lake-level lowering of Lake Drewitzsee (1982-2008) of about 1.2 m (*Rowinsky* 2003, *Lorenz* et al. 2010). In the nearby Müritz National Park, groundwater in the area surrounding Lake Fürstenseer See and the lake itself fell about 1 m from 1982 to 2008 (*Stüve* 2010). Further lakes in that area exhibit lowerings of 0.6-0.9 m in the last 10 years (Nationalparkamt Müritz 2006, *Kobel* and *Spicher* 2010, *Küster* and *Kaiser* 2010). Furthermore, from comparable landscapes of the northeastern part of the federal state of Niedersachen, comprising the Lüneburger Heide and Wendland areas, both diminishing fluvial discharges and lowerings of groundwater levels have been reported [see references below]. In contrast to Brandenburg und Mecklenburg-Vorpommern, however, groundwater withdrawal for agricultural irrigation has been important in this area since the 1960s (*Wittenberg* 2002). Together with an increasing forest area proportion of heath consisting of heather (*Calluna vulgaris*), this is considered to be the main reason for regional hydrologic changes there in the last decades (*Wittenberg* 2002, *Lahmer* 2008, *Ogroske* 2008, *Ogroske* et al. 2008).

To sum up, over the last decades, a negative water balance trend has become a *regional* characteristic of glacial landscapes in northeastern Germany. Reduction of fluvial discharge, groundwater drawdown and lake-level lowering are the main hydrologic effects. As Brandenburg und Mecklenburg-Vorpommern have nearly identical physical landscapes, climates, current land cover and land use histories – in particular, large-scale wetland drainages in the 19th and 20th centuries – the same *causes* for the same hydrologic changes can be assumed, namely (1) reduced groundwater recharge following climate change, (2) effects of melioration measures and (3) effects of dominating semi-natural coniferous (pine) forests.

3.3 Possible drivers of hydrological changes

The anthropogenic changes of the water balance within the Berlin-Brandenburg region have been discussed by *Merz* and *Pekdeger* (2011, this issue), who have pointed out some major effects, namely (1) increased evaporation due to increasing temperatures and an uneven forest age structure with a dominance of older pine trees, (2) widespread intensive drainage (melioration), and (3) local effects of increased groundwater depletion through changes in withdrawal of groundwater for drinking-water demands. Furthermore, localised special effects on groundwater levels can be observed that are due to open-cast mining, surface water reservoirs and cessation of artificial groundwater recharge by closing of sewage farms (e.g. *Scheytt* et al. 2000, *Landgraf* and *Krone* 2002, *Koch* et al. 2005, *Pfützner* et al. 2006, *Grünewald* 2008, *Merz* and *Pekdeger* 2011, this issue).

According to the environmental authority of Brandenburg, decreasing groundwater levels of blind drainage areas on moraine plateaus that cannot be attributed to localised special effects are exclusively driven by climate change and not by immediate anthropogenic impacts such as land and water management (*Tab. 2*, LUA Brandenburg 2009). This report and other publications indicate further possible causes for decreasing groundwater levels for the remaining areas: loss of retention areas (peatlands and floodplains), highly efficient drainage systems and land-use changes (*Tab. 2*).

Concerning the driver 'climate change', it should be pointed out that, at present, projections for regional climate change are only possible for air temperature (but not precipitation!) at a degree of certainty that would allow application in fields such as water management or planning purposes (*Bronstert* et al. 2003a). For the Elbe catchment, a climate change impact assessment showed that temperature increase combined with only small precipitation decreases can result in significant decrease of groundwater recharge (*Hattermann* et al. 2006). Other simulation studies that were based on even higher precipitation decreases (> 40 mm in 2000-2055) came to the same conclusion: that climate change drives groundwater level decrease (*Lasch* et al. 2002, *Lasch* et al. 2005).

Beside these widely discussed drivers of water balance changes, there are others that have been less often mentioned in the literature, but need to be considered in taking a broad overview (*Fig. 6*). Decreasing groundwater levels also result from temperature-driven evapotranspiration increases that, in turn, lead to increasing groundwater and soil water use by vegetation and decreasing groundwater recharge by percolation water. Annual evapotranspiration can further be increased through prolongation of growing periods, mainly because of earlier starts that are made possible by increasing temperatures (*Badeck* et al. 2004).

As already mentioned, melioration can be a driver of water balance changes. Due to the highly artificial drainage system in Brandenburg, during the period of the former German Democratic Republic drainage without water retention infrastructure (e.g. irrigation dams) was not allowed (*Pol-*

