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• *Northeast Germany – Landscape Hydrology – Vegetation – Virtual water*

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The Potential of Land-Use Change to Mitigate Water Scarcity in Northeast Germany – a Review

Das Potential von Landnutzungsänderungen zur Minderung der Wasserknappheit in Nordostdeutschland – ein Überblick

With 6 Figures and 1 Table

Climate change is expected to increase water scarcity in northeast Germany. Land-use change is one of the options of mitigation that is intensely discussed in this region. This review aims at giving a compilation of existing data and modelling studies in order to investigate the potential and the limits of the land-use change approach.

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1. Introduction

Water is essential for life on earth as well as for human civilisation. It is a basic food for man, a primary means of agricultural and silvicultural production and an important means of industrial production. Rivers and channels form waterways for transportation of goods. Freshwater bodies and wetlands play a major role for biodiversity as well as for nutrient and contaminant retention in the landscape. Last but not least, lakes and streams form scenic landscapes that are highly attractive for recreation and tourism, especially in northeast Germany. Thus, any issues that are related to landscape hydrology attract wide interest in the public.

Lakes, wetlands and streams cover a substantial fraction of the lowlands in northeast Germany, that is, in the federal states of Mecklenburg-Vorpommern, Brandenburg, Berlin, and in the north of Saxony-Anhalt. Compared to the rest of Germany, annual rainfall is very low and air temperature during the growing season rather high, resulting in high evapotranspiration and small groundwater recharge. During the last three decades, substantially decreasing lake water and groundwater levels have been observed in many parts of the region (*Gerstengarbe* et al. 2003). As a consequence, lakes have been shrinking and small lakes, streams and wetlands have dried out. This has caused concern in the public as well as in water resources management, environmental agencies, and politics. Various options have been brought forward and discussed for mitigating water scarcity in northeast Germany.

Major consumption of incoming rainfall is by transpiration from agricultural fields and forests. However, substantial differences have been found between different types of land use as well as between different agricultural and silvicultural management strategies. Thus many mitigation strategies focus on reducing water loss via transpiration by land-use optimisation. This topic was addressed, among others, in the NEWAL-NET (*Natkhin* 2011) project which was established in 2005. It aimed at developing a management strategy for a sustainable development of forests in the lowlands of northeast Germany with regard to the predicted climate change, i.e., above all, decreasing availability of soil water and groundwater during the growing season. Some of the management options outlined there are based on different water use by different species. This paper benefits substantially from the work undertaken in this project.

Besides, it provides a review on a variety of experimental and modeling studies, scenario analyses and theoretical frameworks that have been developed both for northeast Germany and for other parts of the world. The latter applies especially to the virtual water concept that has been developed for irrigation cropping systems in Asia but is now discussed to be applied to northeast Germany as well (*Lischeid* 2010). The objective of the paper is to assess the opportunities and limitations of mitigating water scarcity by land-use and land management optimisation in northeast Germany.

2. Study Region: Geology, Soils, Climate, Hydrology, Agriculture

The German lowlands are part of the North German-Polish Basin which has been subject to subsidence and recurrent marine transgressions since the end of the Palaeozoic. Consequently, marine sediments like clay, sand and lime mud have been deposited. Total thickness of these sediments, especially in the northern part of the region, is a few hundred metres (*Lippstreu* et al. 1997, *Stackebrandt* and *Manhenke* 2002). However, the landform configuration has been shaped more recently during the Pleistocene with repeated advances of glaciers from the northeast and subsequent retreats. The terminal moraines now form the hilly regions between the extended lowlands of the former ice marginal valleys. The latters stretch from the southeast to the northwest, or from east to west, respectively, along the former flow direction of the melting water that discharged to the North Sea (*Fig. 1*). Altitude of these lowlands usually is a few tens of metres above sea level, whereas it exceeds 100 m above sea level in parts of the terminal moraines region. Consequently, topographic gradients and river water flow velocities are very low in the lowlands. Due to the young age of the landscape and the very shallow topographic gradients at larger scales, drainage basins are not well developed. Thus, many lakes and wetlands have been connected to the stream network only by man-made ditches.

Soils are mostly sandy in most parts of the region. More loamy soils are encountered in fluvial sediments and in the vicinity of ground moraines, especially in the northern part of the region. In the lowlands peaty soils and fens are abundant. However, both soils and deeper sediments are characterised by very high spatial heterogeneities and short spatial correlation lengths.

Compared to other parts of Germany, precipitation is fairly low and air temperature rather high. Annual mean rainfall in Brandenburg and Berlin is about 610 mm per year (*Gerstengarbe* et al. 2003, *Lahmer* and *Pfützner* 2003, *Dannowski* and *Steidl* 2000). Annual mean temperature 1951-2000 was between 7.8°C and 9.5°C (*Gerstengarbe* et al. 2003), with lower temperatures in the north com-

