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Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas

A. Holsten[a], T. Vetter[a], K. Vohland[a], V. Krysanova[a]

[a]Potsdam Institute for Climate Impact Research, P.O. Box 60 12 03, 14412 Potsdam, Germany
Corresponding author: Anne Holsten: Tel.: +49 0 331 288 2689, E-mail address: holsten@pik-potsdam.de

Abstract

Global warming impacts the water cycle not only by changing regional precipitation levels and temporal variability, but also by affecting water flows and soil moisture dynamics. In Brandenburg, increasing average annual temperature and decreasing precipitation in summer have already been observed. For this study, past trends and future effects of climate change on soil moisture dynamics in Brandenburg were investigated, considering regional and specific spatial impacts. Special Areas of Conservation (SACs) were focused on in particular. A decreasing trend in soil water content was shown for the past by analyzing simulation results from 1951 to 2003 using the integrated ecohydrological model SWIM (Krysanova et al., 1998). The trend was statistically significant for some areas, but not for the entire region. Simulated soil water content was particularly low in the extremely dry year 2003. Comparisons of simulated trends in soil moisture dynamics with trends in the average annual Palmer Drought Severity Index for the region showed largely congruent patterns, though the modeled soil moisture trends are characterized by a much higher spatial resolution. Regionally downscaled climate change projections representing the range between wetter and drier realizations were used to evaluate future trends of available soil water. A further decrease of average available soil water ranging from -4% to -15% was projected for all climate realizations up to the middle of the 21st century. An average decrease of more than 25mmwas simulated for 34% of the total area in the dry realization. Available soil water contents in SACs were generally higher and trends in soil moisture dynamics were lower mainly due to their favorable edaphic conditions. Stronger absolute and relative changes in the simulated trends for the past and future were shown for SACs within Brandenburg than for the state as a whole, indicating a high level of risk for many wetland areas. Nonetheless, soil water content in SACs is expected to remain higher than average under climate change conditions as well, and SACs therefore have an important buffer function under the projected climate change. They are thus essential for local climate and water regulation and their status as protected areas in Brandenburg should be preserved.

Keywords: Soil water, soil moisture, nature conservation areas, Brandenburg, ecohydrological model, climate change

1 Introduction

Soil moisture is a key component of the hydrological cycle, controlling the partitioning of precipitation between runoff, evapotranspiration and deep infiltration (Daly and Porporato, 2005). As a link between the biosphere and the edaphic zone, soil water plays a crucial role for terrestrial ecosystems by determining plant growth. If the soil water level falls below a species-specific threshold, plants experience water stress, and decreased soil moisture under warmer conditions can inhibit photosynthesis (Lindroth et al., 1998).

Various feedbacks between soil moisture and the biological and hydrological cycles exist. For example, vegetation can influence the soil water regime by offsetting drier conditions through decreased transpiration, a phenomenon which is expected to occur more frequently in summer months under a warmer climate (Etchevers et al., 2002; Seneviratne et al., 2002; Yang et al., 2003). In addition, dry soils can cause a negative feedback by amplifying the impact and duration of heat waves (Brabson et al., 2005) and prolonging the effects of meteorological droughts (Nicholson, 2000). The exceptionally hot summer of 2003 in Europe led to large-scale soil moisture depletion and associated ecosystem impacts (Reichstein et al., 2007). If average soil moisture conditions had been maintained in the spring and summer of 2003, then summer heat anomalies would have been about 40% less severe in some regions of Europe (Fischer et al., 2007).

Long-term historical soil moisture records of in situ observational data or estimates derived from remote sensing are available only for a few regions (Trenberth et al., 2007). Examples of studies based on such data have shown significantly decreasing trends in soil moisture in recent decades for Eastern Hungary (Makra et al., 2005), and an increasing trend in recent decades for Ukraine (Robock et al., 2005).

Future projections on soil moisture are represented by only a few studies. For example, Gerten et al. (2007) concluded a global scale decline in soil moisture for many regions up to 2100. This does not necessarily mean that ecosystems are water-limited, as this model assumes increasing water-use efficiency in plants under increasing CO_2 levels. Projections for the regional scale using models require downscaling of climate scenarios (Seneviratne et al., 2002; Bronstert et al., 2003). Expected climate change could generally lead to decreased soil water content in the United Kingdom (Naden and Watts, 2001), and a strong decrease in soil moisture in summer in Switzerland (Jasper et al., 2006) and Southern Europe (Gregory et al., 1997). Etchevers et al. (2002) analyzed the impact of climate change on the Rhone river catchment, finding strong regional variations in simulated soil moisture changes. Naden and Watts (2001) studied future soil moisture changes in areas of ecological interest in the UK, but with a single vegetation type and a limited number of soil types. Larger changes in soil moisture were found for soils with higher clay content. A very fine spatial resolution was applied by Jasper et al. (2006) for soil water analysis in the Thur river basin in Switzerland. They limited the study to a few soil types and concentrated on changes in the summer months. Smaller changes in available soil water were shown for sandy soils compared to clay soils and for forests compared to grasslands or farmland.

The present study aims at investigating past and future trends in soil water dynamics in the Federal State of Brandenburg (Fig. 1), Germany, from 1951 until 2055. The case study area was chosen because it is characterized by relatively dry conditions and predominantly sandy soils (Landgraf and Krone, 2002), and is considered to be one of the most vulnerable regions to climate change in Germany as regards nature and biodiversity conservation, agriculture, forestry and water availability aspects (Zebisch et al., 2005). The study aimed to carry out an area-wide analysis of past and future soil water changes in the State of Brandenburg, and used the regional ecohydrological model SWIM (Krysanova et al., 1998), which considers major vegetation and soil types with a high spatial resolution. SWIM is particularly suited for this analysis since it offers flexibility of spatial resolution, incorporates both hydrological and ecological processes and it has been successfully applied in various studies analyzing hydrological dynamics in the Elbe basin and Brandenburg (Hattermann et al., 2005; Krysanova et al., 2005; Post et al., 2007; Wattenbach et al., 2007).

Trends in simulated soil moisture were compared to trends in average annual values of the Palmer Drought Severity Index (PDSI). Thus simulated soil moisture results could be compared with those produced by an independent method of analyzing drought severity. Furthermore, the impacts for different soil and vegetation types were analyzed. Particular emphasis in this study was given to Special Areas of Conservation (SACs) as defined by the EU Habitats Directive (92/43/EEC) in order to assess the spatially explicit risk for targets of this directive concerning these areas, which are of particular ecological and conservational value. Simulated soil water values for the whole area of the state were compared to results obtained for the SACs.

2 Methods

2.1 Case study area

Brandenburg is characterized by a relatively low average annual precipitation, below 600mm in the period 1951-2000 (Gerstengarbe et al., 2003), and a dense network of rivers and streams (Landesumweltamt Brandenburg, 2006). The spatial differences in average annual temperatures range from 7.8 °C to 9.5 °C in this time period (Gerstengarbe et al., 2003), while precipitation values range from below 500mm in the north-east to over 600mm in the south-west and north-west. More than half of Brandenburg is covered by poor sandy soils. About half of the area is used for agricultural production, and about a third for forestry, with pine trees being the dominant species (Landgraf and Krone, 2002).

