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Longtime effects of deep groundwater extraction management on water table levels in surface aquifers

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Abstract

Purpose A longtime monitoring (2003–2013) of groundwater levels and soil moisture was done in a plain tract surrounded by deposits from the Saale glacial stage in northern Germany. The purpose was to document the changes in the soil water regime over time in relation to changes in management of groundwater extraction and to evaluate if the hitherto management has been suitable for plant water supply for the local grassland production.

Materials and methods Groundwater wells in the surface aquifer were monitored at 11 survey sites, and soil matric potentials were measured with tensiometers at five depths per site. Soil analyses also were done. This report contains the results from three of the 11 survey sites, which best represent the variability of the soils in the area.

Results and discussion The monitoring showed that groundwater extraction from deep aquifers via individual wells altered the groundwater levels in the surface aquifer, even though there was a distance of several meters depth and a geological parting between the two aquifers. The impact of the groundwater extraction was shown by significant correlations between groundwater levels in the surveyed soils and groundwater extraction rates of individual wells. Climatic factors only affected groundwater levels in individual years. The management of the groundwater extraction from 1977 to 2006 severely lowered the groundwater level in the surface aquifer. Due to a limitation of the groundwater extraction rates and a shift in the degree of capacity utilization of the individual wells from 2006 onward, groundwater levels in the area are recovering. Correspondingly, the contribution of capillary rise to plant water supply has increased within the monitoring period.

Conclusions The monitoring proves that the present management of groundwater extraction is more suitable for the groundwater situation than past management. However, groundwater levels have not yet obtained a new equilibrium, so continual monitoring is needed.

1 Introduction

Groundwater extraction from deep aquifers has consequences for groundwater levels in connected surface aquifers. The decline of the groundwater level around a groundwater extraction well creates gradients that can induce flow out of surface water bodies into the aquifer (Sophocleous 2002). The quantification of how geological formations are related with groundwater flow and well productivity is complex, because it involves many factors of hydraulic properties and flow phenomena (Park et al. 2000). These factors must be considered when predicting long-term groundwater recharge by using hydro-pedotransfer functions (Miegel et al. 2013) or evaluating the interaction between groundwater and surface water with numerical simulations (May and Mazlan 2014). Prior to the development of a groundwater resource, one must predict how the water at the point of withdrawal is hydraulically connected to recharge zones and nearby surface water features. The

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prediction is difficult, especially if the sediments from which the water is withdrawn are heterogeneous (Kelly et al. 2013).

Excessive lowering of the groundwater table in surface aquifers can severely alter soil properties and plant water supply. Increasing (lowering) the groundwater level from 30 to 120 cm in a fen with grazed grassland diminished actual evapotranspiration by up to 230 mm per year (Renger et al. 2002). In near surface peat horizons, drainage will lead also to oxidation, subsidence, and shrinkage and, thus, a deterioration of soil functionality (Gambolati et al. 2006; Gebhardt et al. 2010). The connection of the root zone with groundwater generally limits water stress during dry years and thus helps to mitigate yield losses associated with water deficits. However, the water table should not be persistently too close to the surface during the growing season, as this would negatively affect photosynthesis through oxygen stress on roots. Excess water can lead to delayed plant emergence in arable farming caused by cooler springtime soil temperatures and, thus, reduce net primary productivity (Soylu et al. 2014).

In the summer of 2003, a longtime monitoring of the dynamics in groundwater levels and soil moisture and a documentation of physical and chemical soil properties were begun on a plain tract surrounded by deposits from the Saale glacial stage in south-west Schleswig-Holstein, Germany. In 2003, groundwater extraction from the local water works had caused an unforeseen subsidence of the groundwater level in the surface aquifer that exceeded the impact of drainage from furrows, ditches, or pipes. This impeded capillary rise of groundwater to the root zone in the Gleysols on the deposits from the Saale glacial stage and promoted peat degradation in the upper soil horizons of the Histosols in the plain tract (Gebhardt 2007; Gebhardt et al. 2010). Soil settlement processes had even caused damage to buildings in the area.

From 9 years of data for groundwater levels and soil moisture monitoring, we want to appraise:

– How the extraction rates from individual groundwater wells affect the groundwater levels in typical soils within the area
– To what extent lowered groundwater levels can be expected to limit plant water supply in dry periods due to absence of capillary rise
– Longtime trends of the groundwater levels against the background of an overall reduction of the groundwater extraction rate from 2006 onwards. In particular, we want to answer the question, when do the groundwater levels in the surface aquifer reach a new equilibrium?

2 Materials and methods

2.1 Survey area

The survey area is 10 km^2 and is under agricultural use with pasture management dominating in the plain tract, and a mixture of pasture and crops under various tillage managements on the surrounding deposits from the Saale glacial stage. During the monitoring, we established 11 survey sites (S) in the area. This report concentrates on the results from three survey sites, which represent the greatest variations in soil types and properties as well as in the effects of changes in groundwater management over time. Survey site S1 represents the Histosols in the plain tract, while survey sites S2 and S3 represent the Gleysols on the more elevated boundary area (Fig. 1).