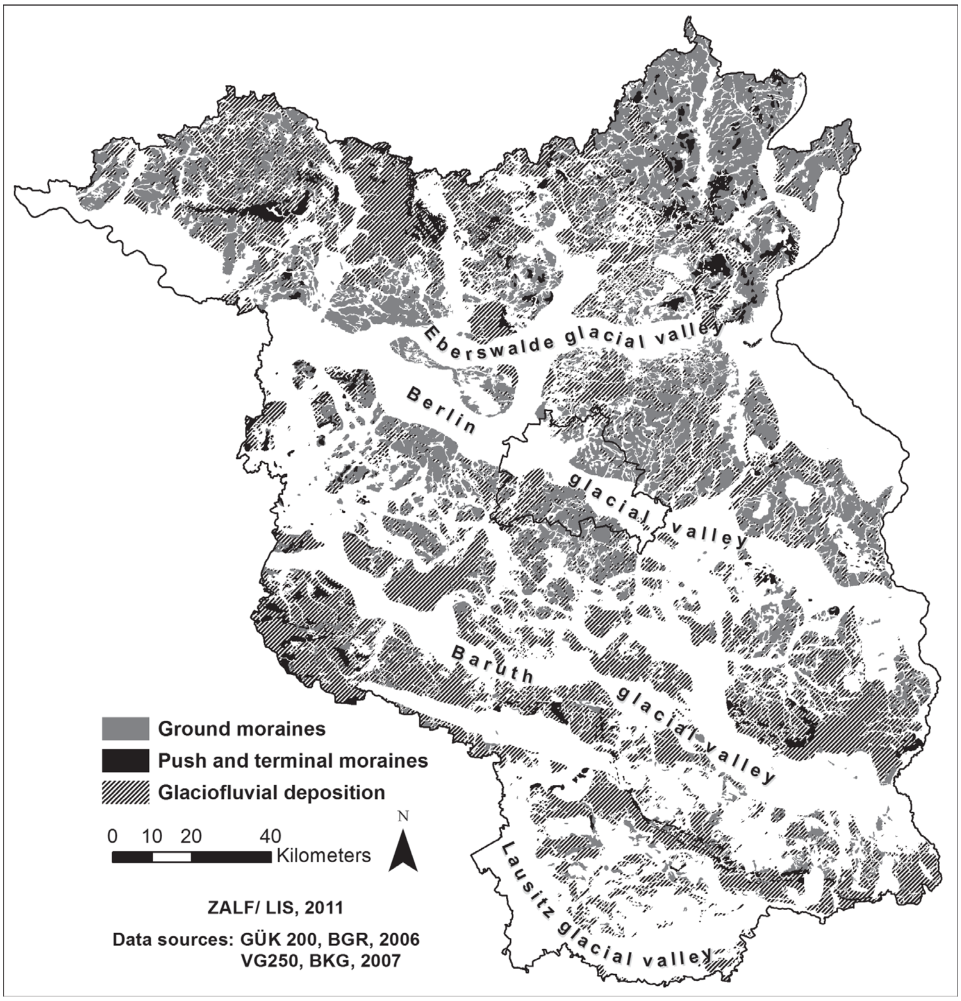

Fig. 1 Topography of Brandenburg (by courtesy of *Uwe Heinrich*)
Topographie Brandenburgs (zu Verfügung gestellt von Uwe Heinrich)

pared to the south. Evapotranspiration amounts to 510 mm per year roughly, leaving 100 mm per year as runoff. About 80 mm per year occurs as groundwater recharge (*Gerstengarbe* et al. 2003, *Lahmer* and *Pfützner* 2003, *Dannowski* and *Steidl* 2000). However, groundwater recharge is negative in the lowlands where the groundwater level is close to the surface. In contrast, it amounts to more than 200 mm per year in parts of the hilly regions (*Lahmer* and *Pfützner* 2003).

Especially on sandy soils with very small water holding capacity, evapotranspiration highly depends on depth to groundwater. It is less than 2 m in 39 % of the area in Brandenburg and Berlin, and more than 5 m in 60 % of the area (*Lahmer*

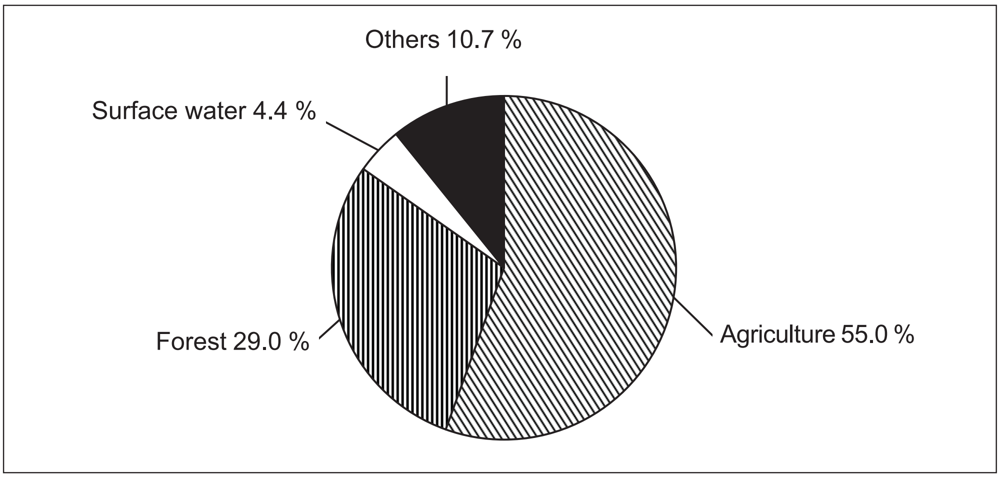

Fig. 2 Land use in the federal states of Mecklenburg-Vorpommern and Brandenburg in 2004. Data: *Deggau* 2006 / *Landnutzung in Mecklenburg-Vorpommern und Brandenburg 2004. Daten: Deggau 2006*

and *Pfützner* 2003). This bimodal distribution reflects the fraction of lowlands in the former ice margin valleys on the one hand, and the hilly regions on the other hand, where even tree roots do not have access to groundwater resources.

