Polish J. of Environ. Stud. Vol. 19, No. 4 (2010), 779-787

Original Research

Relationships between Local Climate and Hydrology in *Sphagnum* Mire: Implications for Palaeohydrological Studies and Ecosystem Management

Sandra Słowińska[1], **Michał Słowiński**[2], **Mariusz Lamentowicz**[3,4,5,6]*

[1]Institute of Technology and Life Sciences, Regional Research Division in Bydgoszcz,
Glinki 60, 85-174 Bydgoszcz, Poland
[2]Department of Geomorphology and Hydrology of Lowlands, Institute of Geography and Spatial Organization,
Polish Academy of Sciences, Kopernika 19, 87-100 Toruń, Poland
[3]Department of Biogeography and Palaeoecology, Faculty of Geographical and Geological Sciences,
Adam Mickiewicz University, Dzięgielowa 27, 61-680 Poznań, Poland
[4]Swiss Federal Research Institute WSL, Ecosystem Boundaries Research Unit,
Wetlands Research Group, Station 2, CH-1015 Lausanne, Switzerland
[5]École Polytechnique Fédérale de Lausanne (EPFL), Laboratoire des Systèmes Écologiques,
Station 2, CH-1015 Lausanne, Switzerland
[6]Laboratory of Soil Biology, Institute of Biology, University of Neuchâtel, CH-2009 Neuchâtel, Switzerland

Received: 29 October 2009
Accepted: 8 February 2010

Abstract

We investigated: a) the hydrology of a small *Sphagnum* mire located in a transitional climate in Eastern Europe, and b) the relationships between the local climate and hydrology of the mire. We hypothesized that temperature is the most important factor determining water table changes in this type of peatland in an exceptional biogeographic setting. Research on the Linje mire revealed that the groundwater table was predominantly influenced by air temperature, which determines the rate of evapotranspiration, particularly in summer. Another important physical factor that significantly influences the variation in groundwater table of the mire is the permeability of the surface deposits. Moreover, the vegetation (especially *Sphagnum*) also has a modifying influence. Our study is the first of this kind in the young glacial area of Poland as well as in Eastern Europe. There is a need to improve precision of the study by installing automatic data loggers, as well as to intensify monitoring of the mire and its surroundings in order to obtain a better picture of the relationships between the mire and forest management in its vicinity. Furthermore, in the future we plan to extend the monitoring to hydrochemistry and microbial indicators (e.g. testate amoebae and bacteria) to use the ecosystem approach in management of this valuable site.

Keywords: *Sphagnum*, mire, micrometeorology, groundwater changes, hydrology, heatwave

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*e-mail: mariuszl@amu.edu.pl

Introduction

Peatlands are important sinks of atmospheric carbon [1-3]. A specific role is played by mires dominated by the *Sphagnum* mosses that cover much of the Northern Hemisphere [4] and show extraordinary abilities to accumulate thick deposits of peat [5]. These ecosystems have accumulated up to about a third of the soil carbon during the Holocene period [6,7]. This stored carbon (250 to 455 Pg 76 of C) is equivalent to about 25 to 50% of the current atmospheric CO_2 burden [8]. Anthropogenic transformation, such as drainage and peat extraction, has resulted in partial or total degradation of mires and disturbance of the peat-forming process. As a result, some peatland ecosystems have become a source of carbon, rather than a sink [9]. In the context of climate change in the Holocene and the last millennium, knowledge of relationships between climate, hydrology and mires has started to play an important role in the management of peat-accumulating wetlands, to preserve them as carbon sinks [10-14]. Hydrogeology vs. climate of *Sphagnum* mires in eastern Europe has been given limited attention. When studying changes in the groundwater table position in peatlands, climatic factors must be taken into consideration [15]. There is little knowledge about the relationship between the local climate and hydrological conditions in mires in regions with a continental climate. Such information is crucial for both palaeohydrological studies and ecosystem management.

Furthermore, monitoring of mires cannot be based solely on fluctuations of the ground water table. In order to model the hydrological processes, there is a need to undertake long-term measurements of other parameters such as air temperature, humidity, and precipitation. Monitoring of changes should also include bioindicators (e.g. plants and microbes) that respond rapidly to any disturbance. Unlike the oceanic areas of Western Europe, where the growth of mires is mainly shaped by precipitation, in continental areas temperature is likely to play the main role in this process, but transitional climate areas might reveal much more complicated relationships [16-18]. The results of palaeohydrological research and the future success of the restoration of peatlands are highly dependent on the interrelations between climate and hydrogeology [14, 19]. Despite many years of hydrological studies in Europe and America, it is difficult to support palaeohydrological reconstruction with explicit references showing that, in the oceanic climate peatlands, wetness is driven by precipitation, and that in the continental climate, temperature is responsible for the water table fluctuations. Those two apparently simple topics await being fully described.