The area contains eight groundwater extraction wells (W). Three are located in the plain tract (W1–W3); five in the deposits from the Saale glacial stage (W4–W8, Fig. 1). The groundwater is extracted from a sandy aquifer at the 22–93-m depth, which is separated from the surface aquifer (consisting mainly of sand, peat clay, and peat) by a layer of glacial loam. However, the partition between the two aquifers is not totally continuous. In the sphere of W1 and W3, a loam cover above the groundwater extraction zone is compact and the groundwater is confined. In the sphere of W2, the loam cover is more permeable and there is contact between the groundwater extraction zone and the surface aquifer. On the deposits from the Saale glacial stage, W4 and W7 are separated from W5, W6, and W8 by a geological compression. The groundwater in the extraction zone of W4 and W7 is confined and covered by a layer of glacial clay. In the sphere of W5, W6, and W8, the groundwater extraction zone is not continuously covered by loam or clay, so there is contact with the surface aquifer (Wichmann et al. 2003).

2.2 Climate

Precipitation (P) was measured on a daily basis at a station within a 3-km radius from the survey sites. The measured precipitation was corrected according to the method of Richter (1995). The corrected precipitation data were used to calculate the climatic water balances for the survey area.

Potential evapotranspiration (ET$_0$) was calculated according to Penman-Monteith and converted into a maximal potential evapotranspiration (ET$_{max}$) by multiplication with a factor according to vegetation type and height (Monteith 1965; Allen et al. 1998; ATV-DVWK 2002), using data from the closest weather station (DWD). A method by Ritchie (1972) was used to determine potential evaporation rate under grassland (E_p*) and to quantify transpiration (E_t) by subtraction (Ehlers and Goss 2003).

Fig. 1 Schematic cross section of the survey area with survey sites (S1–S3) and groundwater extraction wells (W1-8)
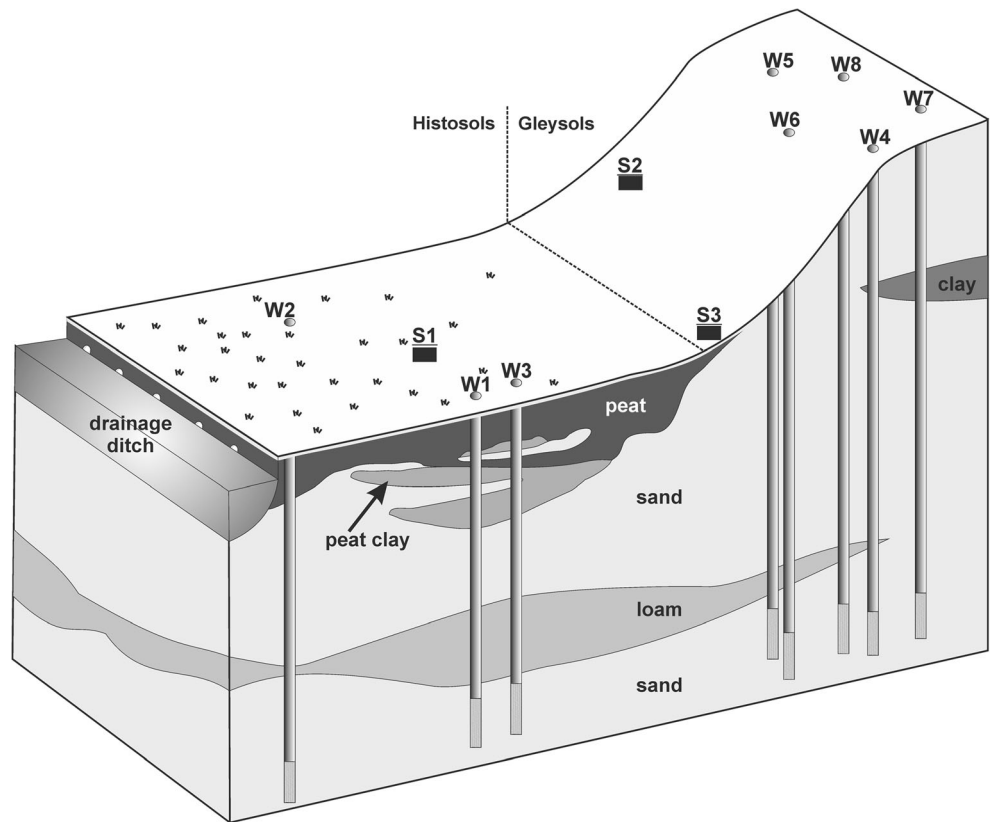
2.3 Groundwater extraction rates

Groundwater extraction in the area was initiated in 1977 and reached its maximum in 1981 with 6,300,000 m³ per year. This led to a severe depression of the surface groundwater levels in the area with a danger of damage to buildings caused by ground settlement and yield losses in agriculture due to deficits in plant water supply in the summer months. Hence, from 1982 to 2006, the water works voluntarily reduced the groundwater extraction to rates of 2,300,000 to 4,500,000 m^3 a^{-1}. In 2006, a new license for groundwater extraction officially limited the maximum extraction to 3,000,000 m^3 a^{-1}.

W7 has the highest percentage in the annual groundwater extraction in every year of the time period 2004–2012 (Table 1). However, the percentage is reduced with the new groundwater extraction license in 2006. This trend is also visible for W1 and W3, with W2 and W4 taking over part of their share from 2007. The percentages of W5, W6, and W8 in the annual groundwater extraction rate are ≤10 % throughout the time period 2004–2012.

2.4 Survey sites and sampling

The three survey sites in this study (S1–S3 in Fig. 1) are pasture land with meadow mowing (two cuts). All three survey sites are located within a modeled potential groundwater depression cone caused by the groundwater extraction (Wichmann et al. 2003).

The soil type at S1 is a Hemic Histosol in the plain tract, drained to average groundwater levels of 63 cm (max. 91 cm, min. 7 cm) below the surface in 2004. The peat horizon is located in 30–60-cm depth and is covered by an anthropogenic layer of highly humus sand that was formerly plowed and thus consists of a mixture of sand and peat fragments.