Most of northeast Germany is covered by the two federal states of Mecklenburg-Vorpommern and Brandenburg. Here, more than half of the area is used by agriculture (*Fig. 2*), where arable land prevails. Another 30 % is covered by forests. Surface water covers another 4.4 %. Settlements, transport installations and other infrastructure make up another 11 % of the area – and nearly 70 % in Berlin (*Deggau* 2006).

3. The Virtual Water Concept

Water consumption by plants competes with alternative water usage, eg., as drinking water, as means of industrial production, or as the basic resource of wetland and freshwater habitats. The water content of agricultural products is usually only a minute fraction of the total water consumption during the growth of the plants. The production of 1 kg of crops requires some thousands of litres of water. Thus, any calculation of water consumption for meat production has to account for that of fodder crops, resulting in even higher figures (*Hoekstra* 2003, *Rockström* 2003). Total water consumption during the production process, including water content of the products, is summarized as the "virtual water" content of the products. It is calculated by dividing total water consumption by crop yield (*Hoekstra* 2003).

This concept was developed by *Allan* (1993, 1994) to account for water consumption in extensively irrigated fields in the Middle East. Production and export of, e.g. cotton, thus implies export of virtual water which should be considered in economic assessments of resources allocation in arid regions (*Allan* 1994, *Liu* et al. 2009).

The virtual water concept has gained great attention and has been considerably extended since it was first formulated, e.g. it has turned out to be useful to differentiate between different types of water resources: “Green water” means rainwater that infiltrates into the soil and feeds the plants. In contrast, “blue water” denotes irrigation water that needs to be pumped from groundwater or surface water. Third, “grey water” is waste water that people want to get rid of, which, however, can be used for irrigation (*Liu* et al. 2009).

This distinction addresses a crucial point, that is, the opportunity costs of the water used (*Liu* et al. 2009): Opportunity costs usually are the highest for blue water, because this may be used for other purposes, e.g., for drinking water supply. For grey water, in contrast, opportunity costs may even be negative, when no alternative usage is possible without additional expensive treatment. In addition, using grey water for irrigation makes efficient use of the water’s nutrient load and of the purification potential of the soil.

On the other hand, however, increasing irrigation may even lower the virtual water content: Applying irrigation to agricultural crops at the end of the ripening season can ensure ripening of the crops that otherwise die off. Thus, a rather small increase of water consumption via irrigation may result in an overproportional increase of crop yield (*Rockström* 2003, *Liu* et al. 2007).

4. The North East Germany Case Study: Land Use and Land Management Options

In northeast Germany, by far the largest fraction of rainwater is consumed by plant transpiration in forests, arable land and grassland. About 510 mm per year out of 610 mm per year of precipitation is lost by evapotranspiration, where transpiration dominates by far (*Gerstengarbe* et al. 2003, *Lahmer* and *Pfützner 2003, Dannowski* and *Steidl 2000*). At a global scale, the largest fraction of water resources is used for agricultural production (*Rockström* 2003). Different crops and species differ substantially with respect to rain consumption. Thus, land-use change and land management are considered as a major tool for reducing water consumption in water-scarce regions.

However, it has to be taken into account that other factors play an important role for evapotranspiration as well. For example, effects of geomorphology and scale effects must be considered (*Cuevas* et al. 2006, *Strayer* et al. 2003, *Herlihy* et al. 1998). Besides, the water holding capacity of the soil, surface runoff depending on soil properties as well as on soil tillage and rainfall intensity, or seasonal patterns of rainfall account for much of the heterogeneities in the available data. In addition, nonlinear interactions have to be accounted for. For example, water holding capacity and rooting depth are negligible as long as precipitation or irrigation occur evenly throughout the growing season. In contrast, soils may develop a hydrophobic topsoil layer that impedes rainwater infiltration, depending on the properties of soil organic material and the length of dry periods (*Doerr* et al. 2000). Comprehensive data sets and sophisticated models are required to account for these effects.

4.1 Lakes and wetlands

Northeast Germany is characterised by a large number of lakes, kettle holes (*Kalettka* 1996) and wetlands. Evapotranspiration from these water bodies usually is highly overproportional. For example, *Herbst* and *Kappen* (1993) found that evapotranspiration of a reed stand in a north German lake was about 187 % compared to evaporation from the lake surface. *Behrendt* et al. (2001) observed an exponential increase of annual evapotranspiration with decreasing depth to groundwater at Paulinenaue, northwest of Berlin. Here, annual evapotranspiration of a reed stand (*Phragmites australis*) was about 2000 mm per year, which was more than threefold the mean annual precipitation. Similarly, evapotranspiration of wetland plants determined in situ by *Dannowski* and *Balla* (2004) and *Müller* et al.

Tab. 1 Runoff for various types of land use in Brandenburg and Berlin under present-day climatic conditions (*Dannowski* and *Steidl* 2000) / *Abfluss für verschiedene Landnutzungstypen in Brandenburg und Berlin unter aktuellen klimatischen Bedingungen (Dannowski and Steidl 2000)*

	Entire year	**Dormant season**	**Growing season**
	[mm yr^{-1}]		
Uncultivated land	309	96	213
Urban areas	244	94	150
Agricultural land	127	75	52
Forest	56	94	-38
Surface water	-103	133	-236

(2005) exceeded 1000 mm per year,which was roughly equal to twice the annual precipitation.