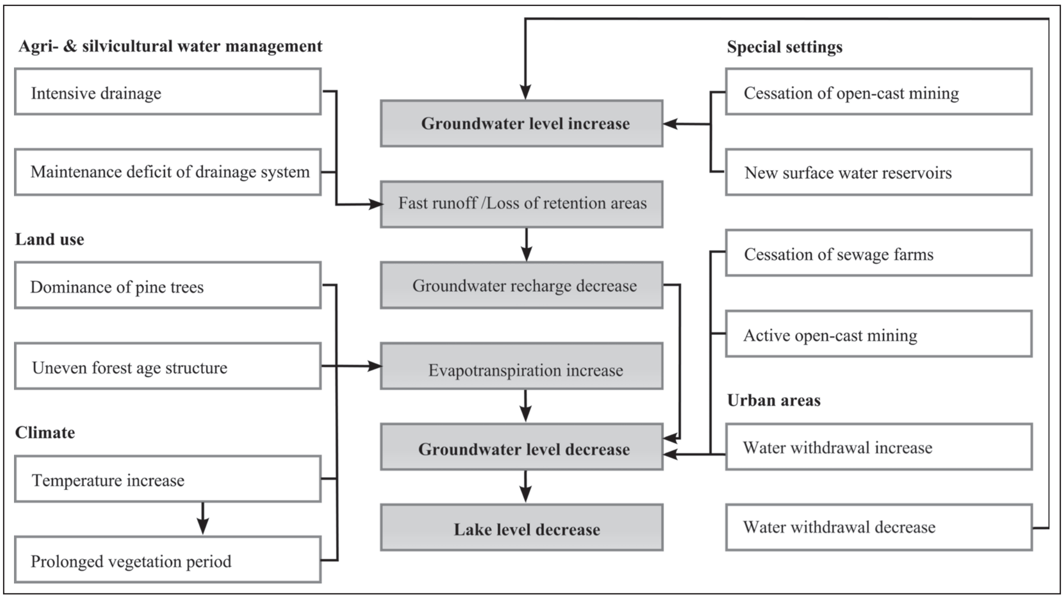

Fig. 6 Overview of causes for water balance changes and their interrelation in Brandenburg / *Überblick der Ursachen und Abhängigkeiten von Wasserhaushaltsveränderungen in Brandenburg*

lack 1991). Consequently, insufficient management and maintenance of the respective infrastructure can lead to water balance changes, too. Such infrastructural problems in Brandenburg can mainly be linked to political instabilities. River melioration maintenance was neglected during World War I and thereafter due to financial and manpower shortages, leading to an increased weather-dependency of agricultural production (*Materna* and *Ribbe* 1995). More recently, the political changes induced by German reunification led to a lack of clarity about who is responsible of irrigation-dam maintenance, resulting in insufficient water retention (*Schleyer* 2002).

Another side effect of drainage influencing regional water balance is the decreased water retention capacity of degraded peatlands (*Zeitz* and *Velty* 2002). Such a loss of capacity is irreversible (*Richert* et al. 2000), the water balance is changed over the long term and can only be improved by new peat accumulation.

It can be concluded that the human impact from land use and water management is the main cause for the deterioration of the regional water balance in Berlin-Brandenburg. During the last three decades, this trend has been further intensified by climate warming.

4. Resulting Impacts for Ecosystems and Society

Reliable prediction of the impact of stress factors such as water scarcity and the degree of resilience of ecosystems and society will largely depend on having an understanding of relevant mechanisms and interactions within the respective systems. The state of knowledge about regional and local hydrological processes, spatial patterns and the intensity of impacts is still limited (*Bronstert* et al. 2009). Therefore, we provide a synopsis of observed impacts of past (sub-recent) water balance changes in Berlin-Brandenburg together with projections of future impacts. The above-described decrease of groundwater recharge and increase of evaporation lead to decreasing groundwater and lake levels, reduction of fluvial discharge, desiccation of wetlands, soil moisture decrease and increasing frequency and duration of dry spells that, in turn, have several impacts on ecosystems and society (*Fig. 7*).

The most obvious impact of water scarcity is a decrease in agricultural production. In particular, losses of hectare yields for silage maize, sugar beets and potatoes can be expected in drought years for Brandenburg (e.g. in the years 2003 and 2006, *Fig. 8*). The forestry sector is affected by droughts as well. As *Riek* (2001) has shown for a pine forest in Brandenburg, biomass production depends on plant-available soil water. The author pointed out that, under water stress conditions, pine trees in particular close their stomata at an early stage in order to save water, subsequently having a negative effect on biomass gains. By way of example, at the Norunda site (Sweden) the growth of spruce and Scots pine was reduced by 36 % during a dry year in 2003 as compared to humid years (2004, 2005), with pine being more affected by drought than spruce (*Granier* et al. 2007). As plant-available water decreases with lowering groundwater levels, a negative affect is expected for those crops or forests that depend on upward water flow within their capillary fringe. At the same time, increasing temperatures increase evapotranspiration and, hence, decrease plant-available water