Table 1 Percentage of the individual wells (W) in the annual groundwater extraction rates in the time period 2004–2012

Percentage in the annual groundwater extraction rate							
Year	W1	W2	W3	W4	W5	W6	W7	W8
04	10	13	18	14	6	3	35	1
05	29	11	22	0	5	1	31	1
06	22	8	22	8	5	3	29	3
07	15	17	15	17	6	5	22	3
08	12	18	12	19	7	6	23	3
09	15	11	13	19	5	8	25	4
10	13	19	13	20	7	6	19	3
11	10	18	13	18	8	8	20	5
12	14	19	13	19	7	6	19	3

The dashed line marks the change in groundwater extraction management from 2007 due to the new extraction license

The soil type at S2 is a Spodic Gleysol developed from sandy material on the terminal push moraine from the Saale glacial stage that surrounds the plain tract, and it is drained to average groundwater levels of 130 cm (max. 159 cm, min. 67 cm) in 2004.

The soil type at S3 is a Histic Gleysol in the transition from the plain tract to the terminal push moraine from the Saale glacial stage with a remaining degraded peat horizon at the 27–47-cm depth covered and underlain by sandy substrates and drained to average groundwater levels of 180 cm (max. 200 cm, min. 100 cm) in 2004. The presence of a peat horizon reveals that the groundwater level must have been close to the surface in the past. Today, like in S1, the upper 30 cm of the soil at S3 consists of an anthropogenic sand cover that was formerly plowed and thus contains sand and peat fragments. However, due to the presently much lower groundwater level, the peat in this soil is far more degraded than at S1.

Undisturbed soil cores and disturbed soil samples were taken from the diagnostic soil horizons at each survey site in 2004 in order to determine the actual condition of the soils (Gebhardt 2007). The following selection of the measured parameters is used in this paper: soil texture, bulk density, and plant available water capacity based on water retention curves.

Effective rooting depth was determined from bulk density and soil texture according to Ad-hoc-AG Boden (2005) and Müller and Waldeck (2011). Potential plant extractable water (W_{extr}) was calculated by summing up the available field capacities (in mm dm^{-1}) in the soil layers within the effective rooting zone. The maximum groundwater level (GW) for a capillary rise of 0.3 mm day^{-1} (GW$_{min}$), and for a capillary rise of 5 mm day^{-1} (GW$_{opt}$) from the groundwater to the lower fringe of the effective rooting zone, was derived from bulk density and soil texture according to Ad-hoc-AG Boden (2005).

2.5 Matric potentials and groundwater levels

Tensiometers were installed at the 15-, 40-, 70-, 100-, and 150-cm depths with three replications at each depth, and matric potentials (ψ_m) were measured once a week.

At each survey site, a groundwater well was installed (filter depth 100–300 cm below surface) and groundwater levels were measured automatically every 30 min. Additional weekly manual control measurements were conducted with a well whistle.

2.6 Plant water supply

In order to evaluate plant water supply on the base of the measured ψ_m, we employed the root water uptake parameters according to Feddes (1978) as implemented, for example, in the program HYDRUS (Šimůnek et al. 2013). Accordingly, root water uptake for pasture is considered to be at its optimum when ψ_m in the root zone is between −25 and −300 hPa

for transpiration rates of 5 mm day^{-1} or between −25 and −800 hPa for transpiration rates of 1 mm day^{-1}. For $\psi_m >$ −10 hPa and $<$−1000 hPa, plant water uptake is expected to be zero due to lack of oxygen or too strong water retention of the soil matrix. In central Europe, rates of capillary rise between 2 and 5 mm day^{-1} can be expected to guarantee that the vegetation is independent of additional water supply through precipitation (Ad-hoc-AG Boden 2005).

3 Results

3.1 Monitoring

3.1.1 Climatic water balances

Climatic water balances in the survey area are positive in all monitored hydrological years (HY), except in HY 2009 (−44 mm), which is the driest year in the monitoring period (Fig. 2a). The mean annual air temperature (T) for the HY 2004–2013 ranges between 8.7 °C (HY 2013) and 11.5 °C (HY 2007), the precipitation (P) ranges between 823 mm (HY 2009) and 1229 mm (HY 2008), and ET$_{max}$ is between 761 mm (HY 2012) and 868 mm (HY 2009).

The winter half years (WH) have positive climatic water balances (330–145 mm) throughout the monitoring period with a periodic transition of wetter and dryer WH that showed a slightly decreasing trend (Fig. 2b).

In the summer half years (SH), E_t and thus water demand of the grassland vegetation is between 463 mm (SH 2004) and 555 mm (SH 2006) (Fig. 2c). Water balances are negative in SH 2005, 2006, 2009, 2010, and 2013, with the lowest value in SH 2009 (−190 mm). Here, the importance of additional plant water supply through capillary rise is most definitive.

In order to distinguish between climatic influences in the individual years and the impact of the fluctuating groundwater levels on soil moisture in the vegetation period, we firstly identified summer half years (SH, period from May to October) with similar climatic water balances. This is the case for the SH 2004 (73 mm), 2007 (88 mm), and 2012 (75 mm).

3.1.2 Soil parameters

The effective rooting depth increases slightly from S1 to S2 and S3 (Table 2). The amount of plant extractable water in the effective rooting zone decreases to nearly half from S1 and to S2 and S3.

GW$_{min}$ and GW$_{opt}$ are lower in S2 and S3 than in S1.

