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Research papers

Hydrological and botanical diversity of a raised bog and its evaluation using *in situ* and remote sensing methods

Rita Linkevičienė [a,b,*], Rasa Šimanauskienė [a,b], Gintautas Kibirkštis [a], Onutė Grigaitė [c], Julius Taminskas [a]

[a] *Nature Research Centre, Akademijos Str. 2, Vilnius LT-08412, Lithuania*
[b] *Faculty of Chemistry of Geosciences, Vilnius University, Čiurlionio Str. 21/27, Vilnius LT-03101, Lithuania*
[c] *Dzūkija National Park and Čepkeliai State Nature Reserve Directorate, Vilniaus Str. 3, Merkinė, Varėna District LT-65334. Lithuania*

A R T I C L E I N F O

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A B S T R A C T

Peatland vegetation requires water-logged conditions for peat-forming plant communities to survive. Changes in water regimes have been found to alter the soil environment and cause shifts in species composition. Occasionally, the spatial and chronological constraints in water table monitoring impede the correct evaluation of the status of these sensitive ecohydrological systems. Therefore, it is important to combine *in situ* and remote sensing methods to assess ecohydrological diversity over large areas of threatened peatland ecosystems. The present study assessed the relationship between hydrological indicators (the *in situ* water table fluctuations of 57 measurement wells and five study plots in the 2019 and 2020 growing seasons); botanical indicators (*in situ* species composition in three raised bog habitat types, namely, bog woodland, a semi-open raised bog, and an open raised bog); and spectral indices (NDVI – Normalised Difference Vegetation Index and NDWI – Normalised Difference Water Index, 2015–2020, Sentinel 2) for the evaluation of heterogeneous raised bog spatial patterns and temporal change. There were statistically significant relationships between vegetation and water table depth in different raised bog habitat types. Deeper water tables prevailed in woodland habitats (trees, green mosses, *Rhododendron tomentosum*) and vice versa in areas where open raised bog plants (*Sphagnum*) occupied the surface. Moderate relationships ($r > |0.4|$, $p < .05$) were detected between some of the botanical and hydrological indicators and spectral indices. The application of high-resolution remote sensing data may be useful for raised bog measurements, and changes in vegetation cover and related spectral indices may become hydroclimatic indicators.

1. Introduction

Raised bogs are distinctive ecohydrological systems that contribute towards various habitats. The major driving force behind these habitats is the hydrological cycle, which is reflected in the condition and composition of raised bog vegetation (Xu et al., 2015; Zhang et al., 2012). Vegetation itself influences the surrounding environment as well as the hydrological regime. Water storage and vegetation are inextricably linked as raised bogs require water-logged conditions for peat-forming plant communities to survive (Mackin et al., 2015; Neefjes, 1989).

Large areas of peatlands are threatened by climate change and human activities (Bhaga et al., 2020; Novoa et al., 2020; Xie et al., 2017). Agriculture, forestry, and peat extraction exert tremendous pressure on the hydrological functioning of northern peatlands, including changes in water table depth (D'Acunha et al., 2018; Middleton et al., 2012). These changes may be triggering the release of greenhouse gases and degrading vulnerable open raised bog habitats (European Commission, 2013). Several studies (Dyderski et al., 2015; Edvardsson et al., 2015; Frelechoux et al., 2003; Šimanauskienė et al., 2019; Smiljanić et al., 2014) have noted that European peatland complexes (including those in pristine condition) are affected by the encroachment of woody vegetation. This has prompted a debate on how climate change is impacting vulnerable ecosystems (Taminskas et al., 2018). For instance, it has been suggested that conservation and management require continuous hydrological monitoring (Bonn et al., 2016) because traditional hydrological surveys—which provide accurate results (Närhi et al., 2010)— are less than effective in measuring the

* Corresponding author at: Nature Research Centre, Akademijos Str. 2, Vilnius LT-08412, Lithuania.
E-mail address: rita.linkeviciene@gamtc.lt (R. Linkevičienė).

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spatial extent of large peatland areas over time (Pullens et al., 2018; Querner et al., 2010; Talbot et al., 2010; Whitfield et al., 2009). Cost-effective remote sensing technology can be used to assess ecohydrological diversity over large areas of threatened peatland ecosystems; consequently, it has become one of the most popular tools in wetland research during the past few decades (Czapiewski and Szumińska, 2022; Mahdavi et al., 2019; Pettorelli et al., 2017).