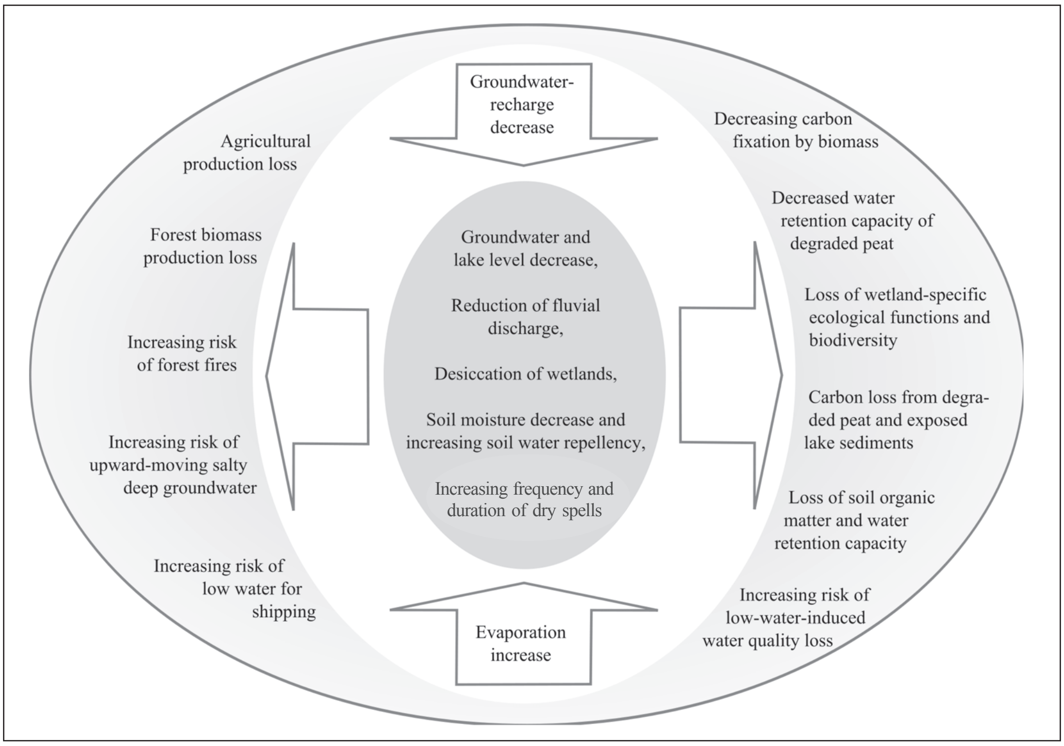

Fig. 7 Overview of impacts linked to water balance changes in Brandenburg
Überblick der Auswirkungen von Wasserhaushaltsveränderungen in Brandenburg

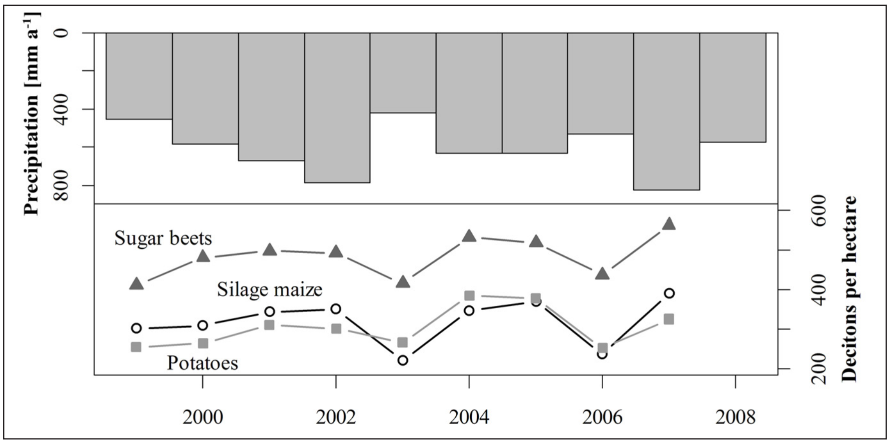

Fig. 8 Comparison of annual precipitation and annual agricultural production per hectare for potatoes, silage maize and sugar beets for the years 2000-2008 (source: Amt für Statistik Berlin-Brandenburg 2008b).
Vergleich von jährlichem Niederschlag und und jährlicher Produktion per Hektar für Kartoffeln, Silomais und Zuckerrüben für die Jahre 2000-2008 (Quelle: Amt für Statistik Berlin-Brandenburg 2008b)

within the soil. Agricultural sites with deep groundwater tables depend on rainfall; here, the temporal (seasonal) variance of rainfall is decisive and not the annual precipitation sums (*Werner* et al. 1997). *Krysanova* et al. (2008b) found statistically significant trends in total number of dry-spell days and frequency of dry spells for the lowland part of the Elbe basin. A climate change impact study suggests that, even under scenarios with both increasing temperatures and rainfall, drought stress decreases only slightly; meanwhile, under scenarios with greater temperature increases and rainfall decreases, drought stress will increase greatly and drought tolerance of simulated tree species will be exceeded (*Lindner* et al. 1997). Regionally downscaled climate change projections representing a range between wetter and drier realisations were used by *Holsten* et al. (2009) to evaluate future trends of available soil moisture conditions. According to the authors, a further decrease of average available soil water, ranging from -4 % to -15 %, was projected for all climate realisations up to the middle of the 21st century. Another impact from regional water scarcity is increased risk of forest fires. As illustrated by *Thonicke* and *Cramer* (2006), low-litter moisture conditions intensify the climatic fire danger concerning fire spread and resulting burnt area. These findings highlight the importance for representatives of agri- and silviculture management to be responsive to the trend of negative water balance in Brandenburg.