3.1.3 Groundwater levels

The groundwater level in S1 shows similar courses in each monitored year (Fig. 3a), dropping to levels 30–80 cm beneath

Fig. 2 Climatic water balance, sum of corrected precipitation (*P*), potential evaporation (*E*$_p$*), potential transpiration (*E*$_t$), and mean air temperature (*T*) for the survey area in hydrological years (**a**), winter half years (**b**), and summer half years (**c**), 2004–2013
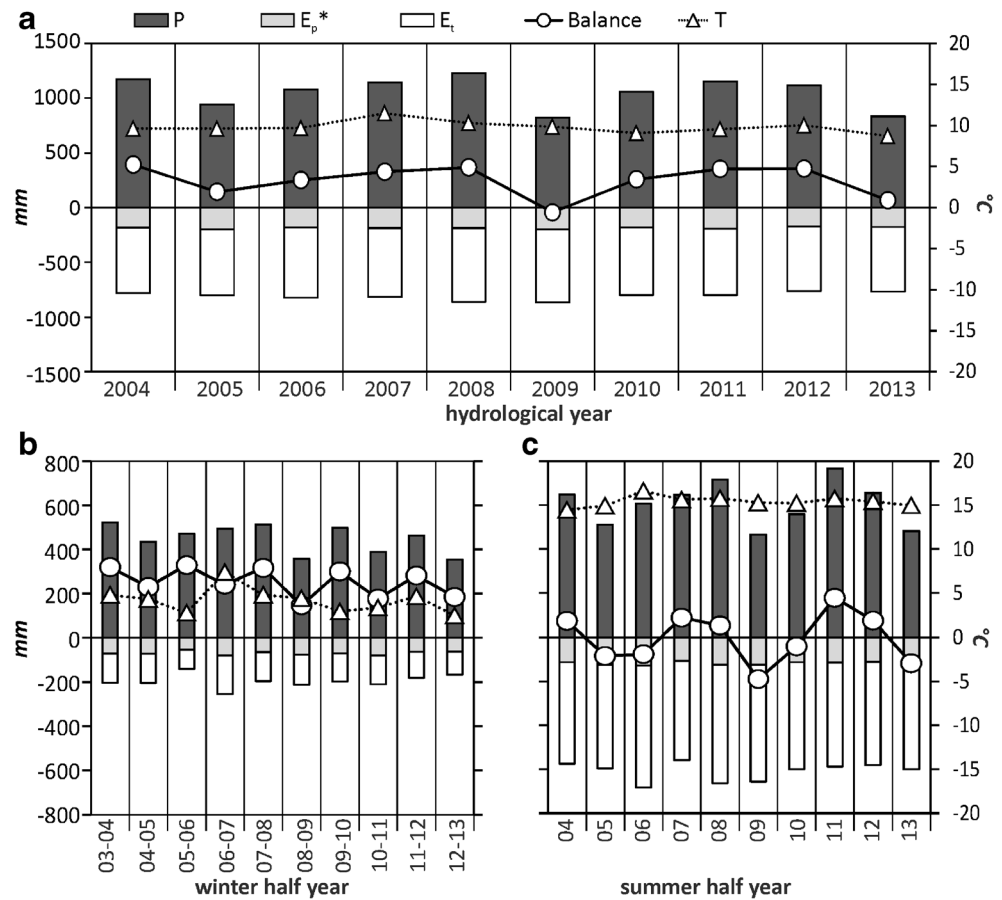
the root zone in summer and rising to close to surface levels in winter. As the groundwater table is relatively close to the surface, the curve shows a rather unsteady course, being strongly affected by precipitation events and evapotranspiration rate.

In S2, the seasonal fluctuation of the groundwater level is visible too, but the course of the curve is steadier than at S1 due to the overall greater distance from the groundwater table to the surface. Besides the dependency on climatic properties, the groundwater level in this soil is visibly affected by the overall reduction of the groundwater extraction because the annual minimum and annual mean groundwater levels are visibly higher in 2012 than in 2007 and 2004 although these years have similar climatic water balances.

In S3, the lowest groundwater levels are about 150 cm below the effective rooting zone in 2004 and 2005. The reduction of groundwater extraction in 2006 leads to considerably higher groundwater levels in the summer of 2007 and the following summers.

Altogether, the courses of the groundwater level in the individual soils align more and more as the monitoring period progresses. Still, because of the climatic differences in the individual years, it is difficult to identify if the groundwater situation has already settled with the current management of the groundwater extraction or if an overall further rise can be expected.

Annual average groundwater levels are universally lowest in P3 with a maximum level of 210 cm below surface in 2004,

Table 2 Effective rooting depth, plant extractable water (available field capacity in the effective rooting zone) with classification according to (Ad-hoc-AG Boden 2005), and groundwater level (GW) for a capillary rise of 0.3 mm day^{-1} (GW$_{min}$) and 5 mm day^{-1} (GW$_{opt}$) in sites S1–S3

Parameter/site	S1	S2	S3
Effective rooting depth, cm	40	50	50
Plant extractable water (W_{extr}), mm a^{-1}	193 (high)	111 (medium)	117 (medium)
GW$_{min}$, cm	100	140	140
GW$_{opt}$, cm	60	80	80