The protected areas considered in this study, so called SACs, comprise 620 sites in Brandenburg in total (Fig. 1), representing about 11.3% of the states area (Landesumweltamt Brandenburg, 2006). Brandenburg has one of the largest shares of wetlands of all German states, most of which are under agricultural use (Landesumweltamt Brandenburg, 2006). Many of these wetlands have already been negatively impacted by regional water shortages with decreasing water levels in ground water, water bodies and fenlands (Landgraf and Krone, 2002). A pilot study showed that Brandenburg is characterized by biotopes with a large share of species adapted to wet and cold conditions due to the relatively large area of fenlands (Holsten, 2007). These species have a high conservation value but could be severely affected by the expected climate change.

Climate change is already being observed in Brandenburg. A notable regional warming of 1Kin recent decades compared to 0.7K on a global scale has been recorded (Lahmer and Pfützner, 2003). A trend towards a decrease in annual rainfall has been noted in Brandenburg in the last few decades, together with a trend towards a shift in precipitation from summer to winter (Bronstert et al., 2003). The climatic water balance (the difference between precipitation and potential evapotranspiration) is negative, and it is expected to become even more negative by 2055, leading to a decrease in groundwater recharge (Bronstert et al., 2003; Gerstengarbe et al., 2003).

2.2 The SWIM model

The ecohydrological model SWIM (Soil and Water Integrated Model) (Krysanova et al., 1998, 2000) is a continuous-time spatially semi-distributed model simulating hydrological processes, vegetation growth, nutrient cycling (carbon (C), nitrogen (N) and phosphorus (P)) and sediment transport at the river basin scale. SWIM simulates all processes by disaggregating the basins to subbasins and hydrotopes, where the hydrotopes sets of elementary units in a sub-basin with the same soil and land use types are the highest disaggregated units. Up to 10 vertical soil layers can be

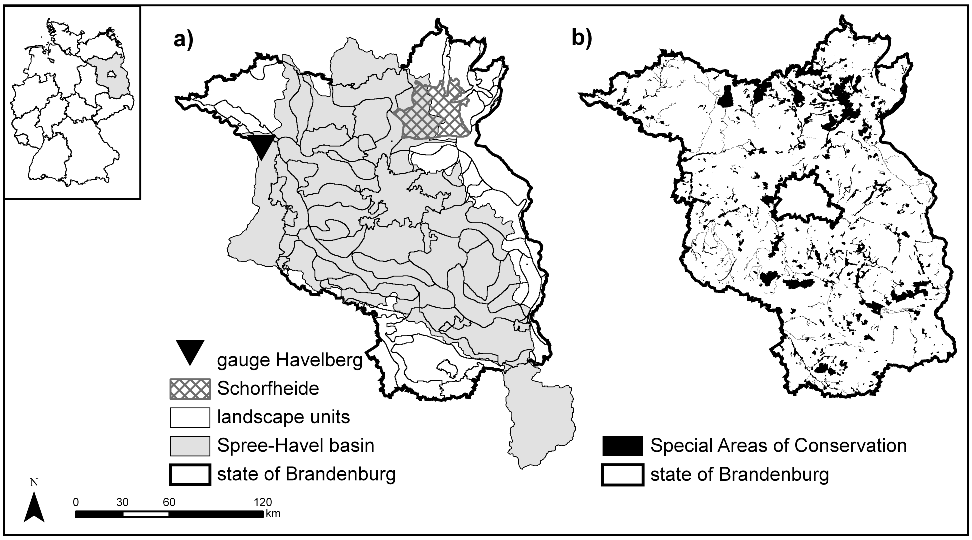


Figure 1: (a) Location of the SpreeHavel basin with the corresponding gauge Havelberg together with the landscape units and the selected unit Schorfheide. (b) Special Areas of Conservation (SACs) within Brandenburg.

considered for hydrotopes. It is assumed that a hydrotope behaves uniformly regarding hydrological processes and nutrient cycles. The spatial disaggregation scheme in the model is flexible. In regional studies climate zones, grid cells of a certain size, or other areal units can be used for disaggregation of a region instead of subbasins.

Water flows, nutrient cycling and plant growth are calculated for each hydrotope. Then lateral fluxes of water and nutrients to the river network are simulated, taking retention into account. Lateral flows between hydrotopes are not simulated in this regional scale model. After reaching the river system,water and nutrients are routed along the river network to the outlet of the simulated basin. The soil root zone is subdivided into several layers in accordance with the soil database. The water balance for the soil surface and soil column includes precipitation, surface runoff, evapotranspiration, subsurface runoff and percolation.

Surface runoff is estimated as a non-linear function of precipitation and a retention coefficient depending on soil water content, land use and soil type (modification of the Soil Conservation Service (SCS) curve number method) (Arnold et al., 1990). Lateral subsurface flow is calculated when the storage in any soil layer exceeds field capacity after percolation. Potential evapotranspiration is estimated using the PriestleyTaylor method (Priestley and Taylor, 1972).

The module representing crops and natural vegetation is an important interface between hydrology and nutrients. A simplified EPIC approach (Williams et al., 1984) is included in SWIM for simulating arable crops and aggregated vegetation types, using specific parameter values for each crop and vegetation type. A number of plant-related parameters are specified for the crop and vegetation types in the database attached to the model. Vegetation in the model affects the hydrological cycle by the cover-specific retention coefficient, impacting surface runoff, and indirectly influencing the amount of transpiration. The latter is simulated as a function of potential evapotranspiration and leaf area index (LAI).

The model has proven to be able to adequately reproduce observed hydrological characteristics (river discharge and groundwater table) in meso-scale and large basins (Krysanova et al., 1998; Hattermann et al., 2002, 2004; Yu et al., 2009). Comparison of simulated soil water with measured data for three field sites in Brandenburg and neighboring states showed an overall reliable representation of the temporal dynamics and magnitudes of soil water contents for different soil depths (Post et al., 2007).

2.3 Statistical methods

Trend analysis was performed using an advanced MannKendall (MK) non-parametric test (Mann, 1945; Kendall, 1975) proposed by Yue et al. (2002). This test allows serial correlation of the data to be taken into account, as positive serial correlation usually leads to a greater tendency to reject the null hypothesis of no trend. After detrending the time series using the Theil and Sen approach (Theil, 1950; Sen, 1968), the significance of serial autocorrelation was tested using the equation of Salas et al. (1980). This method was applied to detect trends in average annual soil moisture for each of the 3326 hydrotopes for the period 1955-2003. Since only 10 of 3326 detrended time series showed significant serial correlation, it was ignored, and the original MK test was used. The p-values equal or lower than 0.05 indicate statistically significant trends at the 5% level, and the p-values larger than 0.05 indicate insignificant trends.