As a consequence of intensive drainage and agricultural use, the peatland soils of Brandenburg have become damaged, natural resources diminished and ecological functions changed from carbon sinks to carbon sources (*Okruszko* 1993, *Schwärzel* et al. 2002, *Zeitz* and *Velty* 2002, *Meier-Uhlherr* et al. 2010). Recent groundwater level lowering in Brandenburg has led to lake shrinking and further peat drainage and is, therefore, a potential driver of total organic carbon (TOC) losses from peatlands, exposed lake sediments and soils (*Landgraf* and *Notni* 2003). Climate scenario calculations (based on temperature change of +2°C and 20 % less rainfall during summer) indicate that CO_2-C release is mainly controlled by water-table depth, with greater release under deep groundwater table conditions (*Kluge* et al. 2008). *Kluge* et al. (2008) propose that, even if a groundwater table can be held at a shallow depth through controlled water management, peat loss and resulting CO_2-C loss can probably not be totally prevented, due to rising summer temperatures, increasing evapotranspiration and greater water demand. Drainage of former groundwater-influenced forest soils leads to soil organic matter loss and partly to a loss of the nutritive value of soils due to acidification. *Konopatzky* and *Menzel* (2007) showed that these drainage-driven changes of soil properties can be observed after a time-lag of 15 to 30 years. Lakes, peatlands and terrestrial soils are important sinks for carbon. Thus future trends of carbon dynamics, and therefore the regional water balance as well, will be of high social interest. Due to the still relatively low resolution of climate models, however, there is a lack of knowledge about these dynamics.

While temperature-induced prolongation of the vegetation periods suggests an increase in carbon fixation, reduction of groundwater levels and, hence, less soil moisture and more frequent summer droughts would probably decrease carbon uptake. *Holst* et al. (2008), for example, reported on a Scots pine forest in the southern upper Rhine plain, where the reduction of soil moisture below the permanent wilting point during a summer drought led to a 40 % reduction of net carbon uptake, mainly due to stomatal conductance and photosynthetic activity.

Drainage also changes physical properties of peat. Recent peat shrinkage has led, for instance, to a peat thickness loss of 65 cm in Brandenburg's Moosfenn (Zauche area) within 7 years (1995-2001, *Landgraf* and *Notni* 2003). If dry conditions persist for a long time, the shrinkage of peat soil becomes to a large extend irreversible (*Ilnicki* and *Zeitz* 2003, *Kluge* et al. 2008). This shrinking leads to a loss of the high water-holding capacity of the original peat soil (sponge effect) and, hence, the problem of water scarcity can be reinforced.

Groundwater lowering can result in decreased river discharge that can in turn have a negative impact on water quality. According to *Pusch* and *Hoffmann* (2000), flow reduction increases the travel time of water, leading to significant concentrations of suspended particulate organic matter due to phytoplankton growth. Subsequent aerobic microbial degradation of organic matter can cause heavy oxygen undersaturation that may negatively impact aquatic invertebrate fauna and fish.

Along the Havel River lakes chain (*Havelseenkette*) west of Berlin, salty deep groundwater can move upwards and contaminate overlying portable groundwater if the volume, and hence the pressure, of the overlying groundwater is reduced. According to modelling results, significant change in groundwater quality is expected if boundary conditions (low groundwater recharge and groundwater withdrawal) remain unchanged (*Nillert* et al. 2008).

5. Actual and Potential Social Responses

Regardless of whether the problem in question is climate change or increasing water scarcity in Berlin-Brandenburg, there are two categories of actual and potential social responses to environmental change: 1) adaptation and 2) mitigation. Whatever the responses turn out to be, the potential conflicts of different stakeholders (e.g. environmental protection, agri- and silviculture, water supply, urban development, recreation, cultural heritage, private property) should always be taken into consideration. As proposed by *Lahmer* (2004), *Werner* et al. (1997) and by *Hüttl* et al. (2000), for example, joint landscape planning is required in order to bring together the contrasting goals of land use, water management and environmental protection.

Adaptive responses to increasing water scarcity would include the enhancement of drought resistance through plant breeding or genetic engineering. Technical solutions for decreasing water needs while guaranteeing social and economic activities, such as improved irrigation systems (*Quast* and *Messal* 2010), can contribute towards adaptation in a sustainable way. Within this study we will focus on mitigative responses to water scarcity. These are responses that concentrate on water retention in the landscape in order to increase regional water storage. It is worth noting that all measures for increasing water storage mitigate not only the occurrence of droughts, but flood events as well (*Krysanova* et al. 2008a).

Water storage trends differ between Berlin and Brandenburg (*Merz* and *Pekdeger 2011,* this issue). The capacity to cope with drought years and low discharge from the Spree River were enhanced over the last decades by mitigative measures such as artificial groundwater recharge with purified surface water in areas next to waterworks, a reinfiltration obligation related to civil works influencing groundwater storage, and the introduction of groundwater pricing mechanisms (Senatsverwaltung für Stadtentwicklung Berlin 2008). In contrast to the metropolis of Berlin, the surrounding state of Brandenburg is characterised by agri- and silviculture. Therefore, with the exception of groundwater pricing mechanisms, Brandenburg needs to rely on mitigative measures to increase natural water retention that are very different from those in Berlin, including: land-use optimisation; wetland restoration, for example removal or modification of drainage systems; and reward mechanisms for groundwater recharge services. The best option might be to rely on a combination of different measures, as their positive effects may support each other, resulting in greater groundwater level increases compared to the sum of individual measures (*Mey* et al. 2008).