Fig. 3 a Course of the groundwater (GW) levels. **b** Annual average groundwater levels with linear trends. *Bars* indicate annual absolute maximum and minimum groundwater levels, S1–S3, 2004–2013
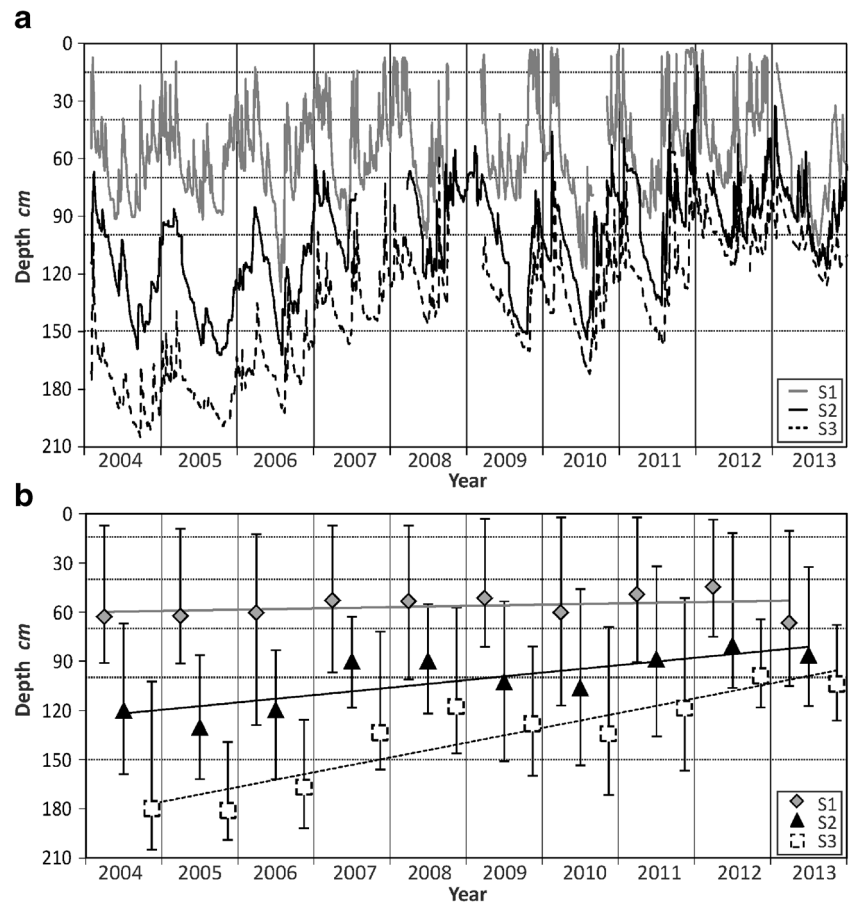
while S1 shows the shallowest groundwater situation with maximum levels of about 100 cm below the surface and minimum levels within the upper 10 cm of the soil (Fig. 3b). The linear trends indicate a rise of the groundwater that is most pronounced in S3 and only little in S1.

3.1.4 Matric potentials in the effective rooting zone

Figure 4 shows the percentages of ψ_m classes for root water uptake according to Feddes (1978) measured at the 15- and 40-cm depths, and they represent the effective rooting zone in S1, S2, and S3 for the summer half years (SH).

Already in 2004, the soil in S1 is too wet for optimal plant water uptake in 50 % of the measurements at the 40-cm depth ($\psi_m > -25$ hPa). In 2012 and 2013, this is even true for 91 and 95 % of the measurements, respectively. At the 15-cm depth, we found optimal ψ_m for plant water uptake (between -25 and -300 hPa) in 100 % of the measurements in 2005. In the monitoring period, the share of $\psi_m > -25$ hPa in the SH increases at the 15 and in 40-cm depths, diminishing the share of the optimal ψ_m range.

Figure 4 also reveals that S2 is the site with the biggest share in ψ_m corresponding with the optimum range of $-25 > < -300$ hPa at the 40-cm depth in the vegetation period. In the SH 2005,

2006, and 2007, this share is 100 % of the measurements. The lowest share is 65 % in 2012 with an increase in wetter soil conditions (35 % of the measurements with $\psi_m > -25$ hPa). Matric potentials (ψ_m) at the 15-cm depth fall below -300 hPa and thus mark too dry conditions for optimal plant water uptake in 10–38 % of the measurements in 2004–2011. In 2012, this does not happen, and in 2013, the share is only 6 %.

S3 is the only site where too dry conditions for optimal plant water uptake ($\psi_m < -300$ hPa) occur at both the 15- and 40-cm depths in the monitoring period. This is true for the SH of 2005 and 2006 and in the dry summer of 2009 (shares of 16, 5, and 5 %, respectively). At the 15-cm depth, ψ_m falls below -300 hPa in 10–45 % of the measurements in 2004–2011. In 2012, this does not happen, and in 2013, the share is only 6 %, just like at S2.

The share of $\psi_m > -25$ hPa in 40-cm depth is larger at S3 than at S2, even though the groundwater table is lower because of the greater water retention capacity of the peat horizon at the 27–47-cm depth at S3 in comparison with the sand at S2.