2.4 Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) (Palmer, 1965) was used in the study to compare patterns of negative trends in soil moisture with patterns of nega-

tive trends in PDSI. This index was developed based on the supply-and-demand concept of the water balance equation which was used in the study. The PDSI is calculated based on monthly average precipitation and temperature data, and taking into account the locally available water content (AWC) of the soil. The method determines all basic components of the water balance, such as evapotranspiration, water recharge, runoff and soil moisture in the surface layer. This hydrological index is used broadly in many applications worldwide.
The PDSI was calculated for spatial units representing uniform landscape units and soil types using climate data interpolated from 83 climate stations in Brandenburg in the period 1951-2003. For the estimation of the PDSI, in addition to meteorological data, data on available water capacity (AWC) of soils was used. The monthly PDSI values were calculated for every unit, and the average annual PDSI values were used for the trend analysis.
Since the PDSI for a subsequent month is dependent on the PDSI of the current and previous months, the errors from a simple regression model are unlikely to be independent. Therefore, the autocorrelation of the calculated time series was analyzed in advance with the function ar() from the R software package nlme and the generalized least square (GLS) function gls() was used including the obtained autoregressive order.

2.5 Hydrological and climate data

Observation data provided by the German Weather Service (DWD) for the period 1951-2003 from 83 climate stations in and around Brandenburg were used as a climatic reference. The regional climate scenario for the period up to 2055 was created by the Climate group at PIK using the regional statistical downscaling model STAR (Werner and Gerstengarbe, 1997; Orlowsky, 2007). A regional temperature scenario was taken from the GCM ECHAM 5/MPI-OM (Roeckner et al., 2003) corresponding to the A1B scenario (Nakicenovic and Swart, 2000). STAR is a statistical downscaling model which re-samples observed data of climate stations through a cluster analysis using temperature trends as an input. STAR produced 100 stochastic realizations of regional climate for the period 2004-2055 based on the ECHAM scenario, with a higher uncertainty for precipitation than for temperature.
Three of these 100 realizations were selected for this study. Since the differences in the temperature of the realizations are relatively small, only precipitation was selected as the differentiating climatic parameter. Thus, three realizations were selected which reflected comparatively wet, medium and dry trends for Germany. Observed and scenario data for the climate stations were then interpolated to the centroids of the landscape units by the inverse distance method. Climatic inputs required by SWIM are daily precipitation, air temperature (maximum, average, and minimum) and solar radiation. Summer is represented by the months from July to September.
River discharge values from 1955 to 2000 were used from the gauge at Havelberg (Fig. 1a), provided by the Federal Institute of Hydrology (Bundesanstalt fr Gewässerkunde).

2.6 Spatial data and model implementation

The Digital Elevation Model (DEM) used in this study has a 25m resolution and was supplied by the State Land Survey Office (Landesvermessungsamt Brandenburg). The biotope map with over 500 vegetation types was obtained from the State Environmental Agency (Landesumweltamt Brandenburg). The biotopes were aggregated to 15 land use categories of SWIM (Krysanova et al., 1998). The categories water and urban land categories were not considered in this study, intensive grassland and extensive grassland were aggregated to give the category grassland. Thus 10 land use types were considered in total. The category evergreen forest is hereafter referred to as coniferous to better account for the regional vegetation. Cropland is here represented by winter wheat as one of the major crops in the study area. This generalization seems acceptable, since a sensitivity study of simulated river discharge to model parameters of SWIM for a basin within the state of Brandenburg showed changes in the dynamic of discharge, but small total changes for different crop types (Krysanova et al., 2000).

The implemented soil map has a spatial scale of 1:1,000,000 (BK 1000), with geophysical soil parameters for 72 soil types. The map was provided by the National Agency for Geo-sciences and Resources (Bundesamt für Geowissenschaften und Rohstoffe). This soil data has already been parameterized for the model SWIM and been widely used in its application, thus allowing a comparison between studies. The soil map gives a total number of 18 soil types for the study area with 12 dominant ones (see Table 1), which, together with the 10 considered land use types, provide an adequate resolution for this regional analysis. The spatial data for the SACs was obtained from the Federal Agency for Nature Conservation (Bundesamt für Naturschutz) in Germany and is shown in Fig. 1b.
In this study the so-called landscape units after Gharadjedaghi et al. (2004) (see Fig. 1a) were used instead of river sub-basins to better account for the edaphic and vegetational patterns of the landscape. The landscape units were delineated by geomorphological as well as conservational criteria. The hydrotopes, as the spatial entity for the hydrological simulation, were identified within the landscape units by overlaying the landscape units (defining the climate parameters) with the land use and soil map using ArcGIS 9.1 by ESRI. Thus, a total number of 3326 hydrotopes was obtained for the study area with a unique combination of soil and land use information within the different landscape units.
After calibration, SWIM was run for all hydrotopes in Brandenburg for the period 1951-2003 using observed climate data, and for three realizations of the climate

Table 1: Names of dominant soil types of Brandenburg and their corresponding soil type number according to the BÜK 1000.

Num.	**Soil type name**
6	Eutric histosols
8	Fluvisols/gleysols from loamy to clayey fluviatile sediments
12	Gleysols from sandy sediments of the ice-marginal valleys and lowlands
17	Haplic podzols/cambic podzols/gleyic podzols from sandy fluviatile sediments
19	Haplic luvisols/eutric podzoluvisols/stagnic luvisols from boulder clay
26	Dystric podzoluvisols/luvic arenosols/dystric cambisols from sandy sediments overlying boulder clay
27	Calcaric and umbric regosols/luvic arenosols from sandy to loamy end moraine deposits
28	Spodo-stagnic cambisols/stagnic podzoluvisols from loamy to sandy deposits overlying boulder clay
29	Stagnic and spodic gleysols from sandy deposits overlying boulder clay
31	Cambic podzols/spodic arenosols from dry dystrophic sand deposits
32	Eutric cambisols/luvic arenosols from eutrophic sand deposits
71	Soils redeposited by man and large open-cast mines (cumulic anthrosols)

Table 2: Precipitation and temperature change (1961-1990 compared to 2046-2055) of the chosen realizations in Brandenburg. The corresponding values for the landscape unit Schorfheide are shown in brackets.

Realiz.	**Annual prec. change (mm)**	**Prec. change in summer (mm)**	**Annual temp. change (K)**
Wet	+69 (+42)	+17 (+5)	+2.8 (+2.9)
Medium	-46 (-56)	-9 (-26)	+2.7 (+2.7)
Dry	-97 (-134)	-45 (-57)	+2.5 (+2.5)

Table 3: Selected hydrotopes of the landscape unit Schorfheide with their corresponding soil and vegetation types.

Reason for selection of hydrotope	**Vegetation type name**	**Soil type**
Common in Brandenburg	Cropland	26
		12
Common in Brandenburg and SACs	Coniferous forest	31
Common in SACs	Grassland	6
	Deciduous forest	27
Interesting hydrotopes for conservation	Wetland forested	6
	Wetland non-forested	6
	Heather	31

scenario (medium, wet and dry) for the period 2004-2055. Due to the starting phase of the model, the first 4 years of each run were not taken into account for the analysis. When comparing past and future values, the time periods 1961-1990 and 2046-2055 were used.