5.1 Land-use optimisation

Land-use optimisation is one possibility for retaining water in the landscape. According to model calculations for the glacially formed Polish lowland produced by *Ryszkowski* and *Kedziora* (1995) and *Werner* et al. (1997), real evapotranspiration is highest, and hence groundwater recharge by deep drainage is lowest, for coniferous forest. The authors reported that groundwater recharge in relation to other land uses follows a particular pattern: coniferous forest < deciduous forest < grassland < crop land < fallow land. This is in line with modelling results that suggest increasing evapotranspiration for the transformation of crop land into forest (*Wechsung* et al. 2000, *Wattenbach* et al. 2007) or decreasing evapotranspiration via a species change from pine to beech (*Müller* 1996) or pine to oak, but changes exhibit, however, a high degree of heterogeneity (*Wattenbach* et al. 2007). Simulation results by *Lasch* et al. (2005) and *Mey* et al. (2008) indicate that decreasing tree density increases annual percolation rates slightly. Under climate change scenarios this effect could, however, not compensate for the negative impact of climate change on groundwater recharge (*Lasch* et al. 2005). A lysimeter study of Scots pine stands in Brandenburg indicated, however, that the degree of canopy closure has no effect on deep drainage (*Müller* 1996); a decreasing canopy closure decreases tree interception, but at the same time better lighting conditions at the forest floor promote ground vegetation with its own interception, which outweighs the difference in tree interception. These results show the importance of taking into consideration side effects of land-use change, such as increasing ground vegetation, in deep drainage model calculations. Afforestation increases mean annual evapotranspiration, especially in the spring, and, due to the time lag between evapotranspiration and soil water response, recharge becomes strongly decreased in mid-summer, when water demand from vegetation becomes critical (*Wattenbach* et al. 2007). In Brandenburg, forest transformation towards more natural, stable and site-adapted forests has already begun. The unbalanced age structure of Brandenburg's forests, with a dominance of 41-60 year old trees, will be adjusted during the coming decades (*Müller* 2000, BMELV 2002). This will allow for a continuous water yield from forested watersheds, as young trees with low and older trees with high water demand will come into balance (*Müller* 1996). In Brandenburg, forest conversion measures are planned to reduce coniferous forest from 75 % to 42 % and increase mixed forest shares from 11 % to 41 % by 2045 (*Müller* 2000). Simulation models promise great effectivity of forest transformation on groundwater recharge (*Mey* et al. 2008, *Natkhin* et al. 2010). A chronosequence study indicated that, after three decades, this practice results in a noticeable improvement of humus forms and increased infiltration rates that might result in decreased overland flow on water repellent soils (*Bens* et al. 2006, *Bens* et al. 2007).

Modelling results suggest that the influence of land-use change on immediate runoff and flood generation is greater for convective rainfall with high rainfall intensities than for frontal activity rainfall (*Bronstert* et al. 2003b, *Lüscher* and *Zürcher* 2003). It is expected that the frequency of convective rain storms over northeast Germany will increase (*Mölders* 1998, *Conradt* et al. 2007). Therefore the increase of infiltration capacity might be a positive side effect of forest transformation with an increasing relevance in future.

Even management strategies for crop land are able to increase water retention in the landscape. While cereals in comparison to root crops and grass are most influenced by changing water supply (*Schindler* et al. 2007), the influence of crop type and crop rotation on deep drainage in Central Europe is great for wet soil-moisture conditions, but negligible if soil moisture is the limiting factor for biomass production (*Schindler* et al. 1997). According to *Werner* et al. (1997), the small influence of crop type on total evapotranspiration in Brandenburg can be explained by the fact that annual rainfall is relatively evenly distributed, with a maximum in the summer months. These authors claim that in regions with rainfall maxima in spring or autumn, evapotranspiration of winter grain and root crops can differ considerably, if the peaks of water demand coincide with periods of no rainfall. Cultivation intensity has, however, only a minor influence on evapotranspiration differences (*Frede* 1995). But if reduction of agricultural land use is understood as a temporary set-aside, then simulation results suggest that evapotranspiration will be lowered, while taking land near river courses out of arable agriculture has the opposite effect (*Wechsung* et al. 2000). *Wechsung* et al. (2000) suggest that by temporary set-aside evapotranspiration will be lowered for all soil types, while runoff and interflow increase for more loamy soils and groundwater recharge increase for sandy soils. These findings propose that sandy soils should be managed extensively for groundwater recharge, while the more fertile loamy soils could be used more intensively as crop land. Additionally, *Wessolek* and *Asseng* (2006) recommend using poor water-holding loamy sand soils for water recharge purposes rather than silty soils with higher water storage capacity, due to simulation results indicating that a trade-off between deep drainage and grain yields can be controlled through N management.

These research findings illustrate that, by means of adequate land-use strategies and appropriate site selection, it is possible to counteract water scarcity.

5.2 Wetland restoration

The former water retention function of peatlands, leading to a balanced discharge regime, has been severely limited by melioration efforts in Brandenburg. Based on a 'business as usual' scenario, *Schultz-Sternberg* et al. (2000) predict a loss of about 85 % of current peatlands by 2035. The implementation of nature restoration projects could, however, avert this danger (*Landgraf* 2010).

The most important project in terms of spatial extent is the Uckermärkische Seen project (*Mauersberger* 2010), funded through a national program for an operating time of 14 years (1997-2010) and with a total budget of 18 million Euros. The project area is situated in northern Brandenburg's Uckermark region and covers an area of 250 km². One aim has been to stabilise the water balance within the project area and to enable the protection of still intact lakes, peatlands and forest swamps. After land purchases (50 km²) the main measures aimed to reduce surface runoff and increase the water levels of lakes, kettle holes, groundwaters and peatlands as well as to restore originally drainless depressions by removal of artificial drains. Such measures include the installation of river-bottom slides in ditches or the removal of surface and subsurface ditches.