Changes in vegetation allow for the evaluation of changes in peatland hydrological conditions and vice versa (Segah et al., 2010). Previous remote sensing applications have been used for the detection of hydrology and vegetation relationships and changes in water conditions in peatlands (Asmuß et al., 2019; Kalacska et al., 2018; Lees et al., 2021; Torabi Haghighi et al., 2018), vegetation mapping (Bhatnagar et al., 2020; Connolly, 2018), soil moisture monitoring (Bechtold et al., 2020; Torbick et al., 2012), and the estimation of water content in plants (Lees et al., 2020). They have been widely discussed in the context of different climatic regions, from the tropical (Miettinen et al., 2012) to the subarctic and boreal (Bourgeau-Chavez et al., 2017; Neta et al., 2010; Torabi Haghighi et al., 2018). Meanwhile, researchers have called for satellite imagery-based studies of water table depth monitoring in a range of peatland habitats (Chasmer et al., 2020a, 2020b; Räsänen et al., 2022). Spectral detection of near-surface moisture content and water table positions, along with their relationship to peat-forming vegetation (e.g., *Sphagnum* spp. in northern peatland ecosystems) has been the focus of a number of studies (Bubier et al., 1997; Harris, 2008; Letendre et al., 2008; Meingast et al., 2014), as has satellite-based peatland forest cover analyses (Meneses-Tovar, 2011). Pflugmacher et al. (2007) have argued that peatland pines were proxies for water table levels. Recent investigations into the relationship between water table depth and tree density (e.g., spruce and pine mires), as well as open mire habitats, have confirmed that it is possible to track water table changes using vegetation indices as predictors (Räsänen et al., 2022). However, there is still a gap in the literature on the subject of transitional semi-open raised bog habitats that are highly dependent on water table depth and extremely vulnerable to fluctuations in moisture. Moreover, tree habitats are usually characterised by stable vegetation cover and spectral values (Taminskas et al., 2020), whereas phenological changes in semi-open raised bog habitat vegetation are expected to show prevailing trends in water table fluctuations as well as overall raised bog evolution.

Spectral indices (NDVI, NDWI, etc.) based on shortwave infrared (SWIR) and near-infrared (NIR) optical bands are reported to have had variable success in monitoring peatland water table depth for various mire types (Räsänen et al., 2022). Spectral indices retrieved from high-resolution optical images (Sentinel 2) could serve as useful proxies for plant health and photosynthesis (NDVI), as well as for moisture content in raised bog surfaces (NDWI; Bhatnagar et al., 2020; Lees et al., 2020). Many studies have shown the effectiveness of these indices in wetlands (Ashok et al., 2021; Lv et al., 2019; Ma et al., 2018). The tracking of vegetation conditions in wetlands with an NDVI index principally related to canopy chlorophyll content (Kogan, 1997) has been widely investigated (Jing et al., 2017; Wu et al., 2014). Moreover, a combination of NDVI and NDWI offers us more information about vegetation and water and therefore more complex analyses of peatland conditions.

Water table depth, which influences surface soil moisture in peatlands, is considered one of the primary factors in plant recruitment and survival (Crosslé and Brock, 2002), species composition (Laitinen et al., 2007; Närhi et al., 2010), and plant health (Lees et al., 2020). Changes in water regimes have been found to alter the soil environment and cause shifts in species composition. When water tables are low and moisture content in vegetation is reduced, the variety of species and photosynthesis rates decrease (Laine et al., 2021). Peatland water regimes and the spatial distribution of their water table depth based on point measurements have been assessed in previous studies (Howie and van Meerveld, 2013, 2019). However, most of these are based on measurements that have spatial and chronological constraints (e.g., they were taken at one time and in one place), and therefore cannot be used to evaluate the seasonal or long-term processes of complex peatland ecosystems. When observing natural and human-influenced peatland water regimes, we frequently encounter difficulties selecting characteristic sites. Inappropriate monitoring points may reflect very particular conditions, that is, they are not representative of the entire peatland complex. The need for a wider network of point measurements that are reliably representative of surrounding areas has been widely reported (Howie and van Meerveld, 2013, 2019). Continuous water table measurements in a wider monitoring network could serve as a basis for the evaluation of phenomena in different raised bog types. According to previous studies, it is expected that water table depth would be lower in treed raised bog habitats (Smiljanić et al., 2014) and higher in open raised bog habitats dominated by *Sphagnum* spp. (Grosvernier et al., 1997). Studies showing the position of water table depth in semi-open raised bog habitats are needed, since semi-open habitats of a transitional trophic and moisture status might be a key factor in the next stage of the evolution of raised bogs (Sotek et al., 2019).