3.2 Contribution of the groundwater to plant water supply

Capillary rise to the lower fringe of the effective rooting zone, and hence the contribution of the groundwater to plant water

Fig. 4 Share in matric potential (ψ_m) classes in the summer half years (*SH*) 2004–2013 in 15- and 40-cm depth at S1–S3
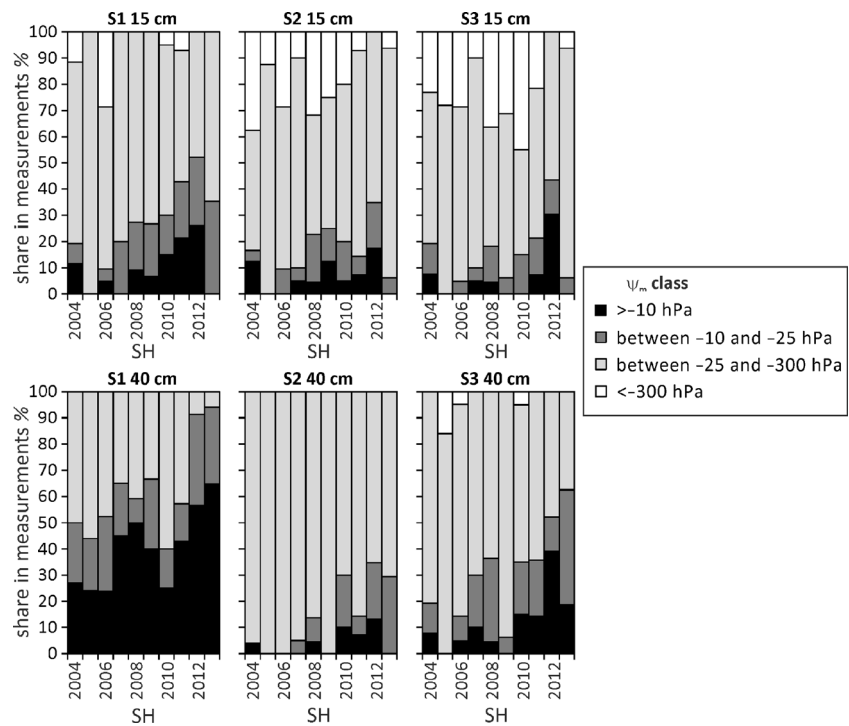
supply, was evaluated. This was done by determining the occurrence of groundwater levels corresponding with a capillary rise of 0.3 mm day^{-1} (GW$_{min}$) and 5 mm day^{-1} (GW$_{opt}$). Table 3 contains the percentage of days in the summer half years (SH) of the monitored period with GW$_{min}$ and GW$_{opt}$. The share of days with groundwater levels ≥GW$_{opt}$ is continuously increasing at S1 and S2, when one considers the similar climatic conditions of SH in 2004, 2007, and 2012. The same is true for the share of days with groundwater levels ≥GW$_{min}$ at S3.

Groundwater levels corresponding to GW$_{opt}$ result in too high ψ_m values for optimal plant water uptake according to Feddes

(1978) in the root zones (40-cm depth) of S1–S3 (Table 4). In the root zones, ψ_m corresponding to optimal plant water uptake has been measured with groundwater levels both exceeding and falling below GW$_{min}$ and GW$_{opt}$ in all three soils.

3.3 Interactions between climate, groundwater extraction rates, and groundwater levels

The summer half years of 2004, 2007, and 2012 have similar climatic water balances (see also Fig. 2), representing relatively moist summers. Hence, we used these years to quantify the

Table 3 Percentage of days with groundwater level (GW) meeting the requirements for a capillary rise of 0.3 mm day^{-1} (≥GW$_{min}$) or for a capillary rise of 0.5 mm day^{-1} (≥GW$_{opt}$) to the lower fringe of the root zone (effective rooting depth, see Table 2) in the summer half years (SH, May–Oct. 184 days) of 2004–2013 at sites S1–S3

Site	S1		S2		S3	
SH	≥GW$_{min}$ %	≥GW$_{opt}$ %	≥GW$_{min}$ %	≥GW$_{opt}$ %	≥GW$_{min}$ %	≥GW$_{opt}$ %
04	100	25	59	0	0	0
05	100	13	27	0	0	0
06	80	25	75	0	3	0
07	100	32	100[a]	7[a]	32	0
08	99	28	100	17	77	4
09	100	26	63	0	39	0
10	79[a]	2[a]	73	0	28	0
11	100	46	100	17	51	0
12	100	52	100	18	100	3
13	–	–	100	16	100	0

[a] Years with missing data in the summer half years

Table 4 Range of measured matric potentials (ψ_m) in 40-cm depth associated with groundwater levels (GW) corresponding to $GW_{opt}{}'$ and range of measured GW corresponding to ψ_m between −25 and −300 hPa (ψ_{mopt}) in 40-cm depth at sites S1–S3

Site	S1	S2	S3
ψ_m hPa when GW = GW_{opt}	$+13 > \psi_m > -30$	$+6 > \psi_m > -20$	$+2 > \psi_m > -16$
GW cm when $\psi_m = \psi_{m\ opt}$	54–122	66–170	106–204

impact of rising groundwater levels on soil moisture under comparable meteorological conditions.

Average groundwater levels are lowest in 2004 and highest in 2012 for all three soils (Fig. 5). This results in an increase of the ψ_m at both the 15- and 40-cm depths. In spite of the lower groundwater level at S3, mean ψ_m at the 40-cm depth are consistently lower at S2. This is due to the higher water storage capacity in the residual peat at the 40 cm depth at S3. With regard to plant water uptake, average ψ_m in the root zone (represented by the 15- and 40-cm depths) are optimal at S2 and S3 in all 3 years and too high at the 40-cm depth at S1 in 2012.

High maximum potential evapotranspiration (ET_{max}) and low climatic water balances lead to low groundwater levels at S1 in the subsequent year with a strong, but not significant, correlation (Table 5). This relatively pronounced climatic impact on the groundwater situation at S1 is due to the fact that the groundwater level in this soil is close to the surface. All other correlations between climate and groundwater levels in the soils are weak.