In the case of Linje mire we had the unique opportunity to track extreme hydrological change during the heatwave of 2006, which was especially pronounced in Central and Eastern Europe. The 2006 heatwave was located further north than in 2003, and especially affected Belgium, France, Germany, Italy, Netherlands, Poland, and Switzerland [20, 21].

In our study we investigated:

a) the hydrology of a *Sphagnum* mire located in a transitional climate in Eastern Europe, and
b) the relationship between the local climate and mire hydrology.

We also wanted to evaluate how data gathered during this study may influence palaeohydrological reconstructions using peat bog deposits from this region of Europe. We think that this simple question "what is more important precipitation or temperature for peat accumulation:" is still not fully answered in the context of oceanic-continental gradient, despite the many works that have been done.

Study Area

Linje mire is located in northern Poland near Bydgoszcz city (northern Poland), within the Complex of the Chełmno and Vistula landscape parks (53°11'15"-53°11'30"N, 18°18'37"-18°18'48"E) [22] (Fig. 1). The area of the

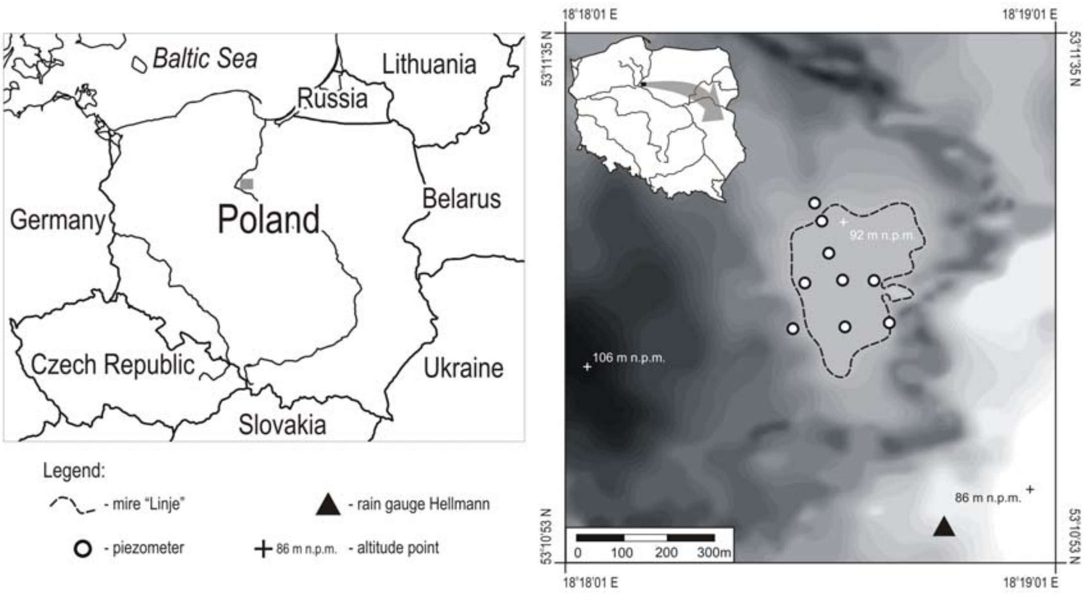

Fig. 1. Map showing the location of Linje mire.

reserve is 12.70 ha, and the mire covers 5.95 ha [23]. The average annual air temperature in the study area is 7.5-8.0ºC, and average annual precipitation ranges from 500 mm to 550 mm. The area is located within the range of the Poznań Phase of the Vistulian Glaciation [24]. The mire is situated at the border between a moraine hill and a sandur with a system of dunes [25].

Linje mire is often regarded as a raised bog [22]. In accordance with the classification of Hájek [26], based on vegetation, the mire should rather be classified as a poor fen, but small patches of ombrotrophic vegetation exist. The stratigraphic study made by Kloss and Żurek [22] at the southern end of the mire (Fig. 4) revealed a thick layer of biogenic deposits (up to 11.9 m). According to Kloss and Żurek [22], the development of the mire began at the end of the Vistulian Period as a result of paludification.