4.2 Forests

In general, evapotranspiration is highest in coniferous forests, less in deciduous forests, and even less on arable land and grassland. Differences are mainly due to varying length of the period of physiological activity, varying aerodynamic roughness of the vegetation structure, and varying rooting depth (*Brown* et al. 2005). *Schindler* et al. (2008) investigated different land-use forms at Müncheberg, east of Berlin, from 1995 through 2005. Annual seepage flux under arable land and grassland was nearly identical with 175 mm per year and 174 mm per year, respectively. In contrast, mean annual seepage flux in a pine forest (*Pinus silvestris*) was only 15 mm per year, that is, less than 10 % compared to the aforementioned.

Correspondingly, the effect of land use on the water balance is reflected in numerous modeling studies. Converting forests into arable and grassland increased runoff in the adjacent stream by 9 % in the model study by *Fohrer* et al. (2001). Converting greenland to forest and arable land decreased runoff by 3 %. Runoff was modelled for the federal states of Brandenburg and Berlin by *Dannowski* and *Steidl* (2000), using the ABIMO model. The difference between uncultivated land on the one hand and surface water on the other hand was about 400 mm per year (*Tab. 1*). In this study, evapotranspiration exceeded precipitation during the growing season in forests and lakes. For the latter, the surplus of precipitation during the dormant season could not compensate for high water losses in summer. However, runoff exhibited substantial spatial variability, depending on local meteorological conditions. Thus, e.g., even some of the pine forests exhibited negative water budgets where precipitation was fairly low.

Past land-use changes are likely to have exerted a major impact on water budgets as well. Based on a comprehensive data set, *Bork* et al. (1998) conclude that the proportion of forested area in Germany decreased from 90 % to 15 % between the early Middle Ages and the beginning of the 14th century. The corresponding increase of runoff was assessed to be 120 mm per year. Given that annual runoff is only about 100 mm per year today in northeast Germany, this change must have had consid-

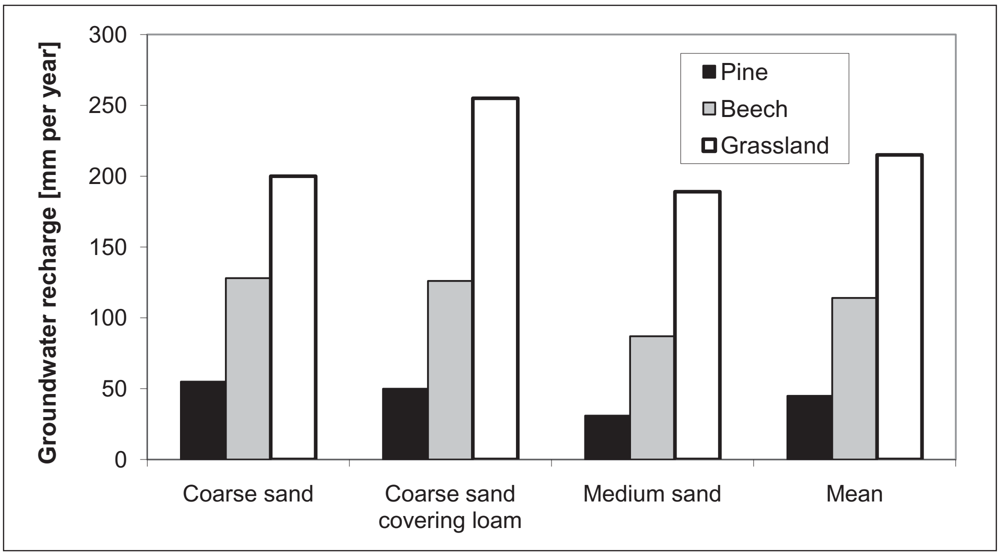

Fig. 3 Simulated annual mean groundwater recharge for different land-use scenarios and soils in the Schorfheide region 1952-2007 (source: *Natkhin* 2011) / *Simulierte jährliche Grundwasserneubildung für verschiedene Landnutzungsszenarien und Böden in der Schorfheide 1952-2007 (Quelle: Natkhin 2011)*

erable effects on lake water levels, extension of wetland areas and river runoff.

Natkhin (2011) studied the effect of land-use change in the Schorfheide region for different soils, using the WaSiM-ETH model. Meteorological data from the region covering the 1952-2007 period were used, and typical soils were considered. Mean annual groundwater recharge amounted to 45 mm per year for pine forests, 114 mm per year for beech stands, and 215 mm per year for grassland (*Fig. 3*). Differences between types of land use were most pronounced for coarse sand overlying loam, illustrating the interplay between the water holding capacity of the soil and the rooting depth.

Correspondingly, *Bolte* et al. (2002) investigated the effect of replacing the actual forests in Germany by natural forests with a higher proportion of deciduous trees. In their scenario, the resulting increase of seepage flux was only 16 mm per year for all of Germany. However, the effect was much larger in northeast Germany due to limited water resources. In another model study, *Wattenbach* et al. (2007) found that replacing all pine forests in the federal state of Brandenburg by deciduous forests would increase mean groundwater recharge by 4.5 %. *Mey* and *Pfützner* (2008) conclude from their results that replacing pine stands by a beech forest in the vicinity of the Luch lake, 30 km southeast of Berlin, would increase the groundwater level by 0.4 m.