Actual available soil water for plants (in mm) was calculated for the upper 100 cm of soil profile of each hydrotope. As all soil types in the study area are parameterized to a depth of over 100 cm, the simulated soil water values allow comparisons to be made between the soils. For spatial presentation of the results, the simulated values were assigned to the generated map of hydrotopes.
Since the study area consists of more than 3000 hydrotopes, a selection for detailed analysis was made using the following two criteria: dominant hydrotopes in the study area and in the protected areas were chosen, together with potentially interesting hydrotopes from a conservational perspective. For the latter reason, two wetlands and a potentially drier heathland hydrotope were chosen for comparison. The dominant hydrotopes in Brandenburg are cropland or coniferous forest on sandy soils. The most common ones in the SACs are represented by deciduous or coniferous forest on sandy soils and intensive grassland on a boggy soil. To ensure better comparison between the selected hydrotopes, they were selected from one specific landscape unit, which is characterized by a uniform climate in the model simulations. Here, the landscape unit Schorfheide was chosen (Fig. 1a), which has a relatively large area of SACs and is characterized by a comparatively strong decrease in precipitation in the considered climate scenario compared to the whole of Brandenburg (Table 2). Other relevant climatic parameters of Schorfheide and of Brandenburg are also shown in Table 2. The dominant soil types and vegetation groups of the unit Schorfheide are sandy soils under forest and cropland. The selected hydrotopes are listed in Table 3.

3 Results

3.1 Model calibration and validation

Havelberg, representing the Havel basin with an area of 24,297 km^2. The administrative region of Brandenburg and the river catchment area do not precisely coincide; 78% of the river basin overlaps with the area of Brandenburg, and 63% of Brandenburg belongs to the basin (Fig. 1a). Calibration of discharge was carried out for the period 1955-1965. The time period 1971-2000 was subdivided into three decades for validation. The following parameters were used to calibrate the model: an evapotranspiration correction factor, three parameters describing snowmelt, a correction factor for saturated hydraulic conductivity, an alpha factor (reaction factor for groundwater), an initial level for groundwater and a correction factor for river routing. The Nash and Sutcliffe efficiency (Nash and Sutcliffe, 1970) and deviation in water balance (or volume error) were used to evaluate the models performance.

The obtained efficiency of 0.78 and -1% deviation in the water balance for the calibration period are comparable to values found in other studies. For example,

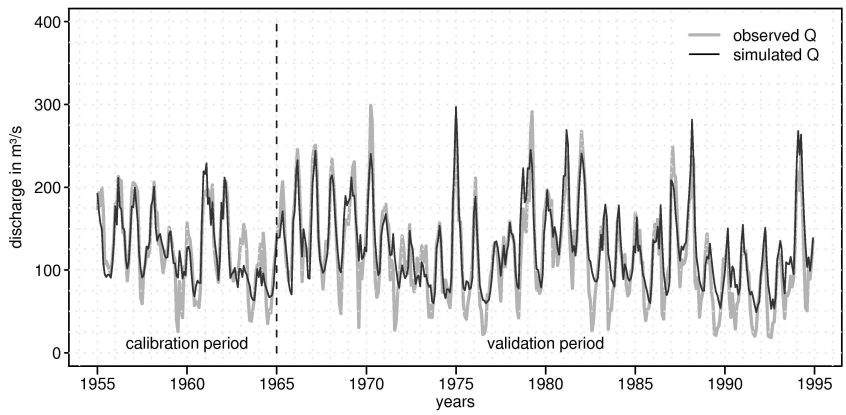


Figure 2: Comparison of observed and simulated water discharge (Q) at SpreeHavel basin outlet gauge Havelberg.

Hattermann et al. (2006) obtained a Nash-Sutcliffe efficiency of 0.7 for the calibration period and 0.54 for the validation period for the river Nuthe, which is a part of the Havel basin. For three decadal periods from 1965 to 1994, the efficiency was 0.81, 0.78, and 0.67-0.81, and deviation in water was +2%, +4% and +18%, respectively. The results (Fig. 2) are satisfactory, especially when taking into account that the Havel is a lowland river with extensive water regulation (drainage networks, irrigation,water supply for the Berlin metropolitan area, and lignite-mining-related water management), which was changing during this period of time.

One possible reason for the higher volume error for the last decade 1985-1994 is the influence of water use for irrigation with its peak in the late 1980s. According to the published data, the irrigation area of Brandenburg in 1995 was about 20,000 ha (Albrecht, 2003). An additional simulation experiment with SWIM for the 1980s demonstrated that the deviation in the water balance of +9% in the period 1981-1990 would be reduced to +5% taking into account irrigation with a water use of $100mma^{-}1$ for an area of 20,000 ha in summer months. Unfortunately, more detailed irrigation data for the whole period were not available.

3.2 Soil water trends in Brandenburg

Overall, there was a negative trend in average annual available soil water content for the observation period 1955-2003 (Fig. 3). There are practically no trends for the medium ($p = 0.58$) and wet realizations ($p = 0.99$) of the climate scenario, but a negative and statistically significant trend for the dry realization ($p = 0.01$).

The spatial distribution of the average available soil water in the period 1961-1990 (Fig. 4) shows high available soil water contents of over 225mm in the Oder river floodplains in the east and in the Elbe and Havel river floodplains the north-west. Dry conditions with water content below 75mm dominate in the Uckermark district in the north-east of Brandenburg. During the exceptionally warm summer of 2003, soil moisture decreased considerably over the whole region by an average of 20mm compared to the average values for 1961-1990 (Fig. 4b).

Even under higher precipitation conditions in the wet realization, a general decrease (-6mm on average) in annual available soil water is expected for the mid 2050s compared to 1961-1990 (Fig. 4c). This could mainly be caused by increased evapotranspiration under a warmer climate. A study for the Elbe basin, in which large parts of Brandenburg are situated, showed that evaporation has a strong influence on the landscape water balance (Hattermann et al., 2007). Temperature and radiation were identified as the main drivers of this process. An increase in available soil water of over 5mm for the wet realization was found for the floodplains of the river Oder and for some parts of the Elbe-Elster plains in the southwest.

However, a strong decrease (-21mm on average) for the almost entire area was simulated for the dry scenario realization (Fig. 4d). The most pronounced decrease was projected for floodplains of the rivers Oder, Elbe, Havel and Spree with grassland and cropland on fluvisols or histosols.Adecrease of more than 25mm was simulated for 34% of the total area.

3.3 Comparison with the drought index

The trends of average annual PDSI are significant ($p \leq 0.05$) for most of the area (Fig. 5a). Comparing patterns with a significant trend in PDSI with patterns of trends in simulated available soil water for the same period (Fig. 5b) revealed some similarities. Generally, the patterns of the strongest trends in available soil water (red areas south of Berlin in Fig. 5b) coincide with the pattern of a strongly significant trend in PDSI ($p \leq 0.01$). Also areas with a small negative trend or no trend in soil water content to the east of Berlin (green and yellow areas in Fig. 5b) match with patterns of insignificant trends in PDSI. This represents an independent validation of the results obtained by the SWIM model.