The main goal of the present study was to identify and evaluate the hydrology of different raised bog habitat types using remote sensing methods. It comprises: (a) an evaluation of the vertical structure of raised bog vegetation and the distinctiveness of raised bog habitat types in relation to tree cover; (b) an analysis of raised bog hydrology using *in situ* measurements; (c) an analysis of the relationship between hydrology and raised bog habitat types; and (d) an evaluation of hydrology and raised bog habitat types according to spectral indices (NDVI and NDWI).

2. Materials and methods

2.1. Study area

Čepkeliai (54°00′ N, 24°30′ E) is one of the largest peatlands in Lithuania (5,858 ha) and one of the very few remaining pristine raised bogs in the Baltic region (Taminskas et al., 2012). The Čepkeliai peatland complex consists of raised bogs (82 % of the total area), fens (16 %), transition mires (2 %), several mineral substrate islands, and 21 small lakes. We studied the raised bog part of the Čepkeliai peatland.

The average depth of the peat is about 2.3 m, but organic deposits can be as deep as 16 m locally, with the peat up to 6 m deep and gyttja below (Stančikaitė et al., 2019). The surface of the raised bog is slightly undulating (128.5–134.4 m above sea level [ASL]) and divided into several parts with different drainage conditions. The Nemunas River catchment streams Ūla, Grūda, and Katra collect water from open-drainage sub-basins, while surplus water from closed-drainage sub-basins is lost by ground-water exchange or evapotranspiration (Taminskas et al., 2018).

The average annual temperature is 6.8 °C. Average monthly temperatures fluctuate from −3.7 °C in January to 17.9 °C in July. Average annual precipitation is ~700 mm, snow cover occurs for ~90 days. Annual net precipitation is ~220 mm (Varėna WS meteorological data, 1981–2010).

The main area of the Čepkeliai peatland has been a Strict State Nature Reserve since 1975. It was included in the Ramsar site list as a Wetland of International Importance in 1993. The Čepkeliai peatland is also part of the European Union ecological network — NATURA 2000 territory.

The open raised bog and semi-open raised bog areas we investigated are classified as priority 7110 *Active raised bog habitats according to the criteria of habitats of EU importance (European Commission, 2013; Rašomavičius, 2012). Bog woodland is also classified as priority habitats of EU importance (91D0 *Bog woodland).

2.2. Data and methods

2.2.1. Hydrological indicators

To assess water table fluctuations, 57 water table measurement wells were installed in various locations throughout the Čepkeliai raised bog at five study plots (A–E), with nine or 15 wells in each (Fig. 1). Since the measurements were carried out manually, the locations of the study plots were selected to perform measurements at all points in one day. The wells were installed using 1.4 m long, 3 cm diameter perforated plastic pipes that were inserted 1 m into a peat layer (in some cases less if the peat layer was thinner; Thom et al., 2019). The elevation of the peatland surface was measured outside the well from the top of the pipe to the top of the moss layer. Water table elevation and peatland surface elevation measurements were taken during the 2019–2020 growing seasons (2019 05 10 – 10 10 and 2020 04 10 – 09 20): every 10 days measurements were taken in study plot A, in the No. 1–9 and No. 52–57 wells, and every month measurements were taken in study plots B, C, D, and E in the No. 10–51 wells. Water table depth was calculated using water table and surface elevation measurements.

In some shallower wells (study plot C, No. 19–25 and No. 27, study plot E, No. 44, 45, and 50), the water table dropped below the borehole bottom (40–60 cm below bog surface), so the data were not analysed. Correlation analysis was performed using the average, minimum, and maximum water table depth values found in 46 wells from 2019 to 2020.