Correlations between groundwater extraction rates and groundwater levels in the soils are overall much stronger than correlations between climatic factors and groundwater levels. Groundwater extraction from W3 lowers the groundwater levels in all three soils in the year of extraction; the correlations are strong and significant (Fig. 6). The same is true for W1 and W7, albeit not always with significant correlations. Extraction from a group, formed by W2, W4, W5, W6, and W8, substitutes extraction from a second group, formed by W1, W3, and W7. As extraction from wells in the second group lowers the groundwater table in the three soils, the

substitution through the first group of wells leads to negative correlations between the groundwater level in the three soils and annual extraction sums of the wells in group 1 (W2, W4, W5, W6, W8). This must not be misinterpreted as higher groundwater levels caused by groundwater extraction but is rather a relief of the groundwater situation caused by extraction from wells that affect the groundwater levels in the soils less.

4 Discussion

4.1 Impact of climate and groundwater extraction on surface aquifers

In cultivated areas, the fluctuation of groundwater levels in surface aquifers is influenced not only by the climatic factors such as precipitation and evapotranspiration (Bradley 1996; Chen et al. 2002) but also by management factors such as surface drainage and groundwater extraction from connected aquifers. Still, when interpreting the longtime effects of anthropogenic impacts on groundwater levels in surface aquifers, climatic fluctuations of the individual years must be incorporated (Heuvelmans et al. 2011). In the surveyed area, the climatic water balances in the individual years visibly affect the course of the groundwater levels in all three surveyed soils but do not show an overall trend, which would explain why the groundwater level has been recovering within the past 10 years. Furthermore, the correlations between climate parameters and the average groundwater levels in the individual years are weak in all three soils, and correlations with annual

Fig. 5 Mean matric potentials (ψ_m) with standard deviation in 15- and 40-cm depth and mean groundwater levels (*GW*) with standard deviation at S1–S3 in the summer half years (May–October) of 2004, 2007, and 2012 with similar positive climatic water balances
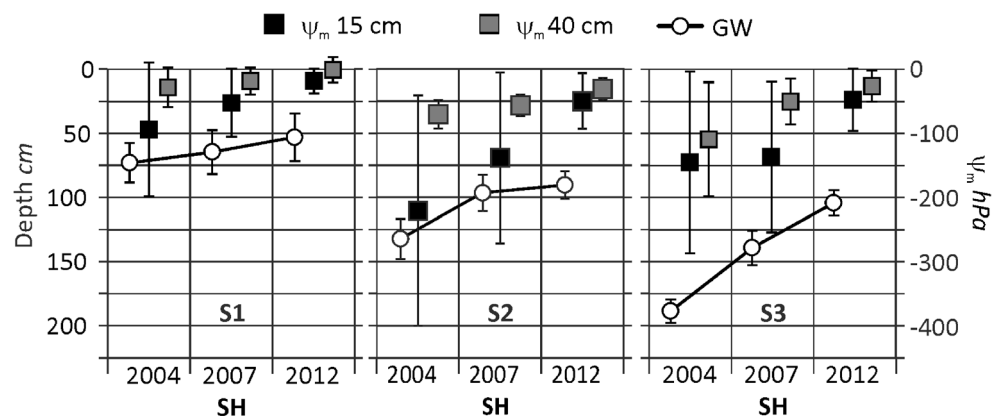
Table 5 Pearson's product-moment correlations between climate (annual climatic water balance, precipitation (P), maximum potential evapotranspiration (ET_{max})) in previous year vs. annual average groundwater level in current year and climate in current year vs. groundwater in current year at S1–S3

| Time scale	Climate factor [mm]/site	S1	S2	S3
Climate in previous year vs. groundwater level in current year	climatic water balance	**−0.53**	−0.15	−0.06
	P	0.19	0.15	0.24
	ET_{max}	**−0.62**	−0.20	−0.12
Climate in current year vs. groundwater level in current year	climatic water balance	0.28	−0.32	−0.19
	P	0.24	−0.36	−0.22
	ET_{max}	0.24	0.01	0.02

Bold types mark strong correlations

groundwater extraction rates of individual wells are much stronger. Thus, the overall altering of the groundwater situation in the survey area is caused by changes in groundwater extraction management, whereas the course of the groundwater level in the individual years is dominantly controlled by climatic factors. Here, the long monitoring period was useful, because it enabled us to compare the groundwater levels in climatically similar years and distinguish between climatic and anthropogenic effects.

The response of aquifers on groundwater extraction is known to be delayed in time (Gleeson et al. 2012; Kelly et al. 2013), especially if there is a certain distance between the location of the extraction and the groundwater recharge area (Sophocleous 2002). Additionally, the interactions between groundwater and surface water can be strongly affected by poorly permeable sediments (Johansen et al. 2011).

Although all three survey sites in the area are located within the potential groundwater depression cone modeled by Wichmann et al. (2003), both the groundwater situation at the beginning of the monitoring period and its development during the monitoring period differ in the individual soils. S1 has the shallowest groundwater situation all through the monitoring period. Already in 2004, the groundwater was not lowered to levels distinctly beneath the impact of the surface drainages in the soil at this site. S2 and S3 experience a pronounced rise of the overall groundwater level within the monitoring period and started with levels beneath the impact of surface drainages. Thus, S1 is less influenced by the groundwater extraction than S2 and S3. S1 is located in the lowland and the soil consists of humus substrates with a high water retention capacity. Moreover, S1 is directly underlain by little permeable layers of peat clay that covers the sand which