This mire is a unique floristic nature reserve, where the arctic-boreal species *Betula nana* is protected. This is one of three sites for this species in Poland, and the only one in the lowlands (the other two are found in the Sudety Mountains). This plant is regarded as a glacial relic, which in periglacial conditions was an abundant component of the vegetation [27]. Palynological investigations of Noryśkiewicz [28] and the analysis of plant macrofossils [29] revealed that *B. nana* has been growing around or within this area since the Alleröd [22, 28, 30].

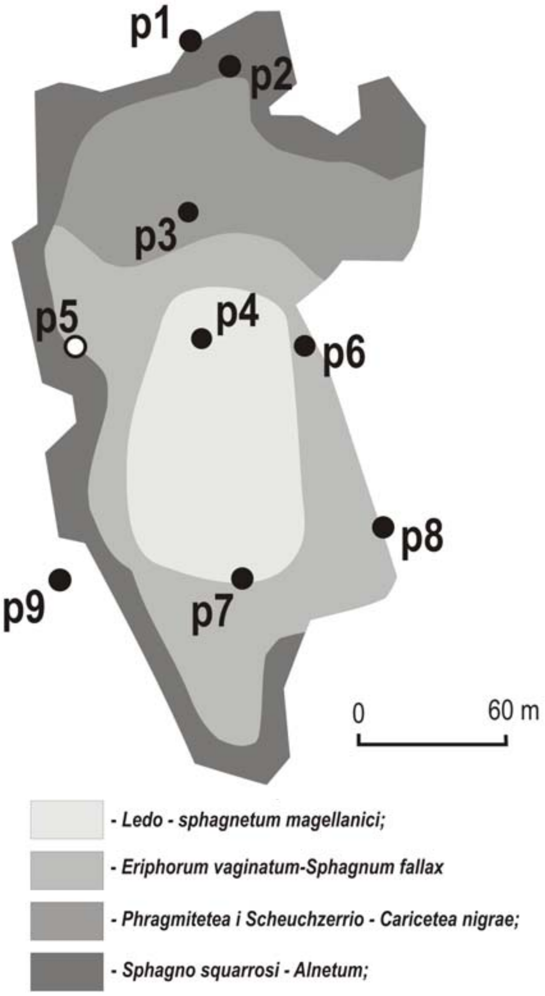

Fig. 2. Study site map showing the distribution of plant communities (according to Kloss and Kucharski 2005) and piezometers on Linje mire. The white point (piezometer p5) is the place that is most dependent on precipitation.

In the 19th century the mires in the vicinity of Gzin and the village of Linje were drained, which was mentioned by Hugo Conventz (according to Komendarczyk [23]). The drainage ditches are still visible in the Linje peatland. The effects of the drainage process also include tall dead pine trunks in the middle of the mire, which prove that the area experienced large water level changes, possibly as a result of drainage. The main north-south drainage ditch carried water from the mire to a lower-lying mire at a distance of about 450 m to the south.

Methods

In order to assess the groundwater table variation, nine piezometers were installed. Six of them were placed within the mire, while the other three were installed at the edge (Figs. 1, 2). Piezometers were made of PVC pipes of 50 mm diameter and 1.10 m to 2 m in length. At the bottom of each pipe (about 25% of the total pipe length), a system of 10 mm holes was drilled [31-33]. The piezometers were placed at the measurement sites along the N-S-E and W-E transects in June 2006. During the research, the piezometers were levelled.

In addition to the groundwater table research, precipitation measurements were also undertaken. A Hellmann rain gauge was installed at a distance of about 600 m from the mire. The rain gauge opening was placed one metre above the ground. Precipitation measurements were taken daily, and the readings from each week were added up in order to compare precipitation with the level of the groundwater table. The Hobo Pro H08-032-08 temperature/relative humidity data logger was installed at the same position as the rain gauge. The results of the groundwater table measurements were taken every week [34] between June and October 2006, and every two weeks between November 2006 and June 2007. Average and maximum daily air temperature and average daily relative humidity were based on measurements made at 10-minute intervals.

For the statistical analyses, i.e. correlation, statistical significance and standard errors, application R was used (R Development Core Team [35]). Stepwise linear regression was calculated with an SPSS package to assess which of the variables has a dominant impact on the water table change.