Since 2002, water table measurements from April to October have

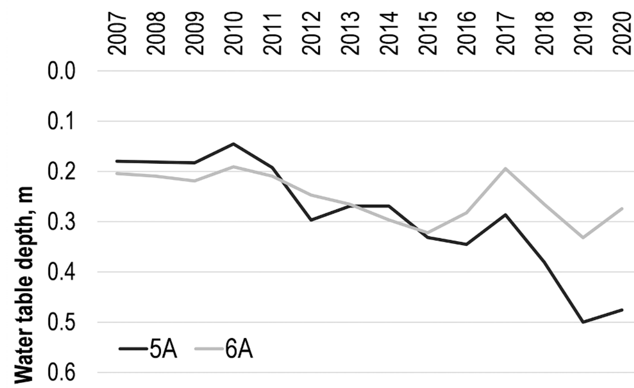

Fig. 2. Average annual water table depth in long-term water level measuring wells of the Čepkeliai raised bog. Location of wells 5A and 6A – see Fig. 1.

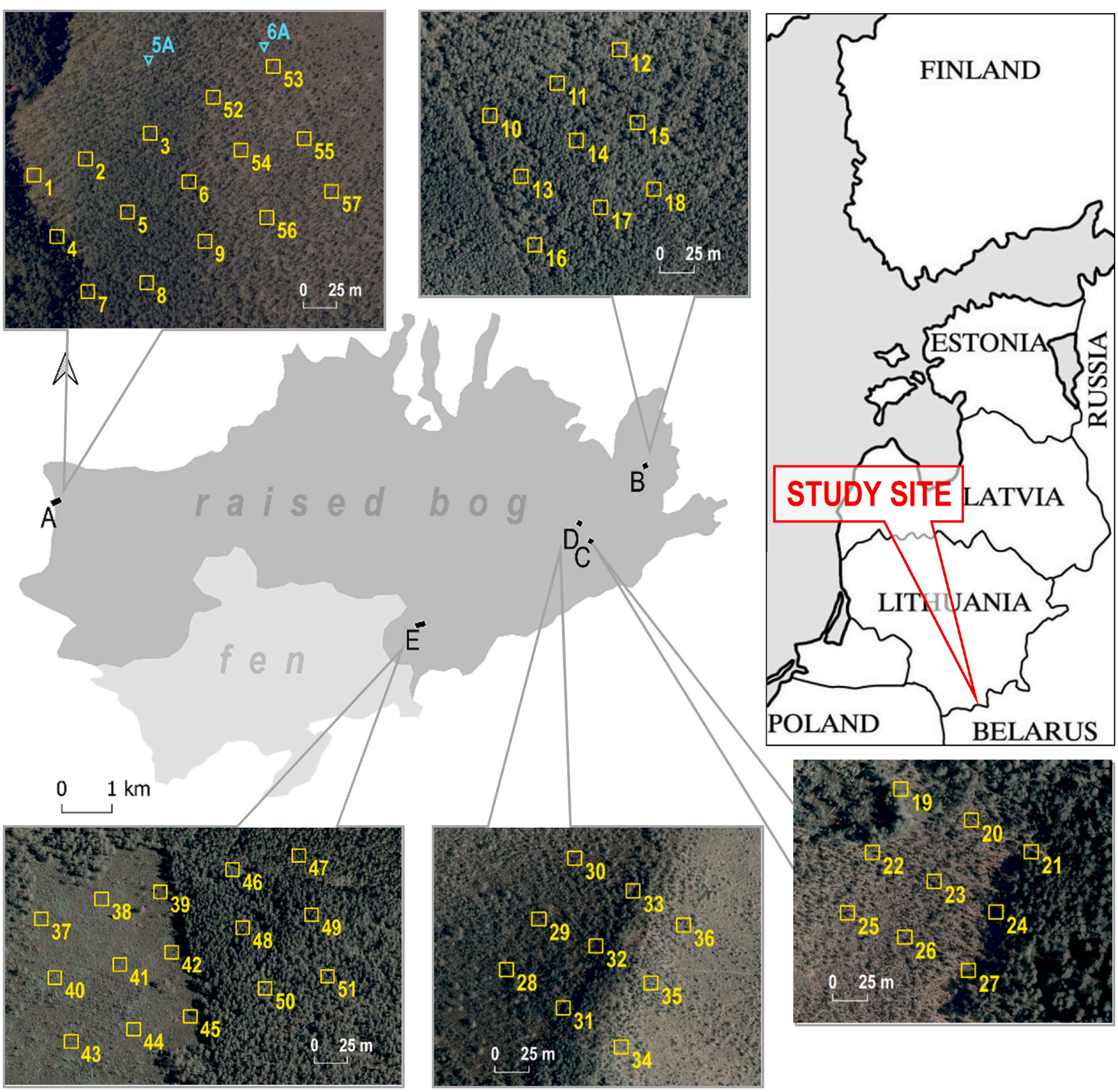

Fig. 1. Location of study plots (A–E) and trial plots (1–57), as well as the location of long-term water level measuring wells (5A, 6A) in the Čepkeliai raised bog, Lithuania.

been taken in wells located in the western part of the Čepkeliai peatland (Fig. 1, 5A, and 6A). Since 2007, raised bog surface measurements have been taken near the same wells. Their data were used to evaluate the trends in water table depth fluctuation in the Čepkeliai raised bog over the last 15 years.

2.2.2. Botanical indicators

For the vegetation assessment, 10 × 10 m trial plots were shaped around the water table measuring wells (Fig. 1). Vegetation descriptions of these trial plots were performed in July 2019. The species composition of the tree, shrubs/dwarf shrubs (referred to in the text as the shrub layer), grass, and moss layers, as well as the percentage cover of each species, were determined (Rašomavičius, 2012). These trial plots are classified as three raised bog habitat types according to the character of tree growth: bog woodland, semi-open raised bog, and open raised bog. The features of these habitats have been described in several studies (Kunskas, 2005; Seibutis, 1958; Tupčiauskaitė, 2012), but clear criteria distinguishing raised bog habitats were not always explained. For the present study, we applied the following criteria for raised bog habitats: the trees in the bog woodland habitat reached a height of more than 5 m, and their coverage exceeded 40 %; in semi-open raised bog, the trees were smaller than 5 m and their coverage ranged between 21 and 40 %; in the open raised bog, the trees reached up to 1 m and they covered up to 20 % (Table 1).