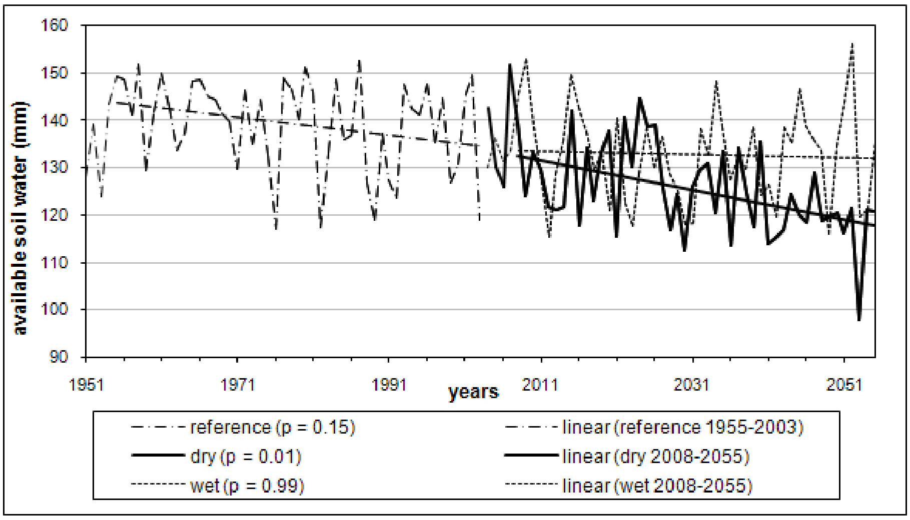


Figure 3: Trend of available soil water in Brandenburg from 1951 to 2055 for the reference period and two realizations.

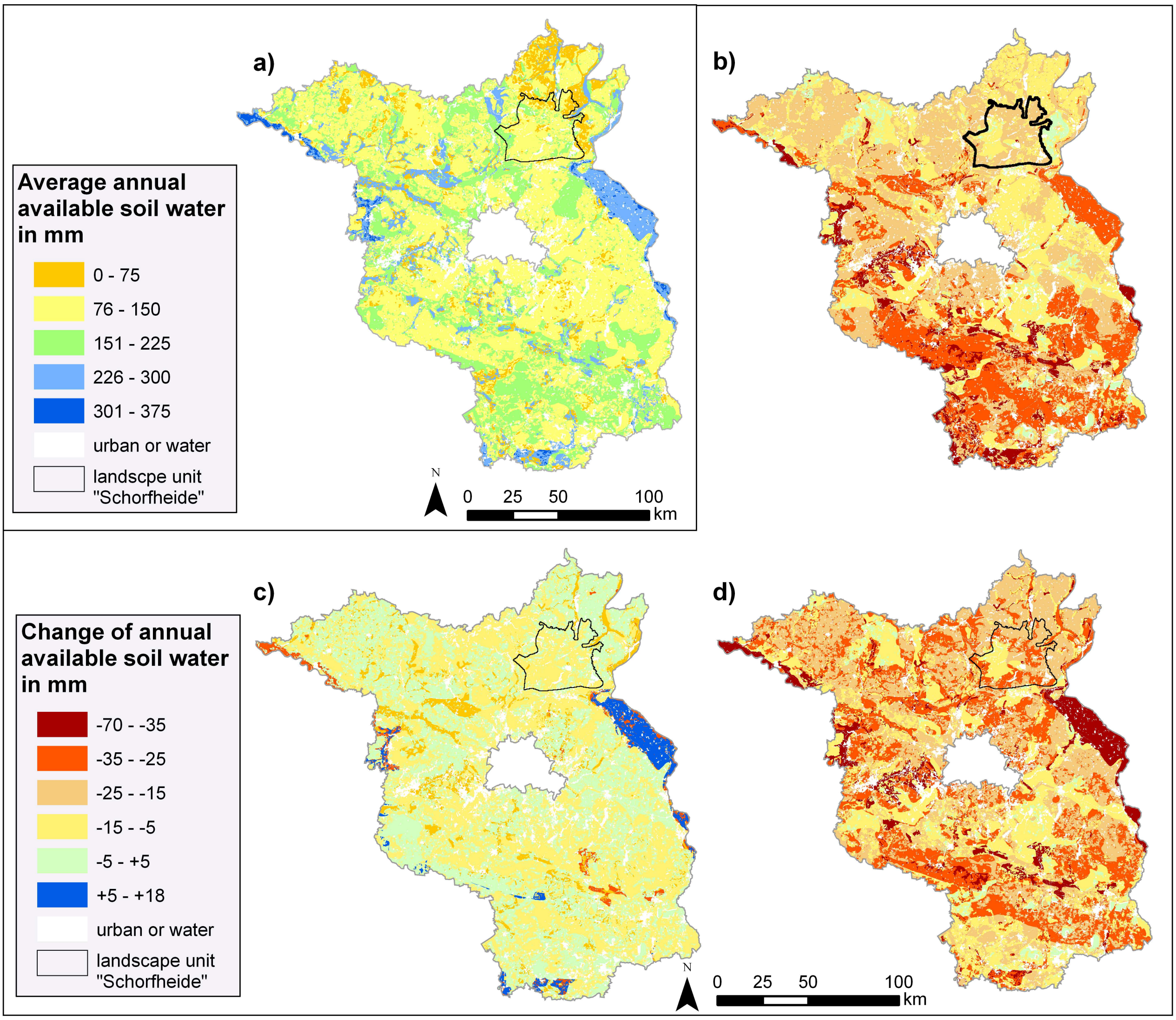


Figure 4: (a) Average annual available soil water from 1961 to 1990; (b) changes in average annual available soil water in 2003 compared to 1961-1990; changes in average annual available soil water from 1961-1990 to 2046-2055 for the (c) wet realization and (d) dry realization.