Fröhlich et al. (2008) investigated the effect of various measures on the groundwater level in a 442 km^2 area in the Schorfheide region in Brandenburg, using a complex hydrological model. Reducing pine forests by 8 % and increasing oak forests by 10 %, as suggested in forest management plans, hardly had any impact on groundwater levels. In contrast, replacing the existing forests by potential

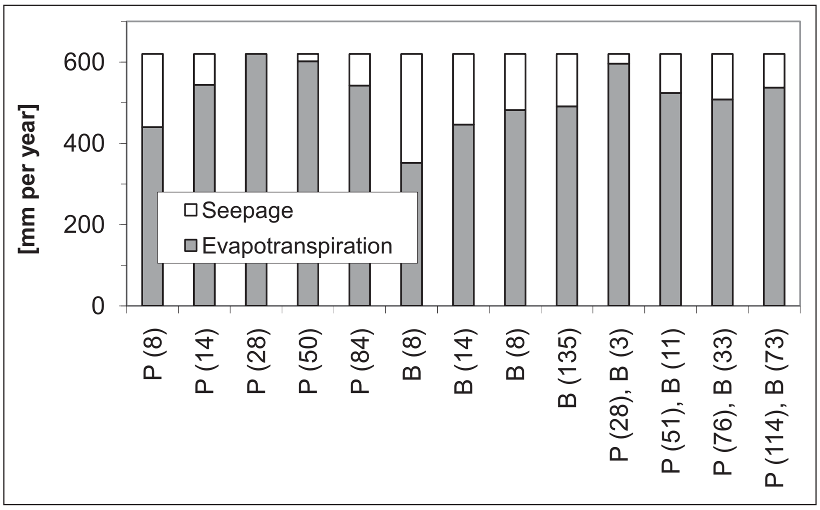

Fig. 4 Water budgets of different forests at a site close to Eberswalde with 620 mm per year mean annual precipitation. "P" denotes pine, "B" beech. In addition, tree age [years] is given in brackets. Data provided by *Müller* 2002 / *Wasserbilanz für verschiedene Forstbestände nahe Eberswalde mit 620 mm/a Jahresniederschlag. „P" steht für Kiefer, „B" für Buche. Außerdem ist das Baumalter [Jahre] in Klammern angegeben. Datengrundlage: Müller 2002*

natural vegetation with a high proportion of oak and beech increased mean groundwater recharge by 63 mm per year. To that end, pine forests had to be reduced by 58 %, beech forests to be increased by 34 %, and mixed pine and beech forests by 21 %.

In addition to tree species, tree age and understory vegetation play an important role. A comprehensive experimental data set was presented by *Müller* (2002). In general, an increase of evapotranspiration with tree age was observed for pine and beech stands. However, evapotranspiration decreased in a later stage in the pine stand – a process which had not been observed in the beech stand (*Fig. 4*). In addition, the mixing ratio of pine and beech had nonlinear effects on the total stand evapotranspiration.

The extensive deforestation during and after World War II, and intensive afforestation thereafter, is reflected by the age distribution of pine forests in Brandenburg. In addition, the fraction of trees less than 20 years old is rather small due to enhanced planting of deciduous trees (*Müller* 2007). This would result in a long-term increase of groundwater recharge, if boundary conditions remained stable. On the other hand, understory vegetation changed considerably since the 1970s. Due to increased atmospheric deposition, a nitrophilic understory established in many pine forests (*Hofmann* 1995), presumably increasing both evapotranspiration and interception.

4.3 Crops

Corresponding to different forest types, crops differ substantially with respect to water use, too. This information can be used to develop and optimise adaptation strategies in the water-scarce region of northeast Germany. However, differences between crops are usually smaller

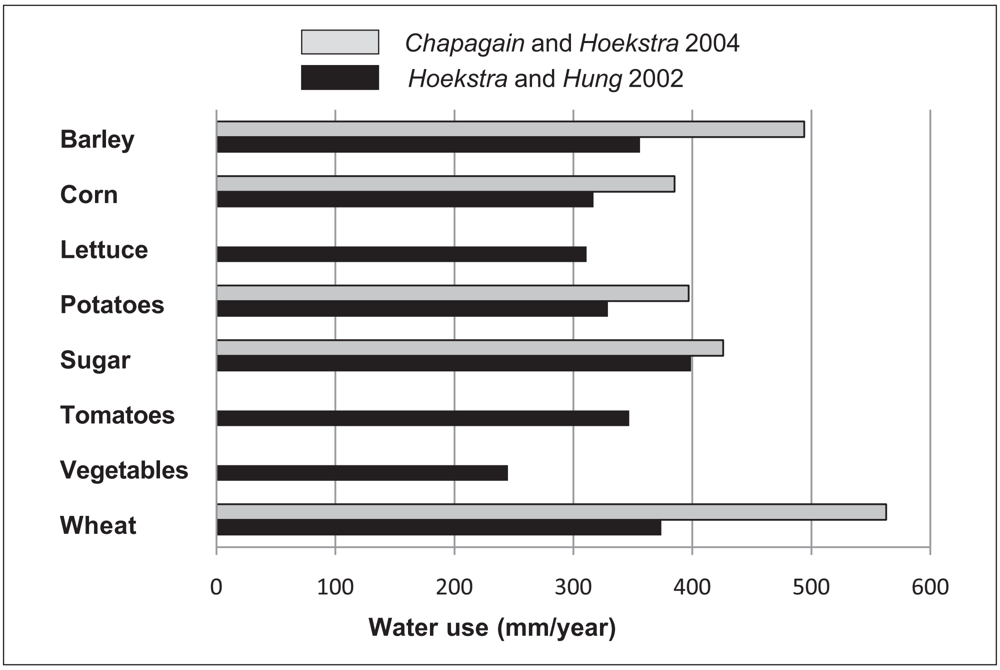

Fig. 5 Assessment of annual water use by different crops in Germany in two studies / *Abschätzung des jährlichen Wasserverbrauchs durch unterschiedliche Feldfrüchte in Deutschland in zwei verschiedenen Studien*