Rewetting of degraded peatlands in northeastern Germany, with a mean annual precipitation of 500-600 mm, is difficult but possible, as illustrated by *Richert* et al. (2000), using a border irrigation technique under conditions with a continuous slope, a deep peat layer with low hydraulic conductivity and a water reservoir with a level above the surface of the fen. The authors conceded, however, that in dry years groundwater levels unavoidably fall during the summer months and lower water levels increase decomposition immediately, adversely affecting renewed peat accumulation. Irreversible shrinkage of peat, resulting in low hydraulic conductivity and hydrological changes in the catchment, often make it impossible to restore the hydrological conditions of the former peat-accumulation system (*Okruszko* 1993, *Schwärzel* et al. 2002, *Zeitz* and *Velty* 2002). According to *Trepel* and *Kluge* (2002), for peatlands that are linked to rivers it is only possible to restore surface flow on top of the peat, by raising river water levels that result in a shallow lake system. This limnic stage is a drawback in the genesis of a valley, but essential for the restoration of wetlands and the later semi-terrestrial stage of peat accumulation. Such a drawback was described in detail for the Moosfenn, near Potsdam, by *Landgraf* and *Notni* (2003). According to these authors, this kettle-hole mire experienced a drought, with tree expansion and peat degradation, at the beginning of the late Subatlantic (approx. 900 years B.P.), flooding to 1.5 m above surface level at the beginning of the late Middle Ages, and the development of a new sphagnum moss cover afterwards.

Rewetting projects are dependent on a water surplus from a positive water balance, but water scarcity is common in Brandenburg. Therefore the use of municipal wastewater for minerotrophic peat-soil rewetting was suggested as an alternative for northeastern Brandenburg (*Wichtmann* and *Timmermann* 2001, *Velty* et al. 2006). During a four-year study, *Velty* et al. (2006) were able to demonstrate that the quality of discharge water was not adversely affected by the application of wastewater containing nutrients. Peat soil cannot, however, be used for continuous phosphorous retention since sorption is limited over the long term.

Despite several peatland protection programs that have been set in motion since 2005, a big breakthrough for peat protection in Brandenburg has not taken place yet (LUA Brandenburg 2009, *Landgraf* 2010).

5.3 Reward mechanisms

Landscapes perform a variety of ecosystem services, such as food production, agricultural commodity production, wildlife habitat, water and air purification, buffering of weather conditions and recreation. In water-scarce areas such as Brandenburg, the ecosystem services of groundwater recharge and water storage become evident. Already a decade ago *Werner* et al. (1997) suggested to create economic incentives to reward groundwater recharge under agricultural land, because recharge is greater under crop land than under grassland or forest. The authors point out, however, that the potentially produced water needs to meet certain quality standards. In addition, this approach of rewarding groundwater recharge only makes sense if the respective land is not influenced by artificial drainage at the same time. Another approach is to create a state-administered financial incentive system for ecological conservation and agricultural production that compensates farmers for income losses. *Kalettka* et al. (2001) present an example of how such a financial incentive system can be worked out, proposing that the prevention of degradation of small glacial depressions (kettle holes, *Sölle* in German), which are ecologically important as habitats and matter sinks, would result in farmers' gross margin losses of between 3 and 221 EUR per ha, depending upon the management practices employed.

Rewarding mechanisms for ecosystem services with regard to water retention in landscapes have not yet been realised in Brandenburg. In 2001, however, the first funding directive (*Förderrichtline Landschaftswasserhaushalt* in German) to improve the regional water balance in Brandenburg came in force. Today's relevant version, from 2007, includes the aim of improving the management of water resources (*Jörns* et al. 2010). The respective measures should target 1) a sustainable improvement of water retention within the landscape, 2) an increase of groundwater recharge, 3) the promotion of soil functions, and 4) sustainable water retention and reservoir management.

6. Conclusions

The deterioration of the water balance situation, in the form of a deficit problem, is apparent over large areas of Brandenburg, although the causes and impacts are spatially heterogeneous. Considering the *published* data on water balance changes with compiling focus on Brandenburg, only an often repeated reference to a few, mostly older, studies can be made (e.g. LUA Brandenburg 2000, *Landgraf* and *Krone* 2002, *Bronstert* et al. 2003a, *Gerstengarbe* et al. 2003). In particular, current *empirical* studies of local to regional focus, containing both broad databases and complex data interpretation (for accordant references see the sections above), are comparatively rare and, if available, are concentrated in only a few regions (e.g. the Schorfheide and Lower Lusatia area). Moreover, it seems that the complexity of disciplinary perspectives on this regional water shortage problem and its economic and ecological consequences – comprising contributions, for example, from hydrology/water engineering, agriculture, forestry, landscape ecology, vegetation science, nature conservation, physical geography and limnology – have so far hardly ever been compiled. Thus, for identification and explanation of current water balance changes and their effects, further multidisciplinary research efforts at different scales, including interregional comparisons, are required. Also within the field of hydrology cross-disciplinarity is required. The close hydrologic interaction of lakes with groundwater strongly suggests the need for regional-scale coupled surface water – groundwater models that could be run for different climate change and land use scenarios.