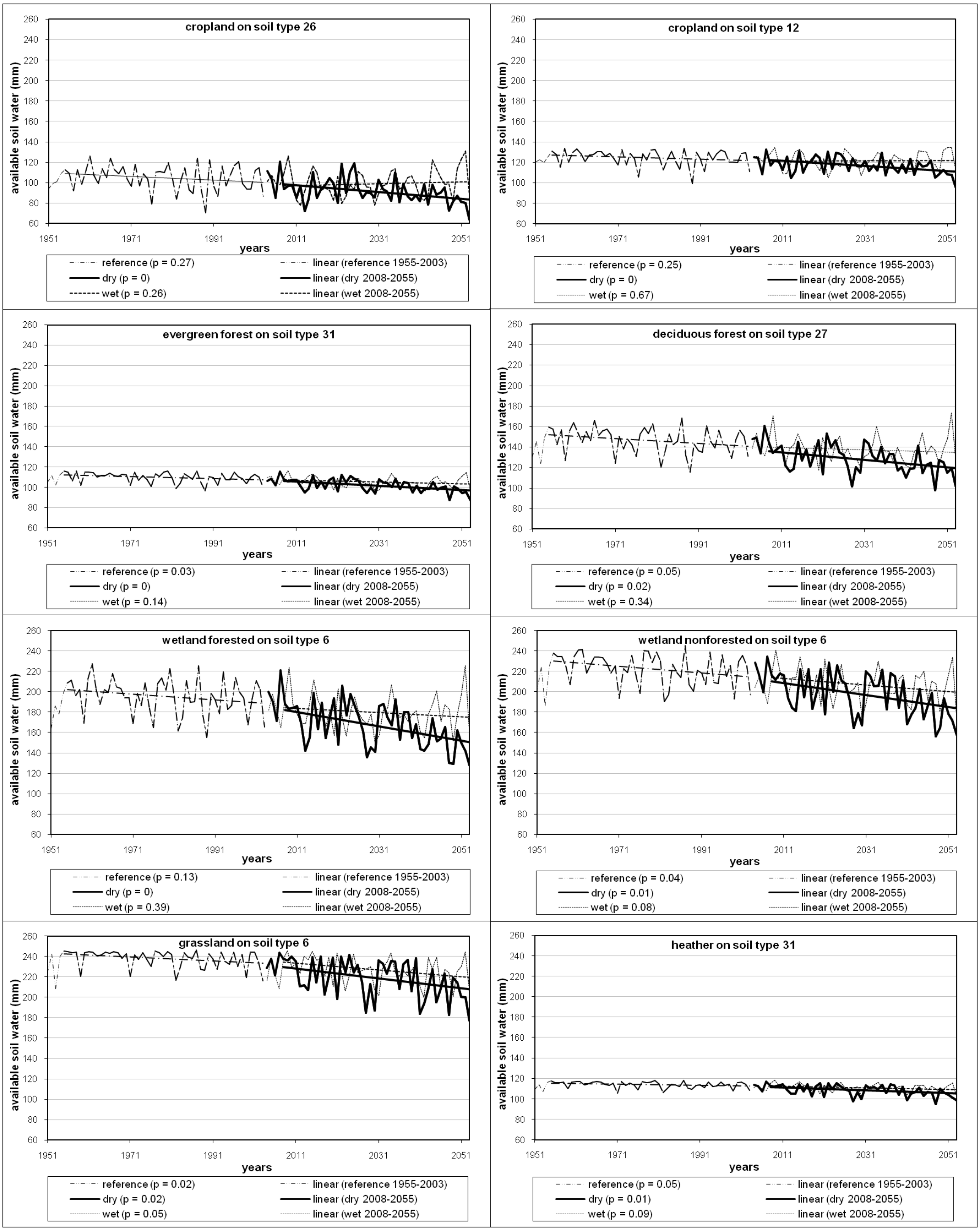


Figure 6: Trends of annual available soil water from 1951 to 2055 for the selected hydrotopes for the reference period and the wet and dry scenario realization.

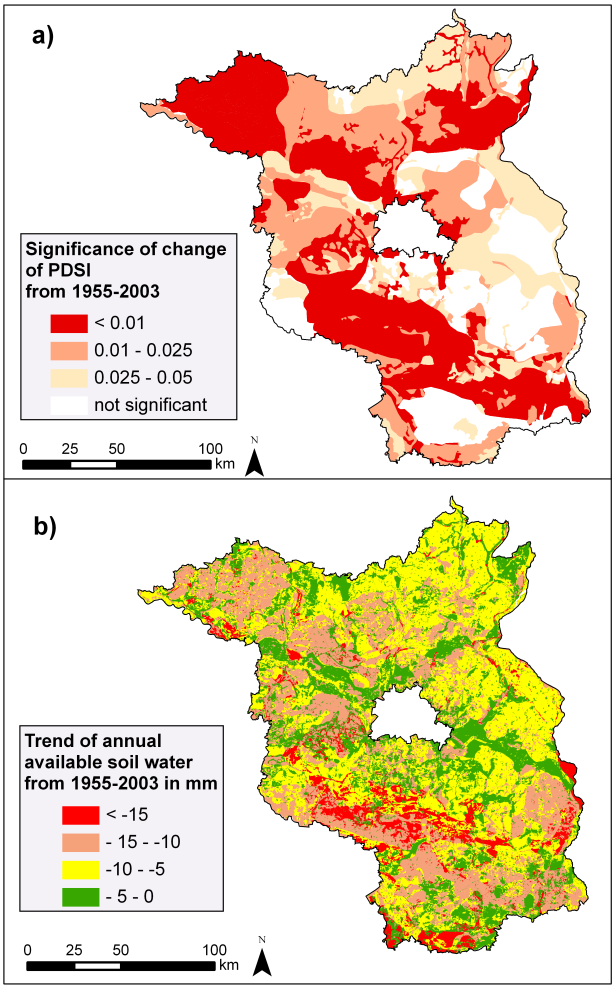


Figure 5: (a) Significance of trend in PDSI from 1955 to 2003 for locations of climate stations and hydrotopes, here without vegetation types and (b) trend of annual available soil water from 1955 to 2003.

3.4 Trends for selected hydrotopes

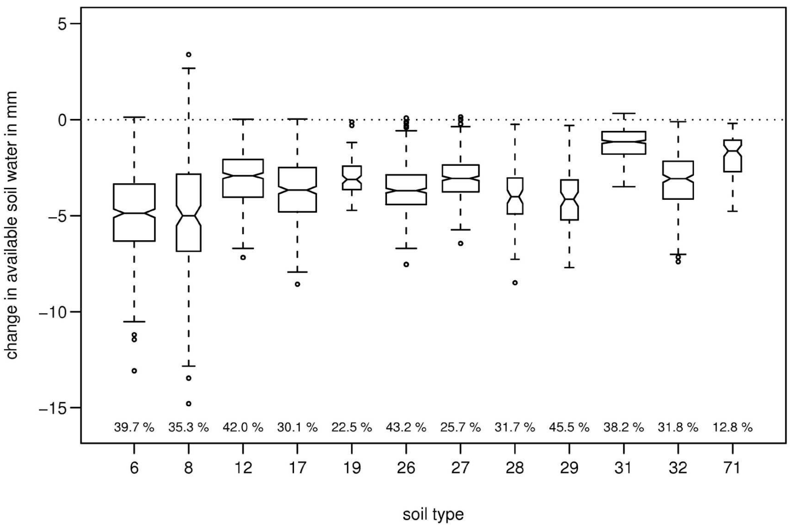
In addition, trends in available soil water were analyzed for some selected hydrotopes (Table 3). The levels of simulated available soil water content differed significantly, from over 140 to 200mm for histosol (6) to lower than 120mm for cambic podzol (31) and dystric podzoluvisol (26) (Fig. 6). Interannual variability differed considerably between hydrotopes. The hydrotopes on histosol (6) showed a much higher variability compared to the hydrotopes on cambic podzol (31). Simulated soil water content in forested wetland on histosol (6) was lower than in non-forested wetland and grassland on the same soil. This is probably due to the higher transpiration in forest.
In five cases out of eight, trends were statistically significant in the period of observations ($p \leq 0.05$). The negative trend was significant for the wet realization in one case (grassland on soil type 6) for the scenario realizations, and all eight cases showed statistically significant trends for the dry scenario realization.

3.5 Influence of factors soil type and land use on soil moisture dynamics

Simulated soil water dynamics were analyzed further by dividing the observation period into two sub-periods, 1955-1980 and 1981-2003, and by calculating differences in soil water content for major land use and soil types in Brandenburg (Fig. 7). Average changes in available soil water were small but negative for all soil and land use types in the sub-periods. Trends were significant for 30-45% of hydrotopes for most of the soils, with the highest significance levels for histosols, gleysols and podzoluvisols, which show over 40% significance level. The percentages varied strongly for different land use types: from only 6% for cropland and bare soil hydrotopes to 70% for grassland.
Changes in available soil water content were less distinct in bare soil and cropland, as the soil water content was already low. The decrease of soil water was more pronounced in non-forested wetlands, set-aside and heathland. Forests with a higher percentage of broadleaf trees were characterized by a stronger decrease in soil water than forests with a higher percentage of coniferous trees, whereas their absolute amount of soil water in the past shows hardly any difference. Also areas with more vegetation cover over the year showed stronger and more significant soil water decreases. Cumulic anthrosols (71) and cambic podzol (31), both soils with a high fraction of sand, were characterized by the smallest decrease in available soil water. Histosols (6) and fluvisols (8), soils with a high silt fraction, showed the highest total decrease in soil water content.