The ecological forms of Scots pine that grow in raised bogs also serve as a criterion of the raised bog habitat types. They differ according to the habitat conditions: *Pinus sylvestris* f. *uliginosa* Abolin – 8–15 m tall (the least altered pine); *P. sylvestris* f. *litwinowii* Sukaczew – 1–6 m tall (with a slightly oval shape); *P. sylvestris* f. *willkommii* Sukaczew – 1–3 m tall (spruce-shaped); *P. sylvestris* f. *pumila* Abolin – a 0.75–1.5 m tall shrub pine (the most decayed pine; Abolin, 1915; Tupčiauskaitė, 2012). Three pines of three ecological types were discovered in the area under study: f. *uliginosa*, f. *litvinowii*, f. *willkommii* (Table 1).

The nomenclature of the bryophytes was based on an annotated checklist of bryophytes of Europe, Macaronesia, and Cyprus (Hodgetts et al., 2020). The nomenclature of the other plant species was applied following the Euro+Med PlantBase (Euro+Med, 2006).

2.2.3. Spectral indices

For the evaluation of vegetation status and moisture content in the plants, two main indices were used: the Normalised Difference Vegetation Index (NDVI) and the Normalised Difference Water Index (NDWI). The former focuses on the difference between the RED and NIR zones of the reflectance spectrum: NDVI = (NIR – RED)/(NIR + RED). In this expression, NIR and RED denote the reflectance of Band 8 and Band 4 used in Sentinel 2. NDVI values lie between −1.0 and +1.0. Very low NDVI values represent non-vegetated or bare soil surfaces, whereas values higher than zero identify the vegetation cover with different photosynthetic capacities: the higher the values, the higher the density of green vegetation (Kogan, 1997).