compared to those between forests on the one hand, and arable land or grassland on the other hand. As a consequence, additional effects of soil type, depth to groundwater level, soil tillage, seasonal patterns of precipitation, fertilisation and pest control need to be considered as well (*Liu* et al. 2007, *Hoekstra* and *Hung* 2002).

Due to limited precipitation and sandy soils with poor water holding capacity water is one of the key minimum factors for plant growth and plant production in northeast Germany. Investigating a typical crop vegetation scheme including winter wheat, sugar beet, summer barley and pea in the Uckermark region in the study period 1992-1999, *Schindler* et al. (2001) found that the total amount of summer precipitation (April-September) explained most of the interannual variance of crop production. In contrast, fertilisation had hardly any effect on crop yield. However, this is not necessarily valid for other regions of Germany.

These side effects are rarely considered when crop water use is assessed, e.g., within the framework of the virtual water concept. Correspondingly, the data given in the literature exhibit substantial variance. For example, figures for annual water use by wheat and barley in Germany differed by up to 150 mm per year in two different studies (*Fig. 5*). In general, differences between crops in each of these studies are smaller compared to those between these studies. In another assessment by *Hoekstra* (2003) water use by maize varies by a

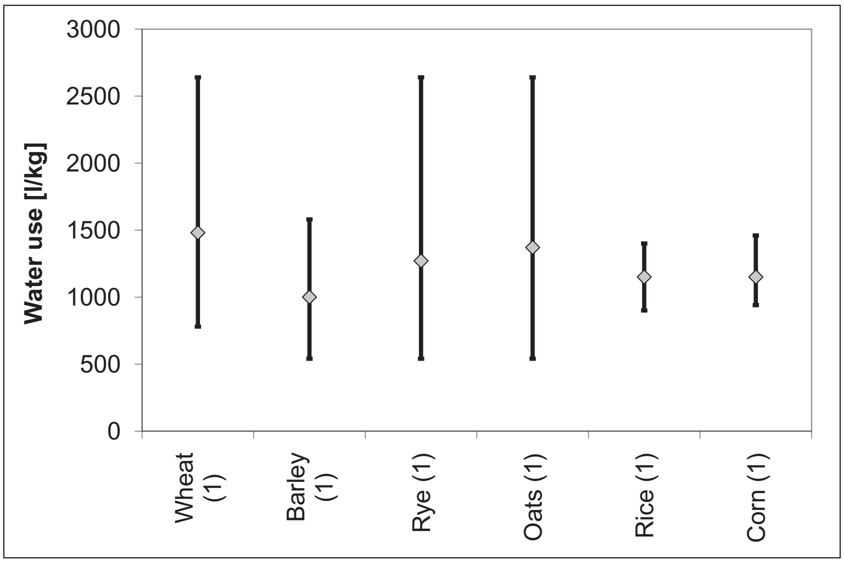

Fig. 6 Water use divided by crop yield by different cereals on non-irrigated fields (mean and range) compiled by *Rockström* (2003) for the tropics (rice; corn, i.e. maize) or the mid-latitudes (other cereals), respectively. Data provided by (1) *Rockström* et al. (1999) and *Doorenbos* and *Kassam* (1986)

Auf den Ertrag bezogener Wasserverbrauch verschiedener Getreidearten ohne künstliche Bewässerung (jeweils Mittelwert und Spannweite) für die Tropen (Reis, Mais) und mittleren Breiten (alle anderen Getreidearten), zusammengestellt von Rockström (2003) auf Basis der Daten von (1) Rockström et al. (1999) und Doorenbos und Kassam (1986)

factor up to four. However, those figures apply to different regions with different climate.

Differences between single crops are partly due to varying length of the required growing period. Thus, water use by vegetables and lettuce is very low, and that of sugar beet very high (*Fig. 5*). On the other hand, different metabolic pathways in so-called C3 and C4 plants play a role. Only the latter, like, e.g., maize, can assimilate carbon during the night and during dry periods when stomata are closed. In contrast, C3 plants have to take up CO_2 during daytime when transpiration water loss is high.

Besides these effects, there is some doubt whether the maximum possible water use efficiency, related to crop yield, does even differ systematically between crops and regions. In the data set compiled by *Rockström* (2003) water use efficiency for various cereals differed by a factor of five (*Fig. 6*). However, he did not find any systematic differences between climatic regions. He concludes that higher transpiration in dry and warm regions is compensated for by higher productivity. The author ascribes lower water use efficiency found by numerous studies in dry warm regions to higher non-productive water loss in gappy crops or yield losses, e.g., due to water scarcity at the end of the growing period. Considering only optimal growing conditions, water use efficiency seems to converge to 1300-1500 l kg^{-1} for various cereals irrespective of the climate region (*Rockström* 2003). *Rockström* concludes that this figure seems to reflect a global physiological minimum, resulting in an absolute minimum water use for food production of 1300 m^3 per year per capita.