In order to visualize the relationships between the individual climatic parameters and water levels recorded by the piezometers, redundancy analysis (RDA) without data transformation was carried out with the use of CANOCO 4.3 software [36]. We applied forward selection in RDA to test which meteorological variable is the most important driver of the change in the water table.

Table 1. Water table statistics for Linje mire (p2-p7) and its surroundings (p1 and p8).

Piezometer	Average depth (cm)	Max. depth (cm)	Min. depth (cm)	Amplitude (cm)	Standard deviation (cm)	Coefficient of variation (%)
p1	69.8	85.0	34.0	51.0	13.1	18.8
p2	30.0	67.5	2.0	65.5	15.7	52.5
p3	15.2	34.5	0.0	34.5	8.5	55.7
p4	14.1	29.0	0.0	29.0	6.8	48.4
p5	10.6	23.0	0.0	23.0	6.3	59.2
p6	18.5	40.5	1.0	39.5	9.2	49.7
p7	11.6	30.0	0.0	30.0	7.0	60.3
p8	131.0	154.0	106.5	47.5	11.9	9.1

Results

Shape of the Groundwater Table Curve

The N-S-E transect crossed the middle section of the mire (Fig. 3). One piezometer (p1) was located in the fluvioglacial sands 10 m north of the mire. Four other piezometers (p2, p3, p4 and p7), were located in the mire, while p8 was placed on the dune that borders the mire from the east. The total length of this transect was about 350 m. The deepest groundwater table was recorded north and east of the mire, where water is naturally drained from the mire. Average groundwater table inclination from p3 towards p1 was 0.9% (distance 90 m), while from p2 (mire edge) towards p1 it was about 2.5% (distance 13 m). The groundwater table inclination from p7 (southern section of the mire) toward p8 (dune) was about 1.2% (distance 77 m).

During the study period, the groundwater table in the mire (p2-p7) was deepest in p2 and p6 (Table 1), i.e. near sand deposits. These were also the piezometers that showed the largest maximum and minimum depths of groundwater table throughout the entire research season. The smallest average, maximum, and minimum depths of the groundwater table, however, were recorded at p5, located at the western edge of the mire, where it is in contact with a dead-ice moraine. Out of all the piezometers located in the mire area,

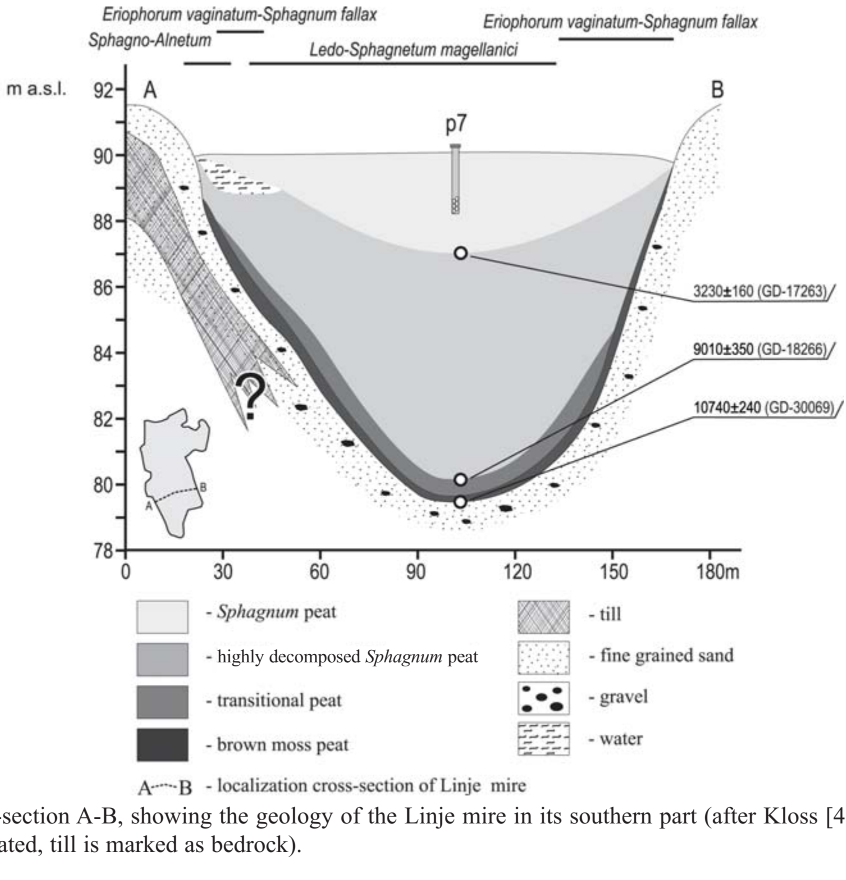

Fig. 3. Geological cross-section A-B, showing the geology of the Linje mire in its southern part (after Kloss [46], modified – radiocarbon dates were calibrated, till is marked as bedrock).

Table 2. Correlation coefficients (n=33) between ground water level and weather conditions from 25 June 2006 to 19 June 2007: weekly precipitation and average weekly air temperature.

Piezometer	Precipitation	Temperature
p1	-0.37*	0.51**
p2	-0.41*	0.49**
p3	-0.44*	0.48**
p4	-0.25	0.51**
p5	-0.48**	0.34
p6	-0.41*	0.47**
p7	-0.43*	0.63**
p8	-0.23	0.41*

* significant at $p<0.05$; ** significant at $p<0.01$.

the smallest variation in groundwater table was recorded in p4 (central section of the mire). Figs. 4 and 5 show the average groundwater table during the study period, and the results from the two days that represent low (30 July 2006) and high (17 April 2007) groundwater table in relation to the mire surface.

The W-E transect went through the central part of the mire (Fig. 5). It was about 110 m long. Average depth of the groundwater table increased eastwards. The inclination of the groundwater table from p4 towards p6 was 0.4% (46 m distance). The parameters of the groundwater table at the individual piezometers are presented in Table 1. Data from p9 were excluded from analysis, as the water table was below its base for most of the study period.

Temporal Variation in Groundwater Table

Deepest groundwater tables were recorded in July. This month recorded low total precipitation (27.5 mm), low relative humidity, and high average and maximum air temperatures (Fig. 6). High air temperature at the peak of the growing season caused intensive evapotranspiration from the mire surface. This, together with the low precipitation, resulted in lowering of the groundwater table. In August the groundwater table rose due to high precipitation (157.3 mm). The lack of precipitation in September and October did not bring such a significant lowering of the groundwater table as in July. However, it was slightly lower than in August. Between November and April the groundwater table rose until it reached its highest level in April (Figs. 4-6).

Local Climate and Spatial Variability in Water Table

The groundwater levels recorded at the individual piezometers were highly correlated with each other (in all cases $r>0.8$; $p>0.01$). This means that the mire, together with the surrounding area, reacts similarly to changes in weather conditions. The groundwater table in the mire seems to be related to air temperature (Table 2). Most of the correlation coefficients are statistically significant and only p5 did not show any significant correlation with temperature. The highest correlation with the temperature is represented by p7 ($r=0.6$; $p<0.01$). In contrast, the correlation coefficients between the piezometers and precipitation are mostly very low and insignificant. The highest value ($r=0.48$; $p<0.01$) is represented by p5, which is located in the western part of the mire. This position also receives surface run-off from the surrounding areas, which makes the groundwater table highly dependent upon precipitation. Piezometer p4, located in the central part of the mire (Table 2), shows the smallest dependence on precipitation, but p7 is the most dependent on average and maximum daily temperature. We applied linear stepwise regression to check which variable is the most important factor for water table variability. Average temperature and precipitation were used as independent variables, and the water table from particular piezometers served as a dependent variable. In most cases (Table 3) temperature was the dominant factor (precipitation was excluded from the model as insignificant). But piezometer 5 revealed significant relationships with the precipitation.

The interrelationships are presented in Table 2, and on the redundancy diagram (Fig. 7), where the values of groundwater table fluctuations at the piezometers (repre-

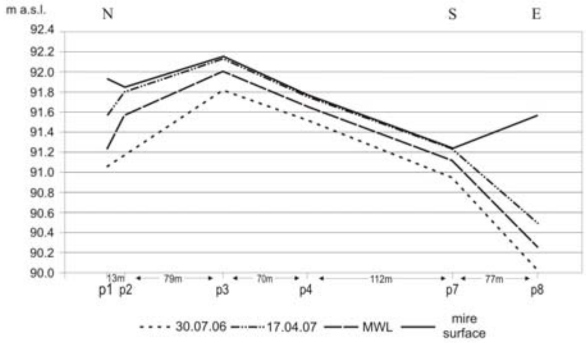

Fig. 4. Groundwater table along the N-S-E transect of the Linje mire. MWL – mean water level.

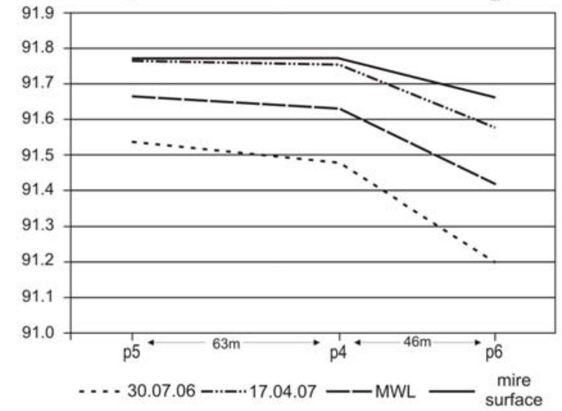

Fig. 5. Groundwater table along the W-E transect of Linje mire.

Table 3. Most important output of linear stepwise regression. Results for the best performing variables were presented, P1-P8 – piezometers.

Piezometer	Best variable	R Square	Adjusted R Square	t	sign
P1	temp	0.266	0.242	3.233	0.003
P2	temp	0.240	0.215	3.033	0.005
P3	temp	0.228	0.203	2.946	0.006
P4	temp	0.290	0.243	3.115	0.004
P5	precip.	0.232	0.208	-3.063	0.005
P6	temp	0.226	0.201	2.904	0.007
P7	temp	0.399	0.380	4.614	0.000
P8	temp	0.169	0.142	2.512	0.017

sented by the vectors) are correlated with the average and maximum temperatures. As analysis revealed, these variables explain 48% of all the groundwater table fluctuations at the piezometers (Fig. 7). The redundancy diagram also presents the correlation between the groundwater table and precipitation at p5, which is the only site where precipitation was significantly correlated with groundwater level throughout the study period. The diagram includes all the climatic parameters. Forward selection procedure in RDA revealed that temperature is the most significant variable explaining water table variability in piezometers.

Discussion

Our study revealed the general features of the hydrological functioning of Linje mire. The shape of the groundwater table curve along the N-S-E transect was convex. This indicates that the area is rain-fed (ombrotrophic). Along the W-E transect, from the west to the centre of the mire, the groundwater table is flat, while eastwards from the centre, the groundwater table declines. This allowed us to conclude that the western part of the mire is topogenic (i.e. groundwater input supplements precipitation here). This is confirmed by the existence of minerotrophic vegetation in this part of the mire.

Phytosociological investigations indicate that Linje mire is minerotrophic, but its central part is slightly raised and ombrotrophic [37]. Although our results may support that hypothesis, the analysis of vegetation structure (e.g. the domination of *Sphagnum fallax* and *Carex rostrata*) does not exclude the influence of groundwater from the catchment. The lagg zone is very diverse. This may result from horizontal water movement in the western part of the mire, and from drainage of groundwater by the dune-covered sandur in the eastern part of the mire. The outcome of this process is the diversity in the ecotones. Analysis of groundwater table variation in relation to climatic factors shows a high correlation. The changes in groundwater table are highly dependent on weather conditions, especially on maximum and average daily temperature. High air temperature and low relative humidity result in intensification of evaporation from the groundwater table and vegetation, which, in turn, brings about lowering of the groundwater table. Thus, temperature and relative humidity are directly connected with evapotranspiration from the surface of the mire. The effect of the heat wave in July 2006 on mire hydrology was interesting in that all of the piezometers reacted synchronically with lowered water tables. Piezometer p2 appeared to be the most sensitive as the water table decreased from -25 cm to -65 cm. This is the first record of the response of a peatland to a heatwave in this region of Europe so that there is no possibility to com-

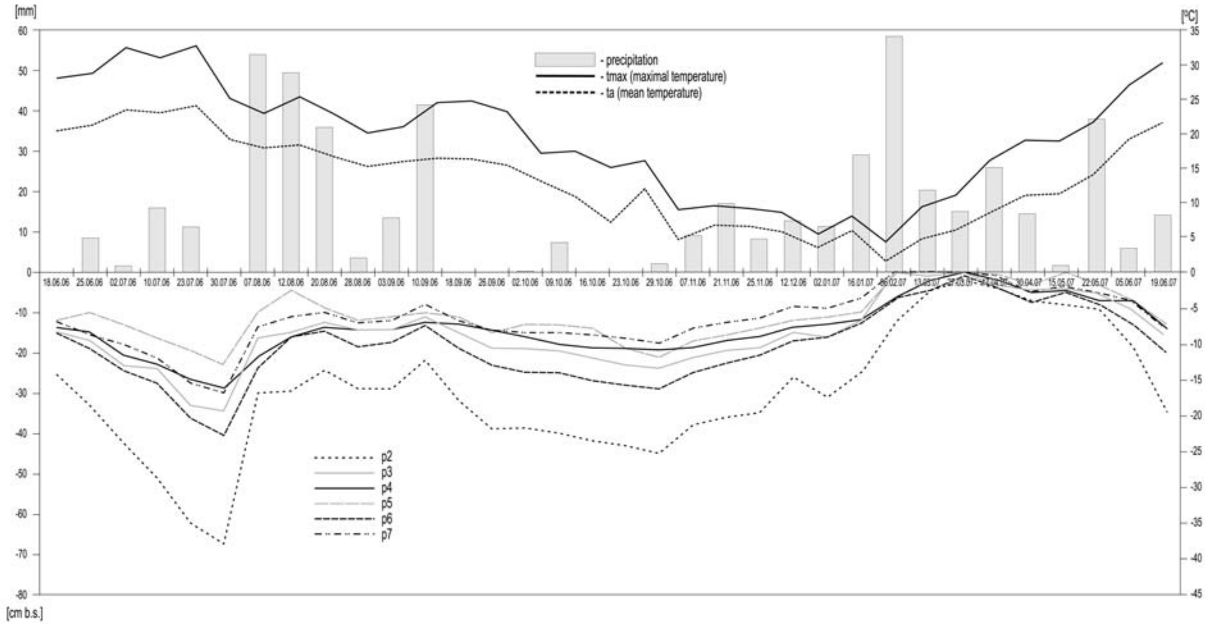

Fig. 6. Temporal variation of the ground water table changes in the Linje mire in comparison with maximum and average air temperatures.

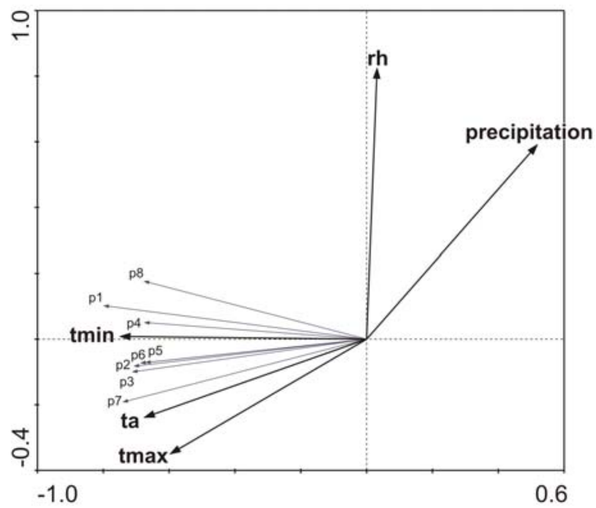

Fig. 7. Biplot of redundancy analysis (RDA), showing relations between water level variation and climatic factors. (rh – relative humidity; ta – average daily temperature; t_{min} – minimum temperature; t_{max} – maximum temperature).

pare with other records. However, it does allow an assessment of the magnitude of the hydrological changes to be made and it shows how important temperature is for the functioning of *Sphagnum* mires.

A relatively low correlation coefficient was recorded between the depth at which the groundwater table is found and the level of precipitation. This does not, however, give an overall view of the interrelationships. During the periods of high average and maximum daily temperature, evapotranspiration increases and thus the water stored in the upper (active) layer of the mire evaporates faster. As a result, in these periods precipitation was less effective than temperature. Due to limited precipitation (500-550 mm), the summer season experienced a groundwater deficit. It may be assumed that during very wet and cool seasons the relations between temperature and precipitation are more stable.

Our data show how complex palaeohydrological reconstructions from mires can be. Furthermore, an apparently simple question about the significance of temperature for peatland growth still needs more research in the different climatic and biogeographical regions. Such data allow for the better understanding of past processes in peatlands.

The results also suggest that in a transitional and continental climate, groundwater table position and the rate of peat accumulation may be strongly influenced by temperature. This prevents the formation of a typical dome of a raised bog. Good examples of such cases are Polish Baltic bogs, which do not develop distinctive domes like the Atlantic bogs of Western Europe. Unfortunately, there are no precise palaeoenvironmental studies of mires that might say which factor – precipitation or temperature – plays a more significant role in shaping the hydrological conditions in Polish mires. However, the work is in progress and the first approaches to this problem have already been made [38, 39].

The results of the Linje mire studies show that reconstruction of the groundwater table does not necessarily mean the reconstruction of precipitation. According to [40], the annual hydrological water deficit shows the strongest correlations with the reconstructed groundwater table. His hypothesis is supported by preliminary results of studies of testate amoebae on permanent plots in the Linje mire. The studies show that the species structure of these organisms best reflects the lowest groundwater table (Lamentowicz, unpublished data), thus testate amoebae should be most effective for reconstructing the lowest groundwater level in the mire.

Recent work of Charman et al. [16] showed that past bog surface wetness (BSW) is driven by precipitation reinforced by temperature. Our work based on instrumental data shows domination of temperature for this climatic setting. Currently, we need more high resolution data from different proxies (e.g. chironomids, testate amoebae, plant macrofossils) and various sedimentary archives (e.g. lakes and peatlands) to track past changes as over the last 10,000 years BSW might have had different relationships with the climate.

The hypothesis of the predominant role of temperature over precipitation in continental climate was constructed on the basis of Swedish and Estonian peat bogs [17, 18]. However, Charman [40] suggested that despite a larger role of temperature, it is precipitation that most strongly influences the balance of raised bogs. Nevertheless, not much information is available from mires located in a typical continental climate zone.

Our study provides a good example of the situation when various parts of the mire may be dependent on diverse climatic parameters, and how crucial the sampling site position is in a peatland for inferences on mire surface wetness and palaeoclimate reconstruction. Piezometer p5, which is located in the western part of the mire, shows the largest dependence on precipitation level and the lowest dependence on average and maximum daily temperature and average daily relative humidity. Additionally, this part of the mire receives surface run-off from the surrounding areas, which results in a significant dependence of groundwater table position on precipitation. Piezometer p4, which is located in the central part of the mire, shows the lowest dependence on precipitation, but p7 is the most dependent on average and maximum daily temperature.

Research on Linje mire reveals that the groundwater table is predominantly influenced by high air temperatures (Fig. 5), which determine the volume of evapotranspiration, mainly during the summer season. Among the physical factors that significantly influence the variation in groundwater table, the permeability of the surface deposits should be taken into consideration. Moreover, the vegetation cover has a modifying influence. The structure of *Sphagnum* mosses enables these organisms to store large amounts of water in their cells thanks to capillary forces [5, 41, 42].

The vegetation of the lagg drained by the nearby dunes is characteristic for the habitats that are both oligotrophic and highly acidic [5, 43, 44]. A different and much richer vegetation composition is recorded in the western lagg, where till is found in the bedrock. This structure results in horizontal water exchange.

Throughout the study period, the amplitude of groundwater table in the area did not exceed 66 cm, and in the central part 23 cm. The vegetation composition (the presence of peat-forming species) and the specific hydrological conditions at the mire indicate that the peat accumulation process is active [44, 45], although drainage was carried out in this area in the 19th century [23]. The recorded differences in groundwater table between the eastern and western parts of the mire might result from varied permeability of the underlying deposits. In the eastern part, the mire is drained by the surrounding dunes. The lagg zone in this area is dominated by *Eriophorum vaginatum*, which is a very good indicator of unstable hydrological conditions. By contrast, till deposits are found in the western part of the mire. The water drained from the mire by the sand deposits can influence the groundwater level within the entire catchment area of the mire by raising it, which was also noted by Dempster, et al. [46]. This phenomenon is best visible during dry summers, when the rapid reduction of the groundwater table in the surrounding area causes the groundwater table in the contact zones to decrease.

Acknowledgements

We thank to Krzysztof Błażejczyk for the support and productive discussions. We thank to Tomasz Giętkowski for the help in the fieldwork. The research was funded Polish Science and Higher Education grants No. 2P04G03228 and NN306085037. The study was also supported by the funds of the Institute of Geography (Kazimierz Wielki University in Bydgoszcz). Further funding to Mariusz Lamentowicz by Foundation for Polish Science (FNP; Outgoing Fellowship KOLUMB) is acknowledged.

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