3.6 Comparison of trends in soil moisture in Brandenburg and SACs

Average soil water content in the reference period and for three scenario realizations was compared for the whole region and for the SACs within Brandenburg, for annual and summer values, respectively. For all realizations, soil water contents were higher in the protected areas (by about 18-23mm) than for the region as a whole (Fig. 8). Average soil water content in the reference period and for three scenario realizations was compared for the whole region and for the SACs within Brandenburg, for annual and summer values, respectively. For all realizations, soil water contents were higher in the protected areas (by about 18-23mm)than for the region as a whole (Fig. 8).
The order of decline in soil moisture for the three scenario realizations corresponded to expectations for Brandenburg and for the SACs. Average annual available soil water decreased by -6mm (-4%) for the wet realization, by -12mm (-8%) for the medium realization, and by -21mm (-15%) for the dry realization for the period 2046-2055 compared to the period 1961-1990. For the SACs, decreases of -10mm (-6%), -16mm (-10%) and -24mm (-15%) were simulated, respectively.
Simulated soil water content in summer was about 29mmlower than the annual value in the period 1961-



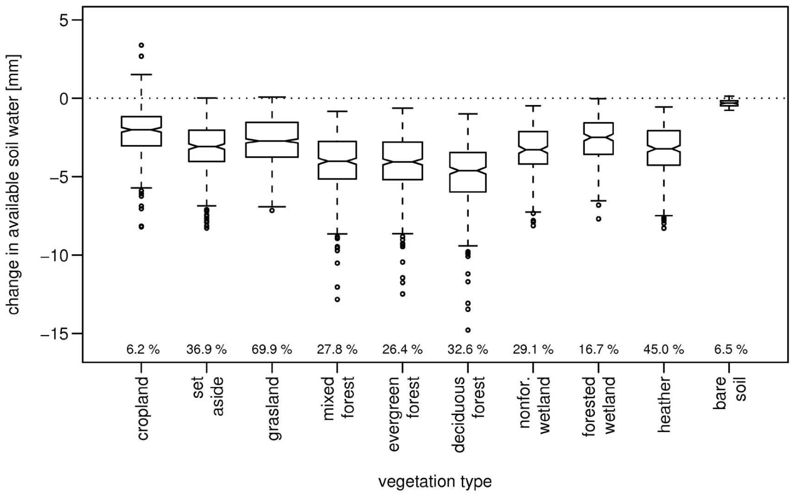


Figure 7: Changes of annual available soil water from 1955 to 2003 for (a) soil types and (b) vegetation types in the area of Brandenburg. The width of the bars represent the sample size (63-705 samples), the percent values on the graphs show a share of hydrotopes (by number, not by area) having statistically significant trend for the same time period.

1990 (21% for Brandenburg, 18% for SACs). This value increased to a difference of 4246mm for the period 2046-2055 in the dry realization for Brandenburg and the SACs. Thus, the amount of available soil water showed a stronger absolute decrease for summer values compared to annual values. The standard deviation in Fig. 8 indicates larger interannual variation for summer than for annual soil water values. The order of decline in soil moisture for the three scenario realizations corresponded to expectations for Brandenburg and for the SACs. Average annual available soil water decreased by -6mm (-4%) for the wet realization, by -12mm (-8%) for the medium realization, and by -21mm (-15%) for the dry realization for the period 20462055compared to the period 1961-1990. For the SACs, decreases of -10mm (-6%), -16mm (-10%) and -24mm (-15%) were simulated, respectively. Simulated soil water content in summer was about 29mmlower than the annual value in the period 1961-1990 (21% for Brandenburg, 18% for SACs). This value increased to a difference of 42-46mm for the period 2046-2055 in the dry realization for Brandenburg and the SACs. Thus, the amount of available soil water showed a stronger absolute decrease for summer values compared to annual values. The standard deviation in Fig. 8 indicates larger interannual variation for summer than for annual soil water values.

4 Discussion

For the first time, changes in soil water were simulated at the very high resolution of hydrotopes by applying the ecohydrological model SWIM (Krysanova et al., 1998). The results indicate that plant-available soil water has decreased in Brandenburg during recent decades, and is projected to decrease even more under climate change. Sound spatial correlation was found in comparing model results obtained for the state of Brandenburg with the Palmer Dry Severity Index (PDSI). The trend in available soil water in Special Areas of Conservation (SACs) within Brandenburg is even more negative than for the whole state with its greater share of agricultural land use and smaller share of wetlands, though the simulated amount of water content

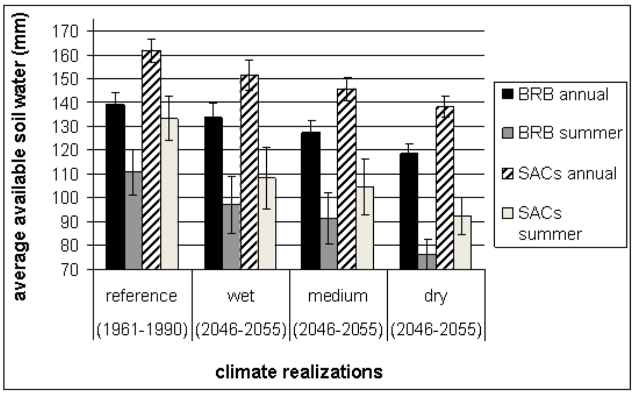


Figure 8: Available soil water in Brandenburg (BRB) and the Special Areas of Conservation (SACs) within Brandenburg throughout the year and in summer in the period 1961-1990 and for the three realizations (2046-2055); the standard deviation is shown by the lines.

is higher.

4.1 Methods and modeling

Projections of soil moisture are still very uncertain (Trenberth et al., 2007). The major uncertainties result from the lack of spatially distributed observed soil moisture data for comparison to the simulated values, and inaccuracies in soil parameterization. Nevertheless, comparison of soil water simulated using the model SWIM with observed values for some sites in Brandenburg has given reasonably good results (Post et al., 2007). In this study, calibration and validation of river discharge was carried out using observations for the Havel river basin, representing nearly the entire area of the state for which soil water changes were simulated (Fig. 1a). The effects of opencast lignite mining and the irrigation system in the south of Brandenburg on the regional hydrology are large. In the 1980s up to 200 million t lignite per year were produced. In conjunction, 1200106m^3 water per year (Arnold and Kuhlmann, 1993) were pumped out of the mining area into the Brandenburg lowlands. Mining activities were strongly reduced after the German reunification with consequent lowering of river discharge. Yet these activities could not be taken into account in this study. Additional runoff due to water pumping during mining activities accounts for about 11m3 s^{-}1 at Havelberg from 1973 to 1999 compared to 1991-1999 (BfG, 2003).
The model structure is based on distinct hydrotopes. The lateral flows thereof are aggregated to the landscape unit level, and then connected by the river network. The model does not consider lateral movement of soil water between the hydrotopes. For most of the state of Brandenburg with its characteristic lowlands, lateral flows are of little significance for soil water dynamics, yet for some moraine hills there could be a more notable effect. Inclusion of lateral water movement between hydrotopes could amplify the range of soil water changes given a certain soil and land cover type (Naden and Watts, 2001; Jasper et al., 2006), and influence the patterns of change. However, the general results and trends would stay valid. If specific small-scale effects are of interest, another three-dimensional model with connected grid cells should be applied. Further research is needed to include more detailed differentiation of soil and vegetation types concerning soil water processes such as root water uptake.