Assessing the global water budget based on a crop growth model, *Liu* et al. (2009) conclude that about 81 % of global crop production is based on green water, that is, rainwater. This figure is close to the 85 % given by *Rost* et al. (2008). In fact, irrigation is restricted to about 20 % of arable land (*Rockström* 2003). Here, more efficient techniques like drip irrigation or rainwater harvesting should be applied which would reduce the total amount of blue water considerably (*Liu* et al. 2009). Evaporation from the soil can be further reduced by, e.g., mulch-till and hedges that reduce wind velocity.

Virtual water import through the import of food and fodder to Germany exceeds virtual water export by far. According to *Hoekstra* and *Hung* (2002) and *Chapagain* and *Hoekstra* (2003) net import of virtual water amounts to $12.2 \cdot 10^9$ or $13.1 \cdot 10^9$ m^3 per year, respectively. In contrast, net export is only $1 \cdot 10^9$ m^3 per year according to *Zimmer* and *Renault* (2003) which means that import is about twelve or thirteen times the value of export.

Sonnenberg et al. (2009) assess the total annual consumption of virtual water by agricultural products in Germany, including meat, to be equal to $117.6 \cdot 10^6$ m^3 per year. Roughly half of this virtual water is imported, with coffee, cocoa, oil seeds, cotton, pork, soybeans and beef being the most important products. Agricultural products sum up to 73.3 % of the total virtual water import in Germany. The rest is ascribed to industrial products and drinking water withdrawal (*Sonnenberg* et al. 2009).

5. Climate Change Effects

Water resources management has to take into account the expected climate change of the next decades. Depending on the selected scenario of greenhouse gas emissions, global climate models differ with respect to the long-term increase of air temperature. Greenhouse gas emissions measured over the last decades correspond to the more pessimistic scenarios for which the models predict an increase of air temperature of about 1K in the next 50 years (*Solomon* et al. 2009).

Spatial resolution of the global circulation models is not sufficient to assess regional effects. Thus, results of the global models need to be scaled down by regional climate models. A dynamic scaling approach is followed by the REMO model (*Jacob* et al. 2008). It is based on a weather forecast model with a detailed simulation of physical processes in the atmosphere at a 10 km resolution, using the output of global models as boundary conditions. Alternative approaches assume that statistical relationships between large-scale patterns, as predicted by global circulation models, and small-scale patterns will remain stable in the next decades and can be used for down-scaling the results of the global circulation models. To that end, the models STAR (*Werner* and *Gerstengarbe* 1997) and WETTREG (*Spekat* et al. 2007) have been developed for Germany.

All the regional models predict a substantial increase of temperature over the next 50 to 100 years in northeast Germany based on the moderate and pessimistic scenarios of future greenhouse gas emissions. Trends are less clear for precipitation. However, most results indicate that precipitation will tend to decrease during the growing season and to increase during the dormant season. In general, the models agree in that evapotranspiration during the summer period is likely to increase whilst groundwater recharge and runoff will most likely decrease in the next decades (*Jacob* et al. 2008, *Spekat* et al. 2007, *Wechsung* 2005, *Gerstengarbe* et al. 2003, *Suckow* et al. 2002).

Gerstengarbe et al. (2003) assessed the effects of climate change on crop yield in northeast Germany. Neither an increase of irrigation nor any possible progress with regard to pest control or plant breeding was considered. Observed crop yield during the 1980-1990 period was compared with model results for the 2040-2050 period, based on a moderate greenhouse gas emission increase scenario. Temperature was predicted to increase by 1.7 K, and precipitation to decrease by 52 mm per year compared to 1980-1990. As a consequence, wheat yield was expected to decrease by 17 %, and maize yield to increase. Taking into account the effect of increasing CO_2 concentration, the predicted wheat yield decreased by 10 %, and maize and barley yield increased by 8 % and 7 %, respectively.

Similar results are reported by *Wechsung* et al. (2008). In their model, the increase of CO_2 partial pressure will compensate for water scarcity for the next 40 years in East Germany. However, the drought risk will increase, especially in Brandenburg. Additional effects of increasing frequencies of extreme events or pest infestation on crop yield might play a role but can only be speculated about. In contrast, fire risk is almost certainly expected to increase, especially in the pine forests in Brandenburg (*Gerstengarbe* and *Werner* 1997). This provides another strong argument for converting pine forests into mixed stands or deciduous forests.

6. Conclusions

Landscape hydrology in northeast Germany is susceptible to minor changes of the water budget, due to the large proportion of area covered by lakes and wetlands on the one hand, and low present-day groundwater recharge and runoff generation on the other hand. Due to climate change, water scarcity is expected to increase further within the next decades. Thus, water resources management considers different land-use options in order to adapt to and to mitigate water scarcity in northeast Germany.

Wetlands and small lakes exhibit the highest rates of evapotranspiration, usually exceeding local precipitation. Thus, these systems provide the largest water sinks per area in northeast Germany. Among the major land-use types in northeast Germany, pine forests rank second with respect to annual water use. Converting them into deciduous forests is considered a major option with regard to increasing groundwater recharge and stream runoff. However, due to long rotation periods, forest conversion is a very slow process compared to the velocity of climate change. Whether this option may compensate for the future increase of water scarcity or even increase water budgets at the landscape scale depends to a large extent on the details of forest conversion and the local boundary conditions.