The latter uses the difference between NIR and SWIR to assess leaf water content at the canopy level: NDWI = (NIR – SWIR)/(NIR + SWIR). In this expression, NIR and SWIR denote the reflectance of Band 8 and Band 12 used in Sentinel 2. The amount of water available in the internal leaf structure largely control the spectral reflectance in the SWIR interval of the electromagnetic spectrum (Gao, 1996). Vegetation internal structure and leaf dry mass controls the reflectance in the NIR interval. The combination of these channels allows us to distinguish the water content in vegetation (Ceccato et al., 2001). The NDWI values lie between –1 and +1, depending on the leaf water content. High values correspond to high vegetation water content and high vegetation fraction cover. Low NDWI values correspond to low vegetation water content and low vegetation fraction cover. In periods of water stress, NDWI values decrease (Ceccato et al., 2001).

The previously mentioned 10 × 10 m (1 pixel) trial plots adjacent to the water table wells (Fig. 1) were also used to estimate NDVI and NDWI from satellite data. Sentinel-2 satellite images (which have been available since 2015) with a spatial resolution of 10 m were obtained from ESA Copernicus Open Access Hub (Copernicus Sentinel data [2015-2020], retrieved from ASF DAAC, processed by ESA). Images taken from April–October were used in the study. The values of both indices (NDVI and NDWI) were determined for each trial plot. The number of usable images obtained each year varied due to cloud cover: one image in 2015 (Aug 4); three in 2016 (Aug 5, 29; Oct 19); three in 2017 (Apr 2; May 12; Aug 8); 16 in 2018 (Apr 7, 10, 20; May 7, 10, 12, 20, 27, 30; Jun 1; Jul 31; Aug 10, 23; Oct 9, 12, 14); 10 in 2019 (Apr 2, 17, 30; May 12; Jun 9, 19; Sept 9; Oct 14, 22); and 7 in 2020 (Apr 6, 11; Jun 8, 25, Aug 7, 14; Sept 16). Due to large data gaps, trial plot No. 29 was excluded from the NDVI and NDWI analysis.

The 8-day MODIS composites (MOD09Q1) of surface reflections (NIR and RED) with a spatial resolution of 250 m for 21 years (2000–2020) were obtained from NASA's LAADS–DAAC (https://ladsweb.modaps.eosdis.nasa.gov). According to the MODIS images, the average NDVI during the growing season (average monthly temperature > 10 °C, May–September) was calculated for the entire Čepkeliai raised bog. These NDVI values were treated as auxiliary data and due to different spatial resolutions (Modis – 250 m, Sentinel 2 – 10 m) are presented separately (Fig. 4). As Sentinel 2 data series have only been available since 2015, NDVI (from MODIS) provides additional information about long term NDVI changes at the site. SNAP, ERDAS, and ArcMap software were used for calculations and analysis of the Sentinel 2 and Terra Modis images.

2.2.4. Statistical analysis

Pearson's linear correlation coefficient was used to evaluate the relationships between hydrological, botanical, and spectral indices. This measures the similarity between changes in two variables (Altman and Krzywinski, 2015) and is often used when analysing the interrelationships between environmental elements (hydrological, meteorological, geological, biological, etc.; (Bloomfield et al., 2011; Burdun et al., 2019; Kim et al., 2021; Peña-Gallardo et al., 2019). To analyse the synchronism of hydrological indicators or spectral index fluctuations in all trial and study plots, correlation matrixes based on chronological measurement data series were created (see Tables 5 and 7). The data were processed using MS Excel Software, and a p value < 0.05 was used to evaluate the statistical significance of the Pearson correlation. The Shapiro-Wilk test using the Real Statistics Resource Pack XREALSTATS was performed to check the normal distribution of variables.

The average, minimum, and maximum values of water table depth (2019–2020), the NDVI and NDWI (2015–2020) of each trial plot, and the percentage cover of vegetation species/layers were used to examine the relationship between the spatial distribution of hydrological, botanical, and spectral indices. The values of 56 trial plots were used to assess the relationships between NDVI/NDWI and vegetation cover, and

Table 1
Criteria of raised bog habitat types based on tree growth characteristics.

Raised bog habitat type	*Coverage of trees, %*	*Predominant height of trees, m*	*Predominant ecological pine form*
Open raised bog	< 20	≤ 1	f. *willkommii*
Semi-open raised bog	21–40	< 5	f. *litwinowii*
Bog woodland	≥ 40	≥ 5	f. *uliginosa*