Changes in groundwater and lake levels develop slowly, and so do their respective impacts. As outlined above, decreasing groundwater levels and shrinking lakes in the Berlin-Brandenburg area are already having multiple impacts on ecosystems and society, which most probably will be increasing in the future. In particular, production declines in agri- and silviculture might have seriously negative economic impacts on the region, if arising market opportunities are not perceived and exploited (e.g. *Wechsung* et al. 2008). *Wiggering* et al. (2008) point out that predictions about climate-induced yield declines are often based on the unlikely assumption of unchanging management strategies, unchanging crop distribution structures and the absence of breeding progress with regard to drought resistance. This highlights the need for both mitigation of and adaptation to decreasing groundwater levels and fluvial runoff in Brandenburg.

The impacts summarised in this study provide a systematic insight into already existing and future environmental modifications which society might adapt to or attempt to counteract. Environmental change models are based on temperature and precipitation time series, which result from climate simulations. As of yet, simulations of future climate scenarios in Brandenburg can only provide satisfactory results, the kind which can be used for planning or water management purposes, for mean air temperature (increase) and not for precipitation (*Bronstert* et al. 2003a). Likewise, empirical climate data show significant (increasing) trends only for temperature, but not for precipitation (*Gerstengarbe* et al. 2003). Several climate impact studies, however, limit their simulations to scenarios with increasing temperature and decreasing precipitation. As future precipitation trends are unknown, climate impact studies that could present results for scenarios with decreasing, increasing, and unchanged precipitation trends would be very helpful. Such an approach would provide sustained results that could be used in flexible adaptation strategies that would consider all alternative predictions, enabling quick responses to further gains in scientific knowledge.

This way of looking at the matter leads to the methodological question of whether recent science is really asking the right questions. As argued by *Hüttl* et al. (2000), the scientific questions generally asked during the forest dieback (*Waldsterben*) debate were too narrow. There might be some analogies between that debate and the current climate change debate. The discussion on the forest dieback phenomenon that went on for more than twenty years envisioned that the majority of forests in Central Europe would die out. Not only did the predictions not come true, but later scientists even discovered that forests were growing better than ever. Obviously, scientists were far from understanding the complex interrelationships between the various components of the ecosystems involved. The question to be asked was not 'How does atmogenic deposition influence forest ecosystems?', but more holistically 'How does human impact influence forest ecosystems?' and 'Which aspects of human influence are most significant in particular regions?' When transferring these insights to the current climate debate and its impacts on the regional water balance, a too-narrowly formulated question to ask would be 'How does climate change influence the regional water balance?' Rather, the situation needs to address questions such as 'How does human impact (including climate change) influence the regional water balance?' and 'Which aspects of human impact on water balance are most significant in which parts of a particular region?' In-depth local case studies should be compared in relation to 1) study area characteristics, such as underlying geology, pedology, topography, land use (history), water withdrawal and drainage, and with regard to 2) processes of water balance change. These questions could lead to spatial problem systematisation, so that regional adaptation strategies can be established.

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Summary: Water Balance Changes and Responses of Ecosystems and Society in the Berlin-Brandenburg Region – a Review

The climate change debate has increased the need for knowledge on both long- and short-term regional environmental changes. In general, these changes may often be a product of multiple causes, which complicates the separation of single driving forces. In this review we focus on current water budget changes within Germany's capital region, Berlin-Brandenburg, over the last 30 years. Available studies from a variety of disciplines (e.g. from hydrology, water engineering, landscape ecology, nature conservation) were analysed in order to (1) identify both local and regional hydrological changes, (2) reveal their potential causes, and (3) discuss responses of ecosystems and society. These studies show that the Berlin-Brandenburg region is widely characterised by decreasing groundwater recharge, leading to decreasing groundwater and lake levels as well as decreasing fluvial discharge. These trends result both from complex regional human impacts (e.g. long-term effects of hydromelioration and changes in forest composition) and more general climate warming. The observed and assumed (future) changes of the regional water balance have created, and will continue to create, multifaceted impacts on existing ecosystems and society (e.g. wetland drying, decrease of biodiversity, decrease of productivity of grasslands and forests, increasing conflicts of interests). Several efforts to respond to the regional water deficit problem have already been undertaken, comprising for instance land-use optimisation, wetland restoration measures and the reestablishment of mixed deciduous forests. In general, however, the reviewed regional material on this topic reveals that the number and complexity of empirical studies are still poor. Thus, for both the identification and explanation of current water balance changes and their effects, as well as for the development and implementation of adaptive strategies, further multidisciplinary research efforts at different scales, including interregional comparisons, are required. Furthermore, both the observation of hydrological changes and the evaluation of adaptive and mitigative responses require at least continuous or, even better, extended monitoring efforts.