Fig. 6 Pearson's product-moment correlations between the annual sums of groundwater extraction rates from extraction wells (W) 1-8 and the annual average groundwater levels at S1–S3, and between the groundwater extraction rates of the individual wells in the same year
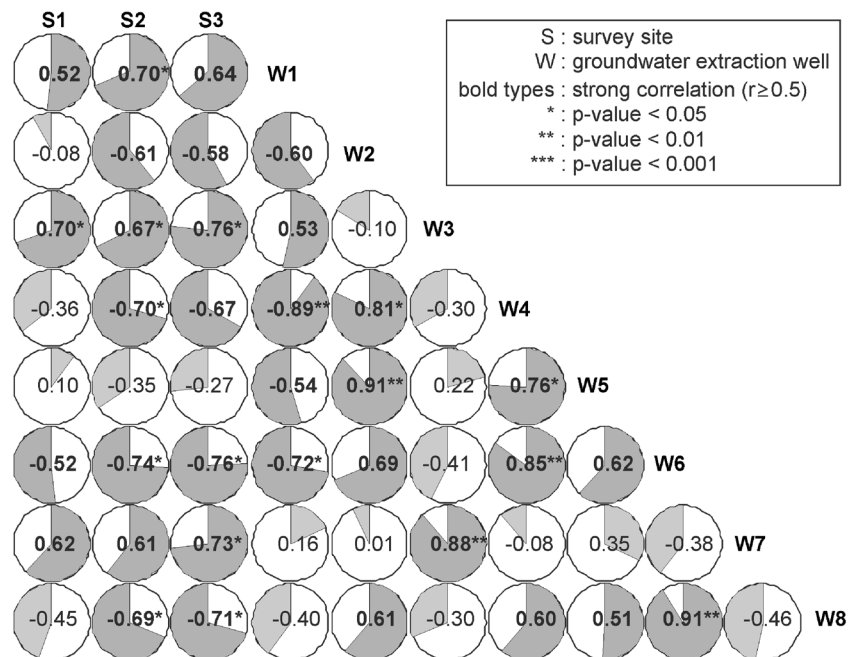
actually forms the surface aquifer. Due to this fact, more water can be stored in the soil close to the surface and the groundwater situation inside the soil will react slower and less distinctly on changes of the groundwater situation in the sandy part of the surface aquifer. In contrast, S2 and S3 are located in more elevated positions and the soil mainly consist of the more permeable sand of the surface aquifer, where leaks in the loam partition between the surface aquifer and the deeper aquifer will more directly affect the near surface groundwater levels.

Considering the soil type and the more elevated position, one would expect the lowest groundwater levels at S2 and not in S3, which is closer to the plain tract and holds a peat horizon. However, today, the strong impact of the extraction from W3 and W7 on the groundwater level at S3 has led to a situation, where the groundwater level corresponds neither with the original soil type nor with the position in the landscape in relation to S1 and S2.

4.2 Groundwater levels and grassland productivity

Soil texture and water table depth have a strong influence on groundwater contributions to evapotranspiration (Soylu et al. 2011). For similar groundwater depths, evapotranspiration rises with an increasing amount of plant available water in the effective root zone. However, temporary wetness with high groundwater levels would hamper the root activity due to lack of oxygen in wet periods (Mueller et al. 2005) and is unwanted in grassland production. Temperate grassland vegetation has 83 % of its root biomass in the upper 30 cm of the soil (Jackson et al. 1996), but in the case of shallow groundwater tables, the rooting zone will end at the upper fringe of the groundwater table.

The boggy lowland in the survey area has been under agricultural use for decades including a long history of surface drainage with furrows, pipes, and ditches in order to allow agricultural production with respect to the development of an optimal root zone and also to guarantee trafficability. The determined optimal and minimum groundwater levels for plant water supply through capillary rise are 60–100 cm below surface in the Histosols of the plain tract and 80–140 cm below surface in the Gleysols on the deposits from the Saale glacial stage. According to Mueller et al. (2005), optimal water use efficiency, and thus highest biomass production for grassland, requires groundwater levels not lower than 20–80 cm below the surface. Schindler et al. (2003) report that plant water supply through capillary rise was not limited when groundwater levels were 70 cm in peat soils in north-east Germany. Deeper groundwater levels worsened plant water supply in the surveyed soils.

However, the monitoring of ψ_m in the surveyed soils has revealed that groundwater levels within this range cause too wet conditions in the effective rooting zone for optimal root water uptake according to Feddes (1978) in all three surveyed soils, even though they also correspond with GW_{opt} derived from Ad-hoc-AG Boden (2005). Matric potentials (ψ_m) for optimal root water uptake occur in the effective rooting zones of the soils in the presence of groundwater levels conform with GW_{min} (100 cm at S1 and 140 cm at S2 and S3) and also at levels 20–60 cm lower. This is, of course, due to additional water supply through precipitation in combination with the water retention capacity of the individually structured bulk soil. These results point out that optimum groundwater levels for plant water supply cannot be well described by defining optimal groundwater levels alone.

5 Conclusions

– The actual management of the groundwater extraction with less utilization of three wells (W1, W3, and W7) from 2006 onwards is more suitable for the groundwater situation in the survey area than the groundwater extraction management before 2006 and has led to a recovery of the groundwater levels in the surface aquifer.

– Estimation of capillary rise on the basis of soil texture and level of the groundwater table alone does not represent actual field conditions, because they cannot take into account climatic properties of the site and variation in individual years.

– The annual courses of the groundwater levels in the survey area mirror the climate of the individual years. This causes variability in the average annual groundwater levels and makes it difficult to identify if the groundwater situation has become stable with the current groundwater extraction management or if an overall further rise must be expected. Therefore, the monitoring will be continued for another 5 years in order to identify and finally prove the new equilibrium.

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