4.2 Changes in available soil water and drought index

SWIM was driven by three climate change realizations, two of which project less annual precipitation than in the past and one projects more (Table 2). The trend of available soil water for Brandenburg showed a slight, insignificant decrease for the wet and medium realizations and a strong and significant decrease for the dry realization. Since the realizations were characterized for Germany and not specifically for Brandenburg, the medium realization does not exactly represent intermediate climatic conditions. The simulated decreases in soil water even for the wet realization indicate a strong influence of evapotranspiration (due to higher temperature) on soil water, exceeding the effect of increasing precipitation in the period up to 2055. Other studies simulated a stronger direct influence of precipitation on soil water content under a temperature increase of less than 4K for regions in France and China (Etchevers et al., 2002; Yang et al., 2003).
Average simulated available soil water was drastically reduced in the year 2003, which was characterized by exceptionally warm conditions throughout Europe (Fig. 4b). Other model studies also report considerable declines in soil moisture for Switzerland and throughout Europe during the summer of this year (Jasper et al., 2006; Fischer et al., 2007). In consequence, a strong reduction of primary productivity of the biosphere in Europe was observed in the same year (Reichstein et al., 2007).
The spatial distribution of soil water indicated that climate parameters generally play a large role (Fig. 4). The climate parameters were considered uniform within each landscape unit. Their spatial boundaries are shown in Fig. 1. In addition, edaphic conditions influence soil moisture. For example, the most pronounced soil water changes occurred in floodplains of major rivers. Soils in these areas are characterized by higher soil water capacities and could thus be subject to larger potential changes.
The comparison of PDSI changes with trends in simulated available soil water generally showed good agreement between these two independent methods, with SWIM allowing a finer spatial resolution (Fig. 5). Results of simulated soil moisture demonstrated the strong influence of both soil and vegetation types (Figs. 6 and 7). Land use changes and changes in soil characteristics were not considered in this study. Other hydrological models, however, have showed that water flow components react very sensitively towards these changes (Bormann et al., 2007; Yu et al., 2009).
The simulated soil water contents for the different

soil types varied according to the field capacity. Hydrotopes with general water limitations like cropland under sandy soils were subject to smaller absolute changes, but larger relative ones. This is in accordance with the results from Jasper et al. (2006), who further point to the associated ecological risk of future soil water changes for soils with currently critical soil water conditions. Soils with a high silt content like histosols or fluvisols were more susceptible to absolute changes than sandy soils. Also, Jasper et al. (2006) indicated higher absolute changes for silt loam than for sandy loam and loam. Naden and Watts (2001) showed a generally minor decrease of soil water for sandy soils compared to clay soils for some sites in the UK under climate change. This can be explained by generally higher levels of soil water in more loamy soils, and by slow capillary transportation of water in sandy soils. Temporal variability was smaller for soils with high sand contents like cambic podzols than for histosols with a high fraction of silt. These results are not in line with expectations (e.g. Mohanty and Skaggs, 2001; Ceballos et al., 2002) and have to be investigated further.

Absolute soil water changes were more pronounced under forest than under cropland and grassland (Fig. 7). Jasper et al. (2006) also showed higher relative soil water changes under climate change for forests than for cropland and grassland, but the ranges of absolute changes differed between climate scenarios used. A study using the same model SWIM showed strong reductions in water yield when land use was converted from grassland to forest, due to an increase in leaf area (Yu et al., 2009). The level of significance of soil water change during the period 1955-2003 was low for cropland and bare soil but relatively high for grassland and forests. However, the latter have a high vegetation cover over the year and have been found to reduce their transpiration during warmer periods. Thus, they balance out soil water decrease to a certain extent compared to soils under less vegetation cover exposed to stronger evaporation (Etchevers et al., 2002; Seneviratne et al., 2002; Yang et al., 2003). The absolute reduction of soil water in deciduous forest was higher than in coniferous ones (Fig. 7), whereas their absolute amount of soil water in the past shows hardly any difference. This could be due to a prolonged vegetation period for deciduous trees under a warmer climate.

Comparison of simulated soil water with observed values in other studies using the model SWIM suggests some overestimation of root water uptake within the first 70-90cm (Wattenbach et al., 2005; Post et al., 2007). Calibration of this process using measured data could improve the results on soil moisture dynamics and give a better representation of water uptake by plants along the soil profile.

Soils in SACs were projected to maintain higher soil moisture compared to soils for the state as a whole (Fig. 8). One likely reason is that histosols or fluvisols with a high water storage capacity are over-represented in SACs (with an areal share of 22% in the SACs compared to 15% in Brandenburg). Thus the absolute future change of soil water in SACs is also larger than for the average soils in Brandenburg. Wetlands must therefore be regarded as vulnerable against climate change.

5 Conclusion

Simulated available soil water already decreased significantly in Brandenburg, and it is expected to decrease further, independently of the scenarios in question. The spatial pattern is differentiated, as soil moisture is affected by climatic parameters, soil types and land use. Comparing simulated soil water trends with an independent method using the Palmer Drought Severity Index showed a congruent pattern on the overall scale, although the SWIM simulation has a much higher resolution.

Special Areas of Conservation (SACs) show the highest absolute decrease in available soil water. As many wetland areas were projected to be affected by soil water decline, measures to stabilize or increase available soil water are necessary. Yet the results clearly show that SACs stored large amounts of soil water compared to the rest of the state and that these areas will keep this role in future. They are therefore important elements of the hydrological cycle due to their relatively high soil water content. A study for the Nuthe basin, which lies within the Havel river basin, showed that wetlands make a significant contribution to the water balance of the basin due to their high water retention capacity (Hattermann et al., 2006). SACs thus have an important function in regulating soil water conditions in dry areas, as they are able to buffer the impact of climate change to a certain extent.

Furthermore, it was shown that vegetation types have a strong influence on the soil moisture dynamics. The changing pattern of vegetation types in the landscape could therefore represent a possible adaptation measure towards projected changes in hydrological conditions. One possibility is the promotion of permanent crops rather than annual ones, since the former have deeper roots and can access groundwater and better overcome dry spells.

The management practices both within and outside the protected areas should be adapted to the expected decrease in available soil water. In order to achieve the stated conservation goals, it is increasingly important to retain water within the landscape of this relatively dry area. Brandenburg is characterized by many small drainage canals. In consequence of the observed and expected changes in available soil water, these drainage canals should rather be closed where possible, and farmers should be compensated for maintaining the increasingly scarce water within the landscape. Another possibility to reduce runoff and soil moisture decrease is to rehabilitate river systems where possible. The Special Areas of Conservation are essential for local climate and water regulation, and should maintain and improve their prominent function and position as protected areas in Brandenburg.

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