Groundwater recharge and runoff generation from grassland and arable land is substantially higher compared to that of forests. Various crops are generally assumed to differ in this respect. However, except for vegetables with a short growing period, there seems to be a physiological minimum water use of cereals in general, irrespective of crop species or climate. That maximum water use efficiency is warranted only given optimal soil tillage, fertilisation, pest control and irrigation, if necessary. Apart from the latter, which still does not pay off for most crops grown in the region today, it seems that crop production in northeast Germany is already fairly close to the water use optimum.

Transpiration is the price to pay for vegetation cover. Correspondingly, groundwater recharge is highest on uncultivated land. From a purely water resources management aspect, the most efficient way to increase groundwater recharge and stream runoff in northeast Germany would be to convert lakes and wetlands into fallows.

However, this would be at odds with numerous competing objectives and is not considered a serious water management option. Besides, wetlands and lakes cover only a minor fraction of the area in northeast Germany.

In contrast, most projects focus on converting pine forests into deciduous forests. In fact, this conversion will yield a substantial decrease of annual evapotranspiration. This option is generally preferred, also with regard to its impacts on forest fire and infestation risk, and the corresponding benefits with respect to biodiversity. Converting pine forests into arable land or grassland would reduce evapotranspiration even more. This is hardly enforceable given conservation issues, existing property rights and legal reasons. However, it is worth considering an alternative patchy mixture of low-intensity pasture and deciduous forests. This so-called "semiopen pasture" system (*Reisinger* 2005) has been considered mainly with respect to biodiversity and nature conservation issues so far. Based on the available data about water use of pine forests, deciduous forests and grassland in the mid-latitudes, such a strategy deserves being considered as a vital water resources management option. However, non-linear effects in these heterogeneous systems need to be studied first. For example, due to the "oasis effect", small forest stands within arable fields transpire much more per area during hot summer days compared to extended forest.

Alternative approaches are based on using water resources unused so far. Grey water, i.e. waste water, is being used for irrigation in many parts of the world. As a side effect, enhanced microbial activity and the associated decomposition of organic pollutants in the topsoil could at least partly be a surrogate for waste water treatment plants. In addition, nutrients contained in waste water could be used by the plants without any pre-treatment. Last but not least, a surplus of irrigated grey water might increase groundwater recharge and stream runoff and increase the water level in lakes and wetlands further downstream. Thus, the opportunity costs of grey water irrigation would be negative. Due to legal restrictions that account for the risk of groundwater pollution, however, waste water irrigation is allowed only in very few cases in Germany. However, it should be considered to use waste water after initial treatment. Both groundwater levels and stream water quality would benefit from this and save further costly treatment in waste water plants. In fact, facing the predicted increase of water scarcity problems in northeast Germany, new concepts are required to adapt to and to mitigate water scarcity.

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Summary: The Potential of Land-Use Change to Mitigate Water Scarcity in Northeast Germany – a Review

Water scarcity has become a major topic in northeast Germany. Annual groundwater recharge is already close to zero in parts of the region. Moreover, groundwater and lake water levels have decreased substantially during the last three decades and are likely to decrease further. By far the largest consumption of rainwater is due to transpiration by agricultural plants and forests. Thus, many mitigation strategies aim at maximising water use efficiency by land-use adaptation and agricultural or forestry management optimisation. This paper gives a review about the opportunities of these approaches, with both the actual and the predicted future climatic boundary conditions in northeast Germany in mind.

Zusammenfassung: Das Potential von Landnutzungsänderungen zur Minderung der Wasserknappheit in Nordostdeutschland – ein Überblick

Wasserknappheit wird in Nordostdeutschland zunehmend zu einem Problem. Die aktuelle jährliche Grundwasserneubildung ist in Teilen der Region schon nahe Null. Zusätzlich weisen Grund- und Seewasserspiegel in den letzten 30 Jahren verbreitet deutliche Rückgänge auf und werden voraussichtlich in Zukunft weiter absinken. Der mit Abstand größte Teil des Wasserverbrauchs in der Landschaft entfällt auf die Transpiration landwirtschaftlicher und forstwirtschaftlicher Kulturen. Anpassungsstrategien an die zunehmende Trockenheit zielen darauf ab, die Ausnutzung der knappen Wasserressourcen durch Landnutzungswechsel und angepasste land- und forstwirtschaftliche Bewirtschaftung zu optimieren. Dieser Artikel gibt einen Überblick über das Potential dieser Optionen angesichts der aktuellen und der prognostizierten klimatischen Bedingungen in Nordostdeutschland.

Résumé: Les options du changement de l'utilisation du sol pour atténuer la pénurie en eau dans le nord-est d'Allemagne – une vue d'ensemble

De plus en plus, le manque d'eau est considéré comme un problème grave dans les régions du nord-est de l'Allemagne. La recharge annuelle de la nappe est presque zéro dans quelques parts de la région. En outre, les nappes phréatiques et les surfaces de l'eau des lacs se sont baissées pendant les dernières trois décennies à beaucoup d'endroits. On suppose que ce trend va se continuer pendant les prochaines décennies. La transpiration des arbres et des plantes agricoles est la plus grande consommation de l'eau. Ainsi la production forestière et agricole doit s'adapter par optimisation de l'exploitation et par des changements de l'utilisation du sol. Cet article résume des résultats des investigations à ce sujet sous des conditions climatique actuelles et futures dans la région.

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