Zusammenfassung: Wasserhaushaltsveränderungen und Reaktionen von Ökosystemen und Gesellschaft in der Region Berlin-Brandenburg – ein Überblick

Die Klimawandeldebatte hat zu einem erhöhten Wissensbedarf bezüglich lang- und kurzfristiger regionaler Umweltveränderungen geführt. Allgemein gesehen resultieren diese Veränderungen oft aus einer Vielzahl von Ursachen, was das Aufzeigen der dominierenden Einflüsse erschwert. In dieser Literaturübersicht konzentrieren wir uns auf Veränderungen des Wasserhaushaltes in der Hauptstadtregion Berlin-Brandenburg während der vergangenen 30 Jahre. Vorhandene Studien der verschiedensten Disziplinen (z. B. aus Hydrologie, Wasserbau, Landschaftsökologie, Naturschutz) wurden analysiert mit dem Ziel (1) lokale und regionale hydrologische Veränderungen zu indentifizieren, (2) deren potentielle Ursachen aufzuzeigen und (3) die Reaktionen von Ökosystemen und Gesellschaft zu diskutieren. Die Studien zeigen, dass die Region Berlin-Brandenburg weitläufig von sinkender Grundwasserneubildung gekennzeichnet ist, die zu einer Absenkung von Grundwasser- und Seespiegeln führt sowie zu einem verringerten Abfluss. Diese Trends resultieren aus komplexen regionalen anthropogenen Eingriffen (z. B. Langzeiteffekte der Hydromeliorationen und von Veränderungen in der Waldstruktur) und allgemein aus der Klimaerwärmung. Die beobachteten und angenommenen (zukünftigen) Veränderungen des Landschaftswasserhaushaltes haben zu facettenreichen Auswirkungen auf vorhandene Ökosysteme und die Gesellschaft geführt bzw. werden auch in Zukunft dazu führen (z. B. Austrocknung von Feuchtgebieten, Verlust an Biodiversität, Verringerung der Produktivität von Grünland und Wälder, Verstärkung von Interessenkonflikten). Zahlreiche Bemühungen, auf das Problem des regionalen Wasserdefizits zu reagieren, wurden bereits unternommen, einschließlich Landnutzungsoptimierung, Renaturierung von Feuchtgebieten und die Wiederherstellung von Laubmischwäldern. Allgemein gesehen kann jedoch aus der regionalen Literaturübersicht zum Thema gefolgert werden, dass Anzahl und Komplexität der empirischen Studien noch zu gering sind. Daher ist für die Identifikation und Erklärung von aktuellen Veränderungen der Wasserbilanz und deren Auswirkungen sowie für die Entwicklung und Umsetzung von Adaptationsstrategien mehr multi-

disziplinäre Forschung auf unterschiedlichen Skalen inklusive interregionaler Vergleiche notwendig. Weiterhin ist für die Beobachtung hydrologischer Veränderungen sowie die Evaluation von Anpassungs- und Verminderungsmaßnahmen wenigstens eine Weiterführung, oder besser, eine Ausweitung des Monitoring erforderlich.

Résumé: Modifications du régime hydrologique et réactions au sein des écosystèmes et de la société dans la région de Berlin-Brandebourg – une vue d'ensemble

Le débat sur le changement climatique a entraîné un besoin accru de savoir sur les changements environnementaux régionaux à longs et courts termes. En général, des causes multiples sont souvent à l'origine de ces changements, ce qui rend difficile la distinction des influences dominantes. Dans cette documentation bibliographique, nous nous concentrons sur les changements du régime hydrologique survenus ces trente dernières années dans la région de la capitale de l'Allemagne, Berlin-Brandebourg. Nous avons analysé les différentes études disponibles dans de nombreuses disciplines, telles que l'hydrologie, le génie hydraulique, l'écologie du paysage, la protection de la nature, dans le but (1) d'identifier les change-ments hydrologiques locaux et régionaux, (2) d'en révéler les causes potentielles et (3) de discuter des réactions au sein des écosystèmes et de la société. Ces études en question montrent que la région de Berlin-Brandebourg est largement caractérisée par une faible recharge des nappes phréatiques, ce qui conduit à un abaissement du niveau des eaux souterraines et des lacs ainsi qu'à un écoulement fluvial réduit. Ces tendances sont le résultat d'interventions humaines complexes et régionales (il s'agit par ex. des effets à long terme de l'hydromélioration et des modifications de la structure forestière); elles sont également à attribuer en général au réchauffement climatique. Les modifications observées et supposées survenir ultérieurement dans le régime hydrologique de la région ont causé et causeront à l'avenir des effets aux multiples facettes sur les écosystèmes existants et sur la société (comme par ex. l'assèchement des zones humides, la perte de la biodiversité, la baisse de la productivité des prairies et des forêts, l'augmentation des conflits d'intérêts). De nombreux efforts ont déjà été entrepris pour réagir au problème du déficit hydraulique régional, y compris par l'optimisation de l'utilisation des terres, la renaturation des zones humides et le rétablissement des forêts d'essences mixtes. Cependant, d'un point de vue général, nous pouvons déduire de la documentation bibliographique régionale sur ce thème que le nombre et la complexité des études empiriques sont encore trop faibles. Il y a ainsi nécessité de mener une recherche multidisciplinaire plus importante à des échelles différentes, en incluant des comparaisons interrégionales, afin d'identifier et d'expliquer les modifications actuelles du bilan hydraulique et leurs effets, et également afin de développer et de réaliser des stratégies d'adaptation. Par ailleurs, il est au moins nécessaire de poursuivre, ou mieux d'augmenter, les efforts de monitoring environnemental afin d'observer les changements hydrologiques et d'évaluer les mesures d'adaptation et celles prises pour l'atténuation des effets négatifs sur l'environnement et la société.

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