Journal of Hydrology 558 (2018) 509–519

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Scots pine (*Pinus sylvestris* L.) based reconstruction of 130 years of water table fluctuations in a peatland and its relevance for moisture variability assessments

Marija Tamkevičiūtė [a,*], Johannes Edvardsson [b,c], Rūtilė Pukienė [a], Julius Taminskas [a], Markus Stoffel [b,d,e], Christophe Corona [b,f], Gintautas Kibirkštis [g]

[a] Nature Research Centre, Akademijos str. 2, LT–08412 Vilnius, Lithuania
[b] Dendrolab.ch, Department of Earth Sciences, University of Geneva, rue des Maraîchers 13, CH-1205 Geneva, Switzerland
[c] Quaternary Sciences, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden
[d] Climate Change Impacts and Risks in the Anthropocene (C-CIA), University of Geneva, 66 Bvd Carl Vogt, 1205 Geneva, Switzerland
[e] Department F.-A. Forel for Aquatic and Environmental Sciences, University of Geneva, 66 Bvd Carl Vogt, 1205 Geneva, Switzerland
[f] GEOLAB, UMR6042 CNRS, 63057 Clermont-Ferrand, France
[g] Dzūkija National Park and Čepkeliai State Nature Reserve Administration, Vilniaus str. 3, Merkinė, LT-65334 Varėna district, Lithuania

ARTICLE INFO

Article history:
Received 8 May 2017
Received in revised form 16 November 2017
Accepted 31 January 2018
Available online 2 February 2018
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of David C. Le Maitre, Associate Editor

Keywords:
Tree rings
Raised bog hydrology
Water table fluctuation
Čepkeliai wetland complex, Lithuania

ABSTRACT

Continuous water-table (WT) measurements from peatlands are scarce and – if existing at all –very short. Consequently, proxy indicators are critically needed to simulate hydrological changes in peatlands over longer time periods. In this study, we demonstrate that tree-ring width (TRW) records of Scots pine (*Pinus sylvestris* L.) growing in the Čepkeliai peatland (southern Lithuania) can be used as a proxy to reconstruct hydrological variability in a raised bog environment. A two-step modelling procedure was applied to extend existing measurements and to develop a new and longer peatland WT time series. To this end, we used instrumental WT measurements extending back to 2002, meteorological records, a P-PET (difference between precipitation and potential evapotranspiration) series covering the period 1935–2014, so as to construct a tree-ring based time series of WT fluctuations at the site for the period 1870–2014. Strongest correlations were obtained between average annual WT measured at the bog margin and total P-PET over 7 years ($r = 0.923$, $p < 0.00001$), as well as between modelled WT and standardized TRW data with a two years lag ($r = -0.602$, $p < 0.001$) for those periods where WT fluctuated at the level of pine roots which is typically at <50 cm depth below the peat surface. Our results suggest that moisture is a limiting factor for tree growth at peatlands, but below a certain WT level (<50 cm under the soil surface), drought becomes a limiting factor instead. To validate the WT reconstruction from the Čepkeliai bog, results were compared to Nemunas river runoff since CE 1812 ($r = 0.39$, $p < 0.00001$, 1870–2014). We conclude that peatlands can act both as sinks and sources of greenhouse gases in case that hydrological conditions change, but that hydrological lags and complex feedbacks still hamper our understanding of several processes affecting the hydrology and carbon budget in peatlands. We therefore call for the development of further proxy records of water-table variability in peatlands to improve our understanding of peatland responses to climatic changes.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

Wetland ecosystems are important carriers of biodiversity and habitats for numerous plant and animal species, as well as a significant agent in the global carbon cycle (MacDonald et al., 2006; Turetsky et al., 2015). Most often, peatlands act as major carbon sinks (Gorham, 1991; Lafleur et al., 2001; Turunen et al., 2002; Sagerfors et al., 2008; Salm et al., 2009), but can also be significant sources of CH_4, CO_2 and NO_x (Matthews and Fung, 1987; Saarnio et al., 2007; Turetsky et al., 2014; Joosten and Clarke, 2002; Tanneberger and Wichtmann, 2011), especially in the case that hydrological conditions should be changing.

Spatiotemporal dynamics of carbon fluxes in raised bogs are closely linked to the hydrological conditions in the peatland (Moore and Knowles, 1989; Freeman et al., 1993; Salm et al.,

* Corresponding author.
E-mail address: m.tamkeviciute@gmail.com (M. Tamkevičiūtė).

https://doi.org/10.1016/j.jhydrol.2018.01.067
0022-1694/© 2018 Elsevier B.V. All rights reserved.

2009; Gažovič et al., 2010; Mitsch et al., 2013). Hydrological shifts in peatlands can be measured as water-table (WT) changes, but the scarcity of instrumental time series, often limited to a few years, has so far hampered a precise knowledge of relationships between C sequestration and WT fluctuations beyond the period covered by instrumental records. Proxy records for peatland WT depth, which indirectly also generate information about C sequestration in the peatlands, are therefore highly valuable to improve both moisture and climate reconstructions.

Several studies have shown that radial tree growth of peatland trees is limited by the moisture status in the water unsaturated zone, and thereby drive the formation of tree-ring width (TRW) patterns that are closely linked to WT fluctuations in peatlands (Boggie, 1972; Pukienė, 2001; Leuschner et al., 2002; Edvardsson et al., 2016). Periods for which the water table has been located close to the bog surface usually generated low oxygen uptake and limited nutrient assimilation by the root system of trees (Linderholm et al., 2002), which most often resulted in depressed tree growth (Boggie, 1972; Edvardsson et al., 2016). Consequently, TRW data from peatland trees have been used to reconstruct hydrological variations within peatlands at annual to decadal time scales (Edvardsson et al., 2015a; Edvardsson and Hansson, 2015). Initial studies, based on peatland trees, have already been performed in the Baltic region by Balevičius et al. (1984), Cedro and Lamentowicz (2011), Smiljanic et al. (2014), and Edvardsson et al. (2015a). Most often, negative correlations have been observed between the moisture status in the peatland and radial tree growth (Smiljanic et al., 2014; Edvardsson et al., 2015a), but lag responses often rendered the interpretation of results difficult. Most of these studies have been based on the correlation between TRW and temperature and precipitation records, which, however, only yielded indirect information on WT changes in the peatland. Further studies are therefore needed to increase our understanding about the complex interaction between hydrology and tree growth at peatlands, as well as to improve our moisture reconstructions using tree-ring data from peatland trees. In this context, an almost natural (semi-pristine) wetland complex in southern Lithuania was chosen. A relatively long instrumental record of hydrological observations already exist from this wetland complex as well as meteorological data from a nearby weather station.

In this study, we explore the potential of Scots pine growing at the peatland as a proxy for WT fluctuations and a tool to extend WT records beyond the limits of the instrumental series at the study site. Our objectives are to: (i) extend the WT series with a P-PET series (i.e. difference between precipitation and potential evapotranspiration); (ii) establish a relation between TRW and WT values; and (iii) develop a WT record based on TRW data and instrumental measurements. These objectives provide the structural sub-headings used in the following Statistical analyses, Results and interpretation, Discussions sections.

2. Material and methods

2.1. Study site

Roughly one tenth (9.9%) of Lithuania is covered by peatlands, of which 2.7% are pristine or semi-pristine and the remaining 7.2% have been drained or managed; these figures are comparable to Lithuania's neighboring countries (Taminskas et al., 2012). The Čepkeliai wetland complex is located in southern Lithuania (54°01′N, 24°32′E), and borders Belarus (Fig. 1). The Čepkeliai State Nature Reserve was established in 1975, and has formed a Ramsar site since 1993. The total area of the reserve is 8477 ha, of which 5858 ha are covered by a wetland complex and the remaining 2725 ha are covered by forests. The Čepkeliai State Nature Reserve was formed to preserve one of the oldest and most natural raised bogs in Lithuania, as well as for the conservation of forested continental sand dunes, lakes, the natural hydrological regime of the raised bog and a rare plant and animal life. The highest point of Čepkeliai is 134 m above sea level (a.s.l.) in the domes of the raised bog, and reaches 127–130 m a.s.l. in the marginal fens. As such, the wetland complex represent one of the largest peatlands in the Baltic region and is, in addition, characterized by unusually large, open raised bog areas (82%), scattered fens (16%), transition mires (2%), small lakes, pools, forested islands and permanently flooded old forested areas (Povilaitis et al., 2011; Taminskas et al., 2012).

The wetland complex at Čepkeliai has been formed during the Holocene in the watershed of the Katra, Ūla, and Grūda streams (Nemunas river catchment). Rapid establishment of trees has been observed in the Čepkeliai raised bog over recent decades (Taminskas et al., 2008b), a process which is believed to be related to hydrological changes in the region (Edvardsson et al., 2015b; Ruseckas and Grigaliūnas, 2008). As clear signs of anthropogenic activities are clearly absent in the Čepkeliai wetland complex and its surroundings (Stančikaitė et al., 2017), colonization of the site with trees is believed to be related to hydrological changes associated with ongoing climate change (Bukantis, 1994; Stonevičius et al., 2017).

Geology and long-term palaeohydrological changes in the region have been discussed extensively in the past (Linkevičienė, 2009; Mažeika et al., 2009; Balakauskas et al., 2013; Stančikaitė et al., 2017), whereas research on bog vegetation and its interaction with hydrology has remained scarce (Balevicius et al., 1984).

2.2. Meteorological data

Meteorological data was obtained from the Varėna weather station (54°14′ 53.79″ N, 24°33′ 6.31″ E, 109 m a.s.l.) managed by the Lithuanian Hydrometeorological Survey, and located about 27 km north of the Čepkeliai wetland complex. At this site, monthly precipitation and air temperature have been measured since 1929. Average annual precipitation in the region is 680 mm yr^{-1}, (max/min values: 423/874 mm yr^{-1}, respectively). About two-thirds of annual precipitation falls during the vegetation period of trees that locally lasts from late May to late September. Over the last decade, precipitation has been above the average, especially during the vegetation period (i.e. +14% between 2004 and 2014 as compared to 1929–2014). Average annual temperature has been +6.4 °C (1929–2014). January is usually coldest with an average temperature of −5.1 °C whereas July is highest with +17.7 °C.

2.3. Hydrological data

Water-table fluctuations at Čepkeliai raised bog have been measured manually in 5 wells (Fig. 2, Table 1), at ten-day intervals from April to November since 2002 with a precision of 0.01 m.

Well 4-G is situated in the sand dunes adjacent to the raised bog, whereas well 4-A can be found in a transition zone at the bog's margin where water from the raised bog dome is collected (Rigg, 1925; Osvald, 1933; Howie and Meerveld, 2011). By contrast, wells 5-A, 6-A, and 3-A are located inside the raised bog. Water level in the wells was measured in m a.s.l. The elevation of the geodetic survey benchmark (RP-2) is H = 135.67 m (54°1′1.47″N, 24°25′53.7″E). Changes in water table are expressed as changes relative top the height of a zero level in each well which was set at the top of the peat layer. For well No 4-A, for instance, the zero level (i.e. the top of the peat layer in 2009) was at an elevation of 133.1 m a.s.l.

Runoff data from the Nemunas river are measured at the Smalininkai gauging station (55°4′ 22.05″N, 22°35′ 15.86″E) by the Lithuanian Hydrometeorological Survey. We used this data to test

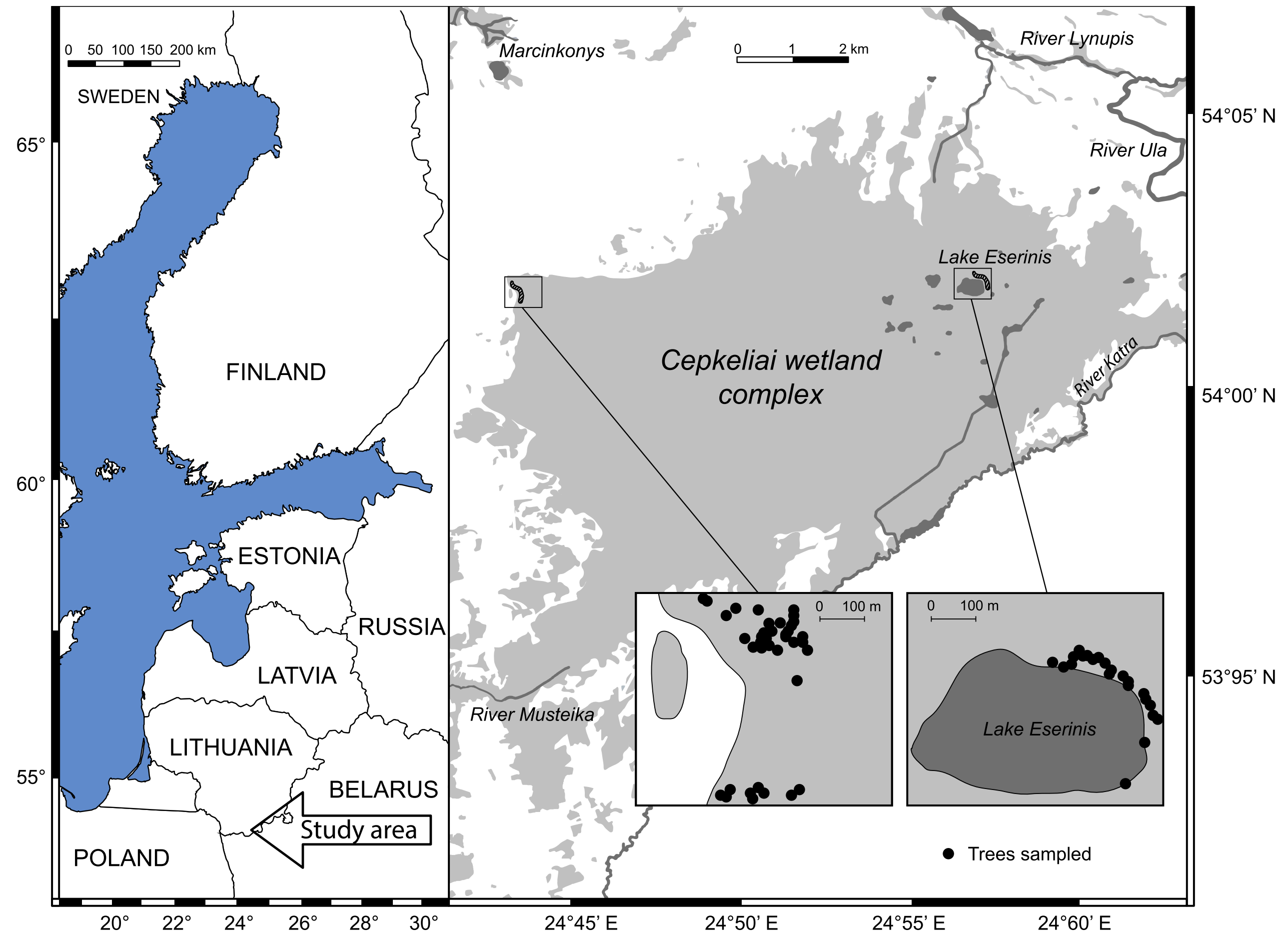

Fig. 1. Location of the study site and tree sampling design in the raised bog of the Čepkeliai wetland complex.

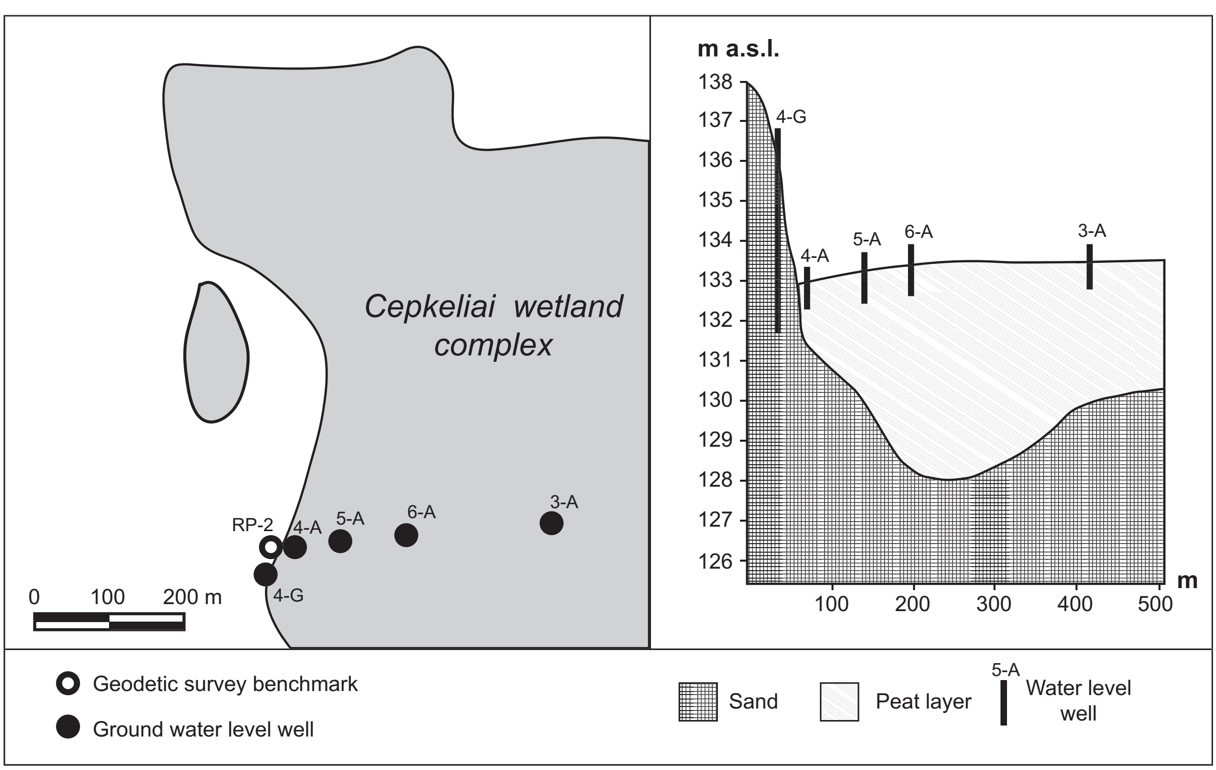

Fig. 2. Location of the water-table wells located in the north-western part of the Čepkeliai wetland complex.

Table 1
Water table (WT) parameters of the wells analyzed at the Čepkeliai wetland complex.

Well, coordinates	Top of well (m a.s.l.)	Distance from bog margin (m)	Soil horizon	Peat layer thickness (m)	Well depth from bog or mineral soil surface (m)	Filter structure
4-G 54° 01′ 00″ N, 24° 25′ 53″ E	136.21	–	Sand	–	4.50	PA Grid 4.0–4.5 m from the mineral soil surface
4-A 54° 01′ 01″ N, 24° 25′ 55″ E	133.29	10.00	Peat	1.50	0.72	Continuously perforated pipe
5-A 54° 01′ 01″ N, 24° 25′ 56″ E	133.60	75.00	Peat	3.20	1.00	Continuously perforated pipe
6-A 54° 01′ 01″ N, 24° 26′ 03″ E	133.69	150.00	Peat	5.10	0.92	Continuously perforated pipe
3-A 54° 01′ 01″ N, 24° 26′ 14″ E	133.50	340.00	Peat	3.50	0.80	Continuously perforated pipe

and validate the tree-ring based water-table reconstructions from the Čepkeliai raised bog. The Smalininkai gauging station has the longest measurement series of river runoff data in Lithuania (1812–today).

2.4. Tree-ring data

In April, September, and October 2014, increment cores from 96 Scots pine trees (*Pinus sylvestris* L.) were collected using a Pressler increment borer. Trees growing near the raised bog lagg zone were sampled as low as 40 cm above the peat surface so as to maximise the number of growth rings in these slow-growing samples. By contrast, trees growing near Ešerinis Lake (Fig. 1) were sampled at conventional breast height (130 cm) as growth was less suppressed in their case. Tree cores were air dried and sanded with increasingly finer grit until tree-rings and cellular structures became clearly visible (Stoffel and Corona, 2014). Thereafter tree-ring widths (TRW) chronologies were computed based on the measurements of annual growth rings with a precision of 0.01 mm, using a Lintab 5 measuring table and TSAPWin software (Rinn, 2003). Series were then cross-dated with conventional dendrochronological techniques (Fritts, 1976). The quality of measurements and TRW chronologies was evaluated with COFECHA (Holmes, 1983), which allowed removal of trees characterized by asynchronous growth.

3. Statistical analyses

To reconstruct hydrological variability in the Čepkeliai peatland, a two-step modelling procedure was employed to (i) extend the instrumental WT series via a P-PET analyses, and (ii) to reconstruct WT fluctuations based on the TRW series from *Pinus sylvestris* growing at the peatland.

3.1. WT reconstruction based on P-PET analysis

To reconstruct fluctuations of the water table in the Čepkeliai raised bog, we first computed relations between annual instrumental WT (IWT) changes and compared them to estimated precipitation vs. Potential evapotranspiration (P-PET) data for time windows ranging from 1 to 10 years. To estimate possible trends and/or changes thereof in evaporative demand, we looked at the four primary meteorological variables wind speed, atmospheric humidity, radiation, and air temperature, as these have been shown to be particularly relevant in long-term water resource assessments (McVicar et al., 2012). At the Varėna meteorological station, net radiation is not measured, which prevented the application of Penmans‘s or Priestly-Taylor equations (Sumner and Jacobs, 2005) to estimate evapotranspiration. We therefore used an equation based on air temperature in which potential evaporation rates are obtained via empirical relationships (Donohue et al., 2010). In concrete terms, and for the purpose of our study, Thornthwaite‘s equation (Thornthwaite, 1948) has been applied as follows:

$$\mathrm{PET} = 16(10\mathrm{T}/\mathrm{I})^{a} \quad (1)$$

where T represents average monthly temperature, I is a heat index for a given area which is the sum of 12 monthly index values i and, where a is an empirically derived exponent as a function of I:

$$\mathrm{i} = (\mathrm{T}/5)^{1.514} \quad (2)$$

$$\mathrm{a} = 0.000000675\mathrm{I}^3 - 0.0000771\mathrm{I}^2 + 0.01792\mathrm{I} + 0.49239 \quad (3)$$

To model PET in the Čepkeliai peatland, we used average monthly temperature from the Varėna meteorological station. The difference (D) between P and PET provides a simple means to measure water surplus or deficit for the analysed time window (Vicente-Serrano et al., 2010):

$$\mathrm{D_i} = \mathrm{P_i} - \mathrm{PET_i} \quad (4)$$

Based on this equation, we estimate that roughly 69% of total precipitation is lost through evapotranspiration in Čepkeliai, of which 82% takes place in during the vegetation period of trees which is locally lasting from late May to late September. On average, the annual potential evapotranspiration is about 469 mm. Relations between P-PET and IWT were thereafter modeled through regression estimates and used to reconstruct WT changes for the period of available meteorological data.

3.2. Relation between TRW and WT

In a second step, relations between modeled mean annual water table (MWT) according to the P-PET analyses were contrasted with annual tree growth to extend the hydroclimatic reconstruction further back in time.

To minimize the influence of non-climatic variations and trends related to tree age and geometry, the TRW data was standardised and transformed into dimensionless TRW indices (Fritts, 1976; Cook and Kairiukstis, 1990) using the ARSTAN_41d software (Cook and Krusic, 2006). To preserve potential low-frequency variations in tree growth, a flexible Friedman's variable span smoother (Friedman, 1984) was used for standardization. Reliability of the TRW chronologies and the common variance of the single series were evaluated with the expressed population signal (EPS; Wigley et al., 1984) and running rbar (Cook and Kairiukstis, 1990), respectively. The limit at which the records were considered reliable and well replicated was set to the commonly accepted threshold of EPS $\geq$ 0.85 (Wigley et al., 1984). Three different TRW chronologies were created using ARSTAN_41d, a raw TRW chronology (Raw), a standardised TRW chronology (STD) and a residual TRW chronology (RES).

Pearson correlation analysis was used to estimate the relationship between TRW series (STD chronology) and WT fluctuations. Lagged correlations between hydrological, meteorological, and dendrochronological data were computed to quantify potential lag effects. Nonlinearity between TRW and MWT was taken into account by nonlinear regression. Segmented regression with a breakpoint at the vertex of best fit second order polynomial curve was used to establish the interval of WT fluctuations in which linear regression model could be applied.

3.3. WT reconstruction using TRW data

Separate calibration (1986–2012) and independent verification (1935–1964) periods were used to validate the WT reconstruction models based on our TRW series developed from the peatland pines. The TRW based water table reconstruction (TRWWT) was considered only for that period for which TRW data were reliable and statistically robust. Nemunas river runoff data was thereafter used to validate the WT reconstructions obtained for the Čepkeliai raised bog.

4. Results and interpretation

4.1. WT reconstruction derived from P-PET assessment

The correlation values (2002–2014) between annual instrumental water table (IWT) measurements in the different wells shown in Fig. 2 and the ratio of precipitation vs. potential evapotranspiration (P-PET) for periods ranging from 1 to 10 years are presented in Table 2. The strongest correlation coefficient ($r = 0.92$, $p < 0.00001$) was observed between average annual IWT at well 4-A, located closest to the lagg, and P-PET over 7 years. The following regression model was used for estimates of WT fluctuations from the P-PET:

$$WT = 0.0014\Sigma_7(P - PET) + 130.79 \quad (5)$$

Estimates from this model were then used to extend the WT series at the lagg (well 4-A) for the period 1935–2002. According to our reconstructions, the WT fluctuated from 133.3 m a.s.l. to 132.1 m a.s.l. This means that the WT has been 20 cm above the zero level in wet years at the bog lagg and that its surroundings were subject to flooding. At the other extreme, in very dry years, the WT at well 4-A was 100 cm below the level of the peat surface.

4.2. Relations of TRW with WT

After crossdating and evaluation of the TRW series, 50 out of 96 trees were included in the final TRW chronologies used for WT reconstructions. The relatively high rejection rate of samples (48%) is related to the large number of missing rings in many tree-ring samples. The final TRW chronologies and related sample depth over time are presented in Fig. 3. The EPS values of the raw (RAW), standardised (STD), and residual (RES) TRW chronologies are above the critical threshold of 0.85 between 1870 and 2014 for all series.

Strongest correlation has been obtained between the measured WT at well 4-A and the STD TRW chronology. A lag effect between tree growth and water level in the peatland was detected as the strongest relation between TRW and MWT which was obtained with a 2-year lag in the TRW record. Moreover, the 2-year lag between TRW and MWT revealed a nonlinear dependence between the two parameters (Fig. 4). Nevertheless, MWT could be segmented into two distinct intervals with a threshold at the vertex of the best-fit curve, i.e. at 132.6 m a.s.l. (i.e. 50 cm below the peat surface), as characterized by different response of TRW to WT fluctuations. Linear negative dependence ($r = -0.57$) of TRW with MWT was observed when MWT fluctuated within a 50 cm layer below the peat surface, but this relation vanished and even turned to insignificantly positive after the MWT dropped below the 50 cm threshold (Fig. 5).

Our records show a dry period, with water levels below 132.6 m a.s.l., between 1965 and 1985. At the beginning of this phase, tree growth was fairly moderate before a growth depression started to emerge in the 1970s, followed by a gradual recovery up to 1981. With the exception of the period just described before, negative correlations between MWT and STD-TRW chronology was observed, suggesting that increasing peat moisture limited tree growth at the peatland. The strongest significant correlation coefficient ($r = -0.604$, $p < 0.00001$) was computed between MWT and STD TRW chronology with an offset of 2 yrs in TRW indices (see Table 3), which supports the idea that the WT fluctuations have a delayed influence on radial tree growth.

The correlation tests show that any rise in water table results in depressed tree radial growth, which is visible in the form of narrower annual growth rings, except for the extremely dry period 1965–1985. In Fig. 6, we compare STD-TRW indices and MWT values with their low frequency components (i.e. a 5-yr moving average). In general terms, those periods associated with depressed radial growth correspond with phases with high water levels, as was the case for instance during 1935–1939, 1945–1950, 1958–1963, 1983–1994, and ever since 2004. Opposite conditions were recorded for periods with low water tables during 1939–1945, 1953–1956, and to a lesser extent, 1995–2003. During these phases, relatively dry conditions allowed better growth in trees. The only exception is observed for the period 1965–1985, as this interval was characterized by water-table levels < 132.6 m a.s.l.; the latter did not trigger any specific trends in tree growth.

Table 2
Correlations between annual instrumental water table (IWT) measurements in different wells (4-G, 4-A, 5-A, 6-A, 3-A) and the ratio of precipitation vs. potential evapotranspiration (P-PET) for periods ranging from 1 to 10 years.

	$\sum_1$(P-PET)	$\sum_2$(P-PET)	$\sum_3$(P-PET)	$\sum_4$(P-PET)	$\sum_5$(P-PET)
4-A	0.14	0.25	0.56	0.78*	0.76*
4-G	0.12	0.19	0.51	0.72*	0.68
5-A	0.17	0.29	0.54	0.74*	0.63
6-A	0.22	0.32	0.53	0.70*	0.50
3-A	0.19	0.27	0.48	0.71*	0.58
	$\sum_6$(P-PET)	$\sum_7$(P-PET)	$\sum_8$(P-PET)	$\sum_9$(P-PET)	$\sum_{10}$(P-PET)
4-A	0.73*	0.92****	0.90***	0.87**	0.86**
4-G	0.61	0.82**	0.82**	0.76*	0.74*
5-A	0.69*	0.88***	0.83**	0.79*	0.77*
6-A	0.58	0.79*	0.76*	0.68*	0.60
3-A	0.64	0.84**	0.80**	0.75*	0.68

Correlation significance levels are marked as follows:
* ($p \le 0.01$).
** ($p \le 0.001$).
*** ($p \le 0.0001$).
**** ($p \le 0.00001$).

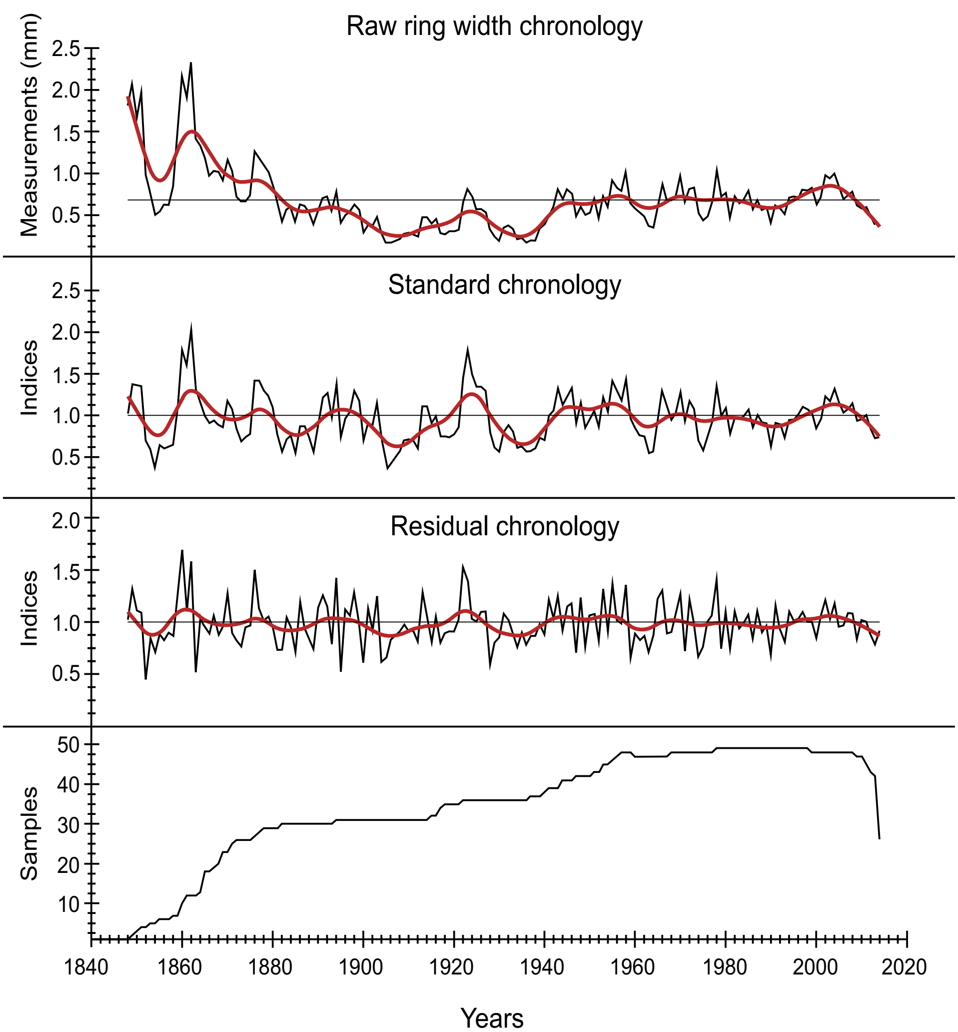

Fig. 3. Raw, standardised, and residual tree-ring width (TRW) chronologies and related sample depth (i.e. trees available in each year of the reconstruction). The black curves show radial tree-growth variability with annual resolution whereas the smoothed red curves are 20-year low-pass filter splines highlighting low-frequency patterns of variability at the site.

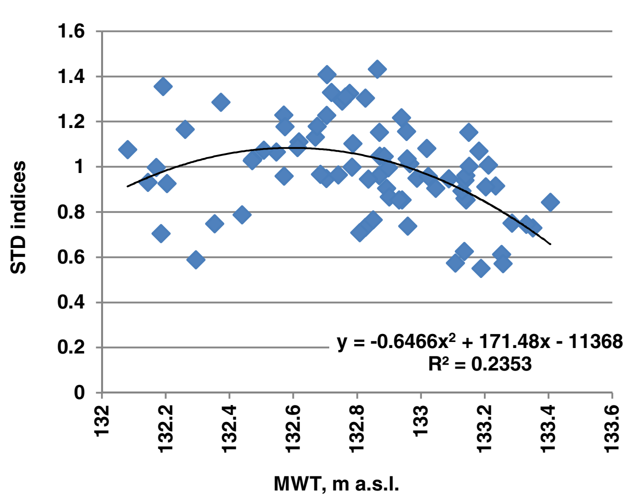

Fig. 4. Scattergram of tree-ring width (TRW) indices (with a 2-yr offset) versus mean annual water table (MWT) at well 4-A; peat surface elevation 133.1 m a.s.l.) in a given year.

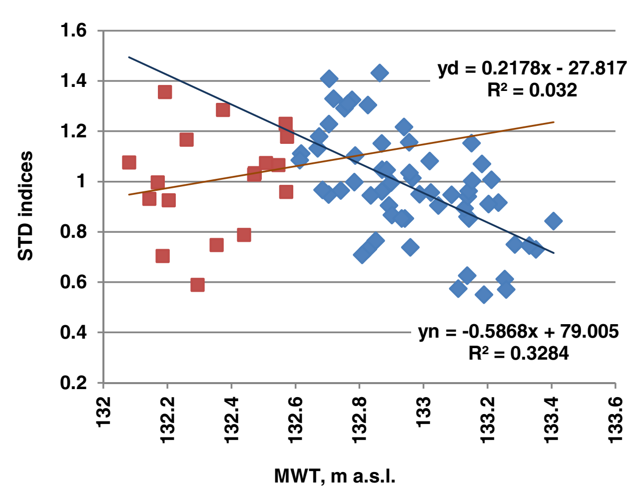

Fig. 5. Linear dependencies of tree-ring width (TRW) indices (with a 2-yr offset) on annual mean water table (MWT; as in Fig. 4) for different intervals of MWT fluctuations: the blue line and symbols mark a negative dependence when MWT was >132.6 m a.s.l. (y_n), the brown line and symbols mark extreme drought years (y_d).

Table 3
Pearson correlation values between mean annual water table (MWT) and the standardised tree-ring width (STD-TRW) chronology indices depending on year offsets in TRW indices.

Offset MWT–TRW (in yrs)	r	p
0	−0.23	>0.05
−1	−0.42	<0.001
−2	−0.60	<0.00001
−3	−0.57	<0.00001
−4	−0.46	<0.001
−5	−0.32	<0.05

4.3. WT reconstruction based on TRW data

A significant correlation was obtained between WT fluctuations as derived from P-PET analyses for well 4-A and the STD-TRW chronology ($p < 0.00001$), provided that the dry period comprised between 1965 and 1985 was excluded from analyses. The linear regression model between both datasets was calibrated over the period 1986–2012, whereas the time window 1935–1964 was used for independent model verification. The correlation coefficient between MWT and STD-TRW chronology, using an offset of 2 years, is $r = -0.602$ ($p < 0.001$) for the calibration period 1986–2012 and the linear regression model is expressed as follows:

$$TRWWT_t = -0.9564STD_{t+2} + 133.91 \quad (6)$$

where $TRWWT_t$ is the reconstructed WT based on TRW in year t, and STD_{t+2} is the tree-ring STD index with a 2-yr offset.

For the verification period, correlation between observed and estimated WT fluctuations is 0.691 ($p < 0.0001$). Based on the significance of this test, our model was thereafter used to estimate WT levels at the site between 1870 and 1935 (Fig. 7).

Periods with high water tables (≥133.0 m a.s.l., or 0.1 m below the peat surface) were reconstructed for the phases 1870–1873, 1879–1888, 1902–1910, 1915–1919, 1926–1939, 1947–1950, 1957–1963, 1983–1990, and since 2005. Low water tables (≤132.8 m a.s.l., or 0.3 m below the peat surface) were detected in 1874–1878, 1889–1897, 1920–1926, 1940–1946, 1952–1956 and 1995–2003. Noteworthy, our tree-ring records are not able

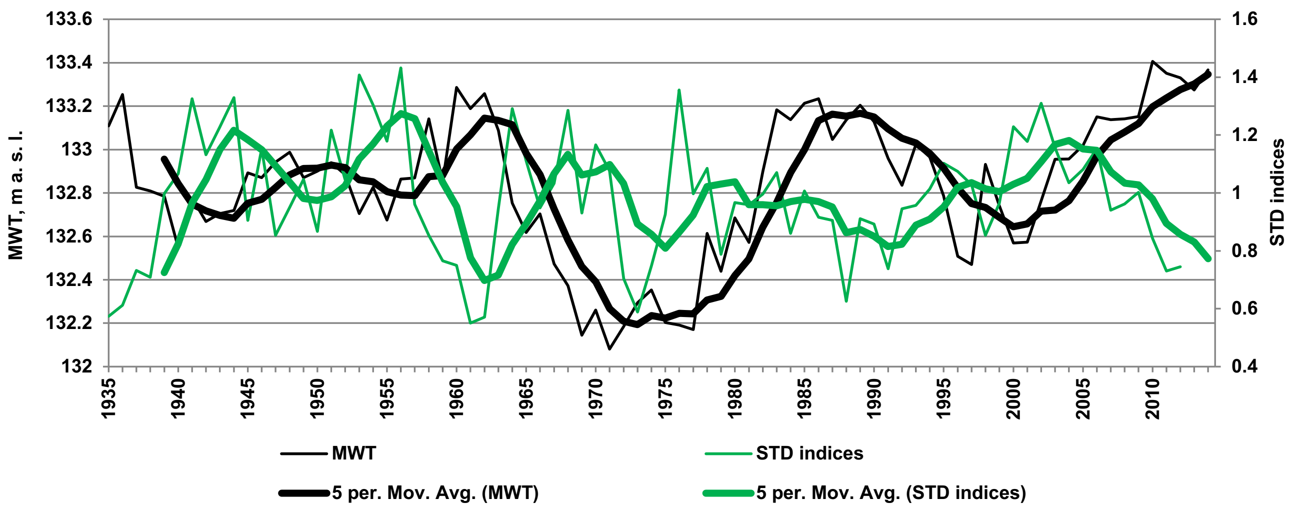

Fig. 6. Mean annual water table (MWT; well 4-A) and tree-ring width (TRW) indices of the standardised (STD) chronology. The best match between curves was obtained when the TRW chronology curve is shifted by 2 years, thus taking account of the lagged response to the MWT.

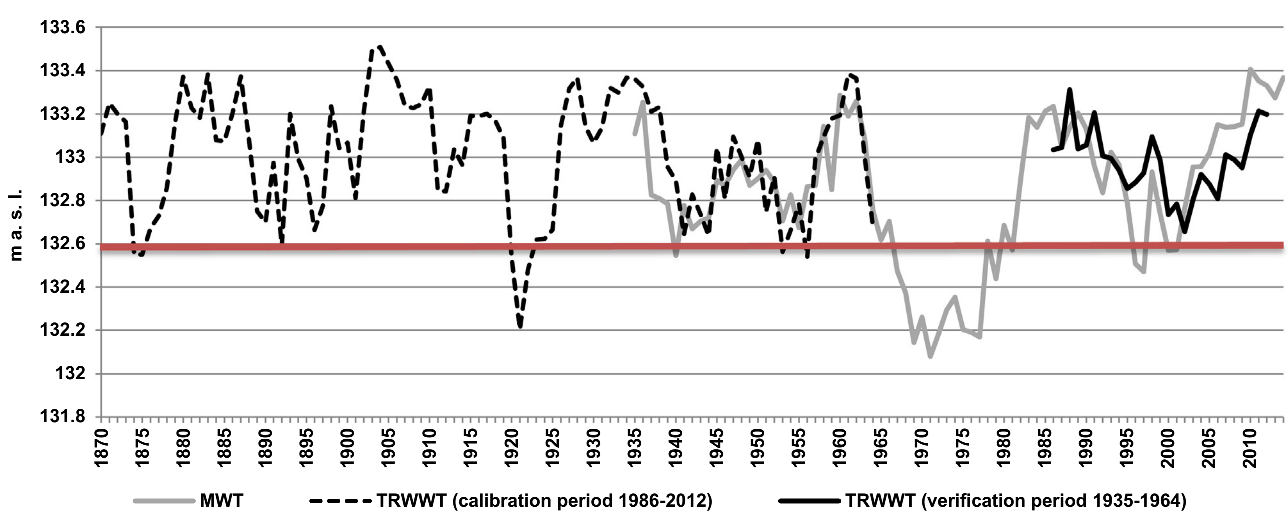

Fig. 7. Reconstructed mean annual water table (MWT) in the raised bog (well 4-A) based on (i) 7-yr P-PET values (solid grey line; $MWT = 0.0014\sum_7(P\text{-}PET) + 130.79$) and (ii) the tree-ring based water table (TRWWT) reconstruction for well 4-A according to the standard tree-ring width (STD-TRW) chronology (dotted line; $TRWWT_t = -0.9564 STD_{t+2} + 133.91$). Calibration period is 1986–2012 (dotted line), verification period is 1935–1964 (solid black line).

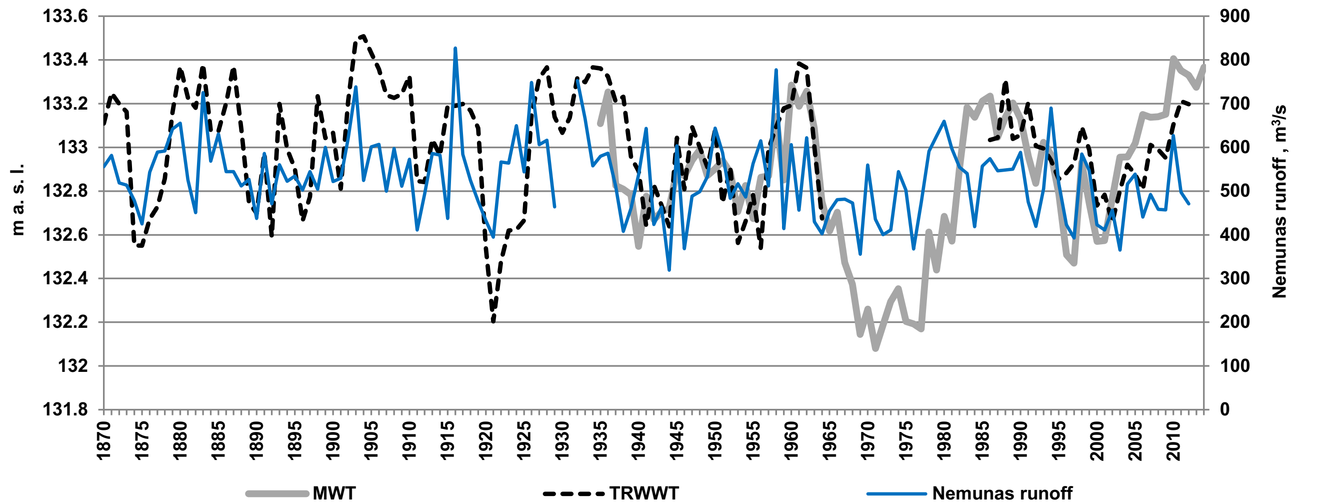

Fig. 8. Reconstructed mean annual water table (MWT) in raised bog at well 4-A according to (i) 7-yr P-PET values (solid grey line; $MWT = 0.0014\sum_7(P\text{-}PET) + 130.79$), (ii) tree-ring width based water table (TRWWT) reconstruction at well 4-A using the standardised tree-ring width (STD-TRW chronology; dotted line; $TRWWT_t = -0.9564\ STD_{t+2}+133.91$) and Nemunas runoff (in m^3/s; blue line).

to reproduce prolonged periods of low water tables during which values drop below 132.6 m a.s.l.

To validate our hydrological reconstructions, the Čepkeliai WT data was compared to mean annual runoff data from the Nemunas river at Smalininkai gauging station. Runoff data is assumed here to represent the common hydrological situation for the entire Nemunas catchment area (Fig. 8). Reconstructed long-term changes for the hydrological regime at Čepkeliai raised bog, which is located in the central course of Nemunas river, are significantly correlated with river runoff data ($r = 0.39$, $p < 0.00001$, 1870–2014).

The agreement between the reconstructed TRWWT and Nemunas runoff data further underline the robustness of our reconstruction. Periods with high WT correspond to narrow growth rings in the TRW records and years with large overall runoff. This coherence suggests that TRW data developed from peatland pine trees can be used as a proxy of WT levels in peatlands. The only exception was the prolonged and exceptionally dry period in which the link between TRW and WT disappeared.

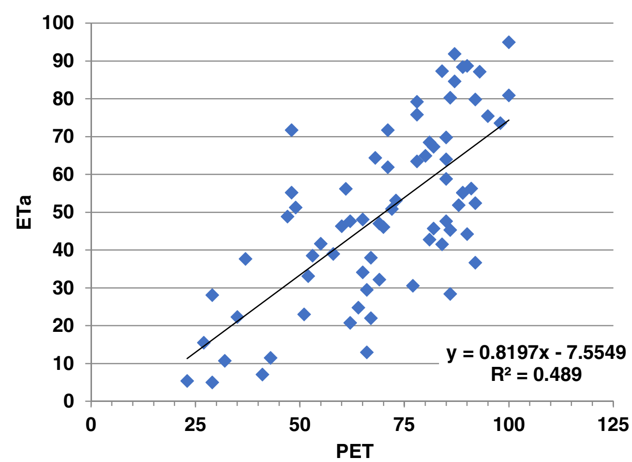

Fig. 9. Comparison of observed actual evapotranspiration (weighing lysimeter, ETa) and modeled potential evapotranspiration (PET) using Thornthwaite's equation at Utena, Lazdijai and Vėžaičiai (Lithuania).

5. Discussion

5.1. WT reconstruction based on P-PET

The different calculation models considered in this study have allowed comparison of different approaches in a field for which data is still scarce and knowledge of processes and drivers remains fragmentary. The application of Thornthwaite's equation, based exclusively on a temperature relationship, has certain limitations and at bests a theoretical justification (Taylor and Ashcroft, 1972). Since temperature and vapour pressure gradients are related to the movement of air as well as to the heating of the soil, the validity of the equation should not be generalized. Moreover, the equation has to be tested empirically whenever the climate is appreciably different from the area in which it has been tested originally (Skaggs, 1980; Nokes, 1995; Xu and Singh, 2001). We opted for Thornthwaite's equation due to a lack of more complete input data, but also because earlier studies by Taminskas et al. (2008a) have obtained a reliable relationship (R^2 from 0.57 to 0.62) between observed actual evapotranspiration and potential evapotranspiration in a set of sites close to our study site. In that study, the utility of Thornthwaite's estimates towards a reconstruction of variability in evapotranspiration was tested by comparing results according to Thornthwaite's equation with the same month weighing lysimeter method estimates of actual evapotranspiration at three locations (Fig. 9).

Our study has also demonstrated the crucial role of a dense WT monitoring network so as to accurately reconstruct WT fluctuations in peat bogs. Indeed, correlations between P-PET, TRW data and raised bog WT fluctuations obviously depend on piezometer location (Table 2). In our case, the strongest correlation was obtained at the raised bog lagg, which is characterized by a lack of surface runoff. The lagg is located in the lowest part of the bog, and might therefore be the best location for the assessment of water resources in the bog water system (Howie and Meerveld, 2011). Strong correlation coefficients between precipitation and IWT in the lagg further indicate that water level in the lagg depends more on the annual amount of precipitation than WT fluctuations in the raised bog slope or in the mineral soil surrounding the peat bog. Interestingly, the lowest correlation coefficients were recorded between P-PET and annual IWT in well 6-A, located on the bog slope at a distance of 150 m from the bog margin (Fig. 2). The steepest slope in bog surface along the cross-section analyzed is located close to this well, and the higher influence of surface runoff at this location apparently determines a decline in the correlation coefficient in this area. Most often, the slope gradient on the bog surface declines as soon as the distance from bog margin increases; bog surface is indeed close to flat in the area where well 3-A is located (at a distance of 340 m from the bog margin, Fig. 2). In this area, WT is linked to P-PET rather than surface runoff from other areas in the bog complex. An increase in the correlation coefficient between IWT and P-PET is therefore observed again, and an increase in correlation is observed between IWT recorded in well 4-G, located on sand dunes and P-PET as compared to well 6-A (inside the bog) and P-PET (Table 2). The water level in well 4-G is, however, most likely affected by both water supply from the bog and groundwater levels in the bog margins. Stronger correlations have been observed between annual IWT and P-PET in wells located in the lagg and on the raised bog as compared to well 4-G located on sand dunes (Table 2). Furthermore, comparison between well 4-G and the wells located at the bog surface shows that water level varies differently inside the bog and on mineral soil sites over the year. This may depend on differences in groundwater recharge in the wells on the bog and mineral soil, especially during the dry season of the year. IWT data from the bog wells is therefore more suitable for TRW analysis than is IWT data from wells located on mineral soils outside the bog. This observation is in agreement with comparisons between pine trees growing under identical climatic conditions but different soil moisture (Edvardsson et al., 2015a). Even though the trees sometimes grew only a hundred meter apart, correlation was often close to absent between the TRW series from the mineral and peat soil pines.

Our studies are also in agreement with results from Howie and Meerved (2011), suggesting that WT in a bog lagg is more integrated indicator of hydrological regime in the wetland.

5.2. TRW relations with WT changes

In general, WT changes in peat bogs are mainly controlled by precipitation, but they also tend to be influenced by temperature controlled evapo(transpi)ration (Charman et al., 2004). Several studies have shown that peat bogs can indeed act as water reservoirs, thereby buffering water, and that WT fluctuations in peat bogs therefore can lag several years behind climatic or environmental changes (Kilian et al., 1995; Linderholm et al., 2002; Edvardsson and Hansson, 2015). This lag may also explain the delayed response that is sometimes recorded in TRW records to climate changes, especially if the series are developed from pines growing on raised bogs (Vaganov and Kachaev, 1992; Edvardsson et al., 2015a). In this study, the strongest correlation was computed between total P-PET over 7 years and STD-TRW chronology with a 2-yr lag. Our results also confirm that tree growth in peatlands reflects the multiannual synthesis of moisture variability as well as a hydrological lag and/or feedback responses (Linderholm et al., 2002; Edvardsson et al., 2015a; Edvardsson and Hansson, 2015).

WT fluctuations within the peat bog are the main driver of radial growth of bog pines. The 2-yr lag observed in our records (Table 3) is consistent with results from the Männikjärve peat bog in Estonia (Smiljanic et al., 2014). Lagged responses of about 3 yrs were detected between the increases in moisture (derived from $\delta^{13}C$ isotopes in annual tree rings) and decreased radial growth of subfossil pine trees in two Swedish bogs (Edvardsson et al., 2014). Drivers of lag responses can be related to the progressive inhibition of root formation or root decay in water-saturated environments or the availability of nutrients in peaty substrates, which have been shown to be highly dependent on the activity of decomposing microbes or mycorrhizae fungi (Kozlowski, 1997; Pallardy, 2008). These processes, however, all depend on WT fluctuations as well (Dimitrov et al., 2010). Physiological adaptation of peatland pines to extremely wet conditions and shortage of nutrients, e.g. peculiarities in carbohydrates storage system, could also influence the existence of a slower reaction to environmental changes (Kozlowski, 1997).

Studies on the contribution of different carbon sources on tree growth show rather variable ratios of new carbohydrates versus remobilised reserves from previous years, ranging from 71% to 35% (Brüggemann et al., 2011), but experiments on bog pines are still lacking (Edvardsson et al., 2016). Whether and to which degree carbon allocation and carbon fluxes in the plant-soil system are affected by environmental stress conditions remains one of the research questions in this field (Brüggemann et al., 2011).

Water saturated peat soils create unfavourable conditions for tree growth due to a number of physical, chemical, and biological processes (Kozlowski, 1997; Linderholm et al., 2002; Edvardsson et al., 2016). Most often, increased peat moisture result in depressed tree growth, which can be analysed *a posteriori* through the presence of narrower annual growth rings (Smiljanic et al., 2014; Edvardsson et al., 2015a). High water tables also restrict the development of tree roots to the upper aerobic peat layers (Coutts, 1982; Kozlowski, 1997; Leuschner et al., 2007), and therefore limit the nutrient pool available for trees in an already nutrient-limited environment (Ohlson, 1995). Moreover, low oxygen levels in peat soils can favor oxygen deficiency in the upper plant tissues and can thus cause inhibition of plant growth (Boggie, 1977). The growth patterns observed in this study are in line with these findings, but also suggest that tree growth can be depressed during extremely dry phases as well. Similar to Smiljanic et al. (2014), we observe that extremely low water levels may cause growth stress as well, a fact which may result from the shallow and horizontal spreading root systems of peat trees (Edvardsson et al., 2016). In our study, a weak positive link between MWT and STD-TRW chronology indices was observed during the unusually dry period 1965–1985, during which the WT was as low as 132.6 m a.s.l. or even lower (i.e. the average annual depth of the water table was 50 cm below the peat surface). Although the water level started to rise again in 1978, the drought signal in the TRW data persisted for some more years. In times with low WT, the surface layers of peat dry out, leaving the shallow roots in the top peat layers with very limited access to water and hence expose the trees to drought stress (Braekke, 1983; Dang and Lieffers, 1989; Pepin et al., 2002). We hypothesize that during these dry periods, TRW will depend less on hydrological drivers.

Taking into consideration recent global warming and the projected intensification of extremes (Rimkus et al., 2011; Stonevičius et al., 2017), one may expect more frequent droughts in the study region and thus also increased drought stress on bog trees. Indeed, our WT reconstructions show enhanced amplitudes of WT fluctuations in the second half of the 20th century.

5.3. WT reconstruction based on TRW

The development of a 130-year WT reconstruction from peatland TRW data represents the core of this study and an important step to a more widespread application of a new proxy record for moisture variability in peatland ecosystems far beyond the period covered by monitoring data. Such proxy records are important due to the close relation of hydrology with carbon sequestration in peatland ecosystems. In general terms, our results show that moister conditions generate harsher growth conditions for bog trees, and are thus in line with previous findings (Leuschner et al., 2002; Edvardsson et al., 2016). At the same time, however, our findings also indicate that unusually dry conditions may result in unfavorable growth conditions as well. Once that the WT falls below a threshold of 50 cm beneath the peat surface, TRW indices will no longer remain statistically dependent on WT depth. In other words, as soon as WT fluctuations fall>50 cm below the peat surface, TRW records will fail to significantly estimate past WT fluctuations. Under current conditions, such conditions must, however, be considered as quite exceptional. To reconstruct WT depths during such extremely dry periods as well, one needs to take alternative proxies into consideration. By way of example, stable isotopes in tree rings may offer an opportunity, however, isotope studies on peatland trees have remained rather limited so far (Sass-Klaassen et al., 2005; Edvardsson et al., 2014). In the case of proxies without annually resolved proxies, like e.g., testate amoebae, could thus be added to strengthen WT reconstructions, especially in a longer-term perspective (Hendon and Charman, 2004, van Bellen et al., 2014, Lamentowicz et al., 2015).

Despite the limitations of TRW data to reconstruct MWT fluctuations during extreme droughts, statistically significant correlation between our reconstruction and the instrumental Nemunas runoff data suggests that TRW records from peatland pines can indeed be used as a reliable proxy of past WT variability in peatlands. Moreover, the reconstructed WT fluctuations in the Čepkeliai raised bog correspond to periods which are associated with dry/wet conditions known from the literature (Balevičius et al., 1984; Taminskas et al., 2008a,b).

6. Conclusions

The radial growth of peatland pine trees is strongly influenced by WT fluctuations, which in turn depend on changes in precipitation and temperature. In our case, the strongest correlation between average annual IWT and P-PET totals has been obtained if the latter was considered for a period of 7 years. Further, strong correlations were obtained between MWT and STD-TRW chronology with a 2-yr lag. While this lagged response sustains the findings in other raised bog studies, more thorough investigations are necessary to really understand the eco-physiological factors predetermining time lags in peatland ecosystem functioning.

The negative dependence of TRW on WT fluctuations was found in this study as well, provided that the latter fluctuated within a 50 cm layer below the peat surface. By contrast, the correlation quickly fades as soon as the WT drops below this threshold. Consequently, and in case of extremely low water levels, narrow TRW may be formed as well, which could possibly result in some bias. Moreover, a weak correlation was observed between very low WT and TRW, suggesting a shift in limiting factors from a moisture-limited radial increment to a growth depending on other limiting environmental factors. Despite these limitations, TRW series from pine trees were used successfully in this study as a valuable proxy to reconstruct WT fluctuations in the bog lagg zone. In addition, the reliability of TRW chronologies is further demonstrated by the significant correlation observed between our reconstruction and Nemunas runoff series. Considering the widespread availability of pine remains in peat deposits of boreo-nemoral peat bogs (Edvardsson et al., 2016), the newly established relations can be used to reconstruct hydrological variability over major parts of the Holocene.

Acknowledgments

This study has been funded by the Lithuanian-Swiss cooperation program to reduce economic and social disparities within the enlarged European Union under the name CLIMPEAT (Climate change in peatlands: Holocene record, recent trends and related impacts on biodiversity and sequestered carbon) project agreement No CH-3-ŠMM-01/05. The authors are grateful to Lithuanian Hydrometeorological Service under the Ministry of Environment for the meteorological and hydrological data provided and Dzūkija National Park for the help during the fieldwork. Furthermore, we thank editors and anonymous reviewers for their advice.

References

Balakauskas, L., Taminskas, J., Mažeika, J., Stančikaitė, M., 2013. Lateglacial and Early Holocene palaeohydrological changes in the upper reaches of the Ūla river: an example from south eastern Lithuania. The Holocene 23, 117–126.

Balevičius, K., Giniūnas, K., Jankevičienė, R., Prūsaitė, J., Šešelgis, K., Tamošaitis, J., 1984. Čepkelių raisto vandeningumo kitimas remiantis dendrochronologiniais duomenimis. Čepkelių rezervatas [Čepkeliai wetland water content variation based on dendrochronological data. Čepkeliai reserve]. Vilnius 44–45. [In Lithuanian].

Boggie, R., 1972. Effect of water-table height on root development of *Pinus contorta* on deep peat in Scotland. Oikos 23, 304–312.

Boggie, R., 1977. Water-table depth and oxygen content of deep peat in relation to root growth of *Pinus contorta*. Plant Soil 48 (2), 447–454. https://doi.org/10.1007/BF02187253.

Braekke, F.H., 1983. Water table levels at different drainage intensities on deep peat in northern Norway. Forest Ecol. Manage. 5 (3), 169–192. https://doi.org/10.1016/0378-1127(83)90070-1.

Brüggemann, N., Gessler, A., Kayler, Z., Keel, S.G., Badeck, F., Barthel, M., Boeckx, P., Buchmann, N., Brugnoli, E., Esperschütz, J., Gavrichkova, O., Ghashghaie, J., Gomez-Casanovas, N., Keitel, C., Knohl, A., Kuptz, D., Palacio, S., Salmon, Y., Uchida, Y., Bahn, M., 2011. Carbon allocation and carbon isotope fluxes in the plant-soil-atmosphere continuum: a review. Biogeosciences 8, 3457–3489. https://doi.org/10.5194/bg-8-3457-2011.

Bukantis, A., 1994. Lithuanian Climate. Vilnius. p. 186 [In Lithuanian].

Cedro, A., Lamentowicz, M., 2011. Contrasting responses to environmental changes by pine (*Pinus sylvestris* L.) growing on peat and mineral soil: an example from a Polish Baltic bog. Dendrochronologia 29, 211–217. https://doi.org/10.1016/j.dendro.2010.12.004.

Charman, D.J., Brown, A.D., Hendon, D., Karofeld, E., 2004. Testing the relationship between Holocene peatland paleoclimate reconstructions and instrumental data at two European sites. Quaternary Science Reviews 23 (1–2), 137–143. https://doi.org/10.1016/j.quascirev.2003.10.006.

Cook, E.R., Kairiukstis, L.A., 1990. Methods of Dendrochronology, Applications in the Environmental Sciences. Kluwer Academic Publishers, International Institute for Applied Systems Analysis, London. 10.1007/978-94-015-7879-0.

Cook, E.R., Krusic, P.J., 2006. ARSTAN_41: a tree-ring standardization program based on detrending and autoregressive time series modeling, with interactive graphics. Lamont Doherty Earth Observatory of Columbia University, New York, Tree-Ring Laboratory.

Coutts, M.P., 1982. The tolerance of tree roots to waterlogging. New Phytologist 90 (3), 467–476. https://doi.org/10.1111/j.1469-8137.1982.tb04479.x.

Dang, Q.L., Lieffers, V.J., 1989. Climate and annual ring growth of black spruce in some Alberta peatlands. Can. J. Bot. 67 (6), 1885–1889. https://doi.org/10.1139/b89-239.

Donohue, R.J., McVicar, T.R., Roderick, M.L., 2010. Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a.changing climate. J. Hydrol. 386, 186–197.

Dimitrov, D.D., Grant, R.F., Lafleur, P.M., Humphreys, E.R., 2010. Modeling the effects of hydrology on ecosystem respiration at Mer Bleue bog. J. Geophys. Res. 115, G04043. https://doi.org/10.1029/2010JG001312.

Edvardsson, J., Hansson, A., 2015. Multiannual hydrological responses in Scots pine radial growth within raised bogs in southern Sweden. Silva Fennica 49, 1–14. https://doi.org/10.14214/sf.1354.

Edvardsson, J., Edwards, T.W.D., Linderson, H., Hammarlund, D., 2014. Exploring climate forcing of growth depression in subfossil South Swedish bog pines inferred from stable isotopes. Dendrochronologia 32, 55–61. https://doi.org/10.1016/j.dendro.2013.08.002.

Edvardsson, J., Rimkus, E., Corona, C., Simanauskiene, R., Kazys, J., Stoffel, M., 2015a. Exploring the impact of regional climate and local hydrology on *Pinus sylvestris* L. growth variability e a comparison between pine populations growing at peat soils and mineral soils in Lithuania. Plant Soil 392, 345–356. https://doi.org/10.1007/s11104-015-2466-9.

Edvardsson, J., Šimanauskiene, R., Taminskas, J., Baužiene, J., Stoffel, M., 2015b. Increased tree establishment in Lithuanian peat bogs detected using a combination of field and remotely sensed approaches. Sci. Total Environ. 505, 113–120. https://doi.org/10.1016/j.scitotenv.2014.09.078.

Edvardsson, J., Stoffel, M., Corona, C., Bragazza, L., Leuschner, H.H., Charman, D.J., Helama, S., 2016. Subfossil peatland trees as proxies for palaeohydrology and climate reconstruction during the Holocene. Earth-Sci. Rev. 163, 118–140. https://doi.org/10.1016/j.earscirev.2016.10.005.

Freeman, C., Lock, M.A., Reynolds, B., 1993. Fluxes of CO2, CH4 and N2O from a Welsh peatland following simulation of water table draw-down: potential feedback to climatic change. Biogeochemistry 19 (1), 51–60. https://doi.org/10.1007/BF00000574.

Friedman, J.H., 1984. A Variable Span Smoother, Department of Statistics Technical Report LCS 5. Stanford University, Stanford.

Fritts, H.C., 1976. Tree Rings and Climate. Academic Press, London, p. 567.

Gažovič, M., Kutzbach, L., Schreiber, P., Wille, C., Wilmking, M., 2010. Diurnal dynamics of CH4 from a boreal peatland during snowmelt. Tellus B 62 (3), 133–139. https://doi.org/10.1111/j.1600-0889.2010.00455.x.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1 (2), 182–195. https://doi.org/10.2307/1941811.

Hendon, D., Charman, D.J., 2004. High-resolution peatland water-table changes for the past 200 years: the influence of climate and implications for management. Holocene 14, 125–134. https://doi.org/10.1191/0959683604hl695rp.

Holmes, R.L., 1983. Computer assisted quality control in tree ring dating and measurement. Tree-ring Bull. 43, 69–78.

Howie, S.A., Meerveld, I.T., 2011. The essential role of the lagg in raised bog function and restoration: a review. Wetlands 31, 613–622. https://doi.org/10.1007/s13157-011-0168-5.

Joosten, H., Clarke, D., 2002. Wise use of mires and peatlands - Background and principles including a framework for decision-making. International Mire Conservation Group/International Peat Society. p. 304.

Kilian, M.R., Van der Plicht, J., Van Geel, B., 1995. Dating raised bogs: New aspects of AMS 14C wiggle matching, a reservoir effect and climatic change. Quaternary Sci. Rev. 14 (10), 959–966. https://doi.org/10.1016/0277-3791(95)00081-X.

Kozlowski, T.T., 1997. Responses of woody plants to flooding and salinity. Tree Physiol. 1, 1–29. https://doi.org/10.1093/treephys/17.7.490.

Lafleur, P.M., Roulet, N.T., Admiral, S.W., 2001. Annual cycle of CO_2 exchange at a bog peatland. J. Geophys. Res. 106 (D3), 3071–3081. https://doi.org/10.1029/2000JD900588.

Lamentowicz, M., Gałka, M., Lamentowicz, Ł., Obremska, M., Kühl, N., Lücke, A., Jassey, V.E.J., 2015. Reconstructing climate change and ombrotrophic bog development during the last 4000 years in northern Poland using biotic proxies, stable isotopes and trait-based approach. Palaeogeogr. Palaeoclimatol. Palaeoecol. 418, 261277. https://doi.org/10.1016/j.palaeo.2014.11.015.

Leuschner, H.H., Sass-Klaassen, U., Jansma, E., Baillie, M.G.L., Spurk, M., 2002. Subfossil European bog oaks: population dynamics and long-term growth depressions as indicators of changes in the Holocene hydro-regime and climate. The Holocene 12 (6), 695–706. https://doi.org/10.1191/0959683602hl584rp.

Leuschner, H.H., Bauerochse, A., Metzler, A., 2007. Environmental change, bog history and human impact around 2900 BC in NW Germany—preliminary results from a dendroecological study of a sub-fossil pine woodland at Campemoor, Dümmer Basin. Vegetation Hist. Archaeobot. 16 (2–3), 183–195. https://doi.org/10.1007/s00334-006-0084-4.

Linderholm, H.W., Moberg, A., Grudd, H., 2002. Peatland pines as climate indicators? A regional comparison of the climatic influence on Scots pine growth in Sweden. Can. J. For. Res. 32 (8), 1400–1410. https://doi.org/10.1139/x02-071.

Linkevičienė, R., 2009. Impact of river capture on hydrography and water resources: case study of Ula and Katra catchments, south Lithuania. The Holocene 19 (8), 1233–1240.

MacDonald, G.M., Beilman, D.W., Kremenetski, K.V., Sheng, Y., Smith, L.C., Velichko, A.A., 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. Science 314, 285–288.

Mažeika, J., Guobytė, R., Kibirkštis, G., Petrošius, R., Skuratovič, Ž., Taminskas, J., 2009. The use of carbon-14 and tritium for peat and water dynamics characterization: case of Čepkeliai Peatland, Southeastern Lithuania. Geochronometria 34, 41–48.

McVicar, T.R., Roderick, M.L., Donohue, R.J., Li, L.T., Van Niel, T.G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman, S., Dinpashoh, Y., 2012. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. J. Hydrol. 416–417, 182–205.

Matthews, E., Fung, I., 1987. Methane emission from natural wetlands: global distribution, area, and environmental characteristics of sources. Glob. Biogeochem. Cycles 1 (1), 61–86. https://doi.org/10.1029/GB001i001p00061.

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., 2013. Wetlands, carbon, and climate change. Landsc. Ecol. 28 (4), 583–597. https://doi.org/10.1007/s10980-012-9758-8.

Moore, T.R., Knowles, R., 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Can. J. Soil Sci. 69 (1), 33–38. https://doi.org/10.4141/cjss89-004.

Nokes, S.E., 1995. Evapotranspiration. In: Ward, A.D., Elliot, W.J. (Eds.), In: E. Environmental hydrology, Boca Raton, New, York, pp. 91–130.

Ohlson, M., 1995. Growth and nutrient characteristics in bog and fen populations of Scots pine (*Pinus sylvestris*). Plant Soil 172 (2), 235–245. https://doi.org/10.1007/BF00011326.

Osvald, H., 1933. Vegetation of the Pacific Coast bogs of North America. *Acta Phytogeogr.* Suec 5, 1–32.

Pallardy, S.G., 2008. Physiology of woody plants, 3rd ed. Elsevier/Academic Press. p. 454.

Pepin, S., Plamondon, A.P., Britel, A., 2002. Water relations of black spruce trees on a peatland during wet and dry years. Wetlands 22 (2), 225–233. https://doi.org/10.1672/0277-5212(2002) 022[0225:WROBST]2.0.CO;2.

Povilaitis, A., Taminskas, J., Gulbinas, Z., Linkevičienė, R., Pileckas, M., 2011. Lithuanian wetlands and their water protective importance. p. 327. [In Lithuanian].

Pukienė, R., 2001. Natural changes in bog vegetation reconstructed by sub-fossil tree remnant analysis. Biologia 2, 111–113.

Rigg, G.B., 1925. Some Sphagnum bogs of the north Pacifics coast of North America. Ecology 6, 260–279. https://doi.org/10.2307/1929201.

Rimkus, E., Kažys, J., Bukantis, A., Krotovas, A., 2011. Temporal variation of extreme precipitation events in Lithuania. Oceanologia 53, 259–277.

Rinn, F., 2003. TSAP-Win user reference manual. Rinntech, Heidelberg.

Ruseckas, J., Grigaliūnas, V., 2008. Effect of drain-blocking and meteorological factors on groundwater table fluctuations in Kamanos Mire. J. Environ. Eng. Landsc. Manage. 16 (4), 168–177.

Saarnio, S., Morero, M., Shurpali, N.J., Tuittila, E.S., Mäkilä, M., Alm, J., 2007. Annual CO_2 and CH_4 fluxes of pristine boreal mires as a background for the lifecycle analyses of peat energy. Boreal Environ.Res. 12, 101–113.

Sagerfors, J., Lindroth, A., Grelle, A., Klemedtsson, L., Weslien, P., Nilsson, M., 2008. Annual CO2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere. J. Geophys. Res. 113, G01001. https://doi.org/10.1029/2006JG000306.

Salm, J.O., Kimmel, K., Uri, V., Mander, Ü., 2009. Global warming potential of drained and undrained peatlands in Estonia: a synthesis. Wetlands 29 (4), 1081–1092. https://doi.org/10.1672/08-206.1.

Sass-Klaassen, U., Poole, I., Wils, T., Helle, G., Schleser, G.H., van Bergen, P.F., 2005. Carbon and oxygen isotope dendrochronology in sub-fossil bog oak tree rings – a preliminary study. IAWA J. 26, 121–136.

Smiljanic, M., Seo, J., Läänelaid, A., Maaten-Theunissen, M.V., Stajić, B., Wilmking, M., 2014. Peatland pines as a proxy for water table fluctuations: Disentangling tree growth, hydrology and possible human influence. Sci. Total Environ. 500–501, 52–63. https://doi.org/10.1016/j.scitotenv.2014.08.056.

Skaggs, R.W., 1980. Drainmod Reference Report. Methods for design and evaluation of drainage-water management systems for soils with water tables. North Carolina State University, Raleigh, NC.

Stančikaitė, M., Gedminienė, L., Edvardsson, J., Stoffel, M., Corona, C., Gryguc, G., Uogintas, D., Zinkutė, R., Skuratovič, Ž., Taraškevičius, R., 2017. Holocene vegetation and hydroclimatic dynamics in SE Lithuania-Implications from a multi-proxy study of the Čepkeliai bog. Quaternary Int. https://doi.org/10.1016/j.quaint.2017.08.039.

Stoffel, M., Corona, C., 2014. Dendroecological dating of geomorphic disturbance in trees. Tree Ring Res. 70, 3–20.

Stonevičius, E., Rimkus, E., Štaras, A., Kažys, J., Valiuškevičius, G., 2017. Climate change impact on Nemunas River basin hydrology in the 21st century. Boreal Environ. Res. 22, 49–65.

Sumner, D.M., Jacobs, J.M., 2005. Utility of Penman-Monteith, Priestly-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. J. Hydrol. 308, 81–104.

Taminskas, J., Mažeikis, A., Valiuškevičienė, L., 2008a. Comparison of potential evapotranspiration estimation according to air temperature. Annales Geographicae 41 (1–2), 81–89 [In Lithuanian].

Taminskas, J., Linkevičienė, R., Mažeika, J., Kibirkštis, G., 2008b. The impact of global climate change for hydrometeorological contitions of Čepkeliai Peatland: the elements of vertical water cycle. Annales Geographicae 40 (2), 50–60 [In Lithuanian].

Taminskas, J., Pileckas, M., Šimanauskienė, R., Linkevičienė, R., 2012. Wetland classification and inventory in Lithuania. Baltica 25, 33–44.

Tanneberger, F., Wichtmann, W., 2011. Carbon credits from peatland rewetting. Climate - biodiversity - land use. Science, policy, implementation and recommendations of a pilot project in Belarus. Schweizerbart, Stuttgart. p. 223.

Taylor, S.A., Ashcroft, G.L., 1972. Physical Edaphology. W.H. Freeman and Co., San Francisco, CA.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. Geograph. Rev. 38, 55–94. https://doi.org/10.2307/210739.

Turetsky, M.R., Kotowska, A., Bubier, J., Dise, N.B., Crill, P., Hornibrook, E.R., Minkkinen, K., Moore, T.R., Myers-Smith, I.H., Nykanen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.S., Waddington, J.M., White, J.R., Wickland, K. P., Wilmking, M., 2014. A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. Glob. Change Biol. 20 (7), 2183–2197. https://doi.org/10.1111/gcb.12580.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., Van Der Werf, G.R., Watts, A., 2015. Global vulnerability of peatlands to fire and carbon loss. Nat. Geosci. 8, 11–14.

Turunen, J., Tomppo, E., Tolonen, K., Reinikainen, A., 2002. Estimaiting carbon accumulation rate of undrained mires in Finland – application to boreal and subarctic regions. The Holocene 12, 69–80.

Vaganov, E.A., Kachaev, A.V., 1992. Dendroclimatic analysis of the growth of pine in forest-bog phytocenoses of Tomsk Oblast. Lesovedenie 6 (1), 3–10 [in Russian].

Van Bellen, S., Mauquoy, D., Payne, R.J., Roland, T.P., Daley, T.J., Hughes, P.D.M., Loader, N.J., Street-Perrott, F.A., Rice, E.M., Pancotto, V.A., 2014. Testate amoebae as a proxy for reconstructing Holocene water table dynamics in southern Patagonian peat bogs. J. Quaternary Sci. 29 (5), 463474. https://doi.org/10.1002/jqs.2719.

Vicente-Serrano, S.M., Begueria, S., Lopez-Moreno, J.I., 2010. A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. J. Clim. 23 (7), 1696–1718. https://doi.org/10.1175/2009JCLI2909.1.

Wigley, T.M., Briffa, K.R., Jones, P.D., 1984. On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. J. Clim. Appl. Meteorol. 23 (2), 201–213.

Xu, C.Y., Singh, V.P., 2001. Evaluation and generalization of temperature-based methods for calculating evaporation. Hydrol. Process. 15 (2), 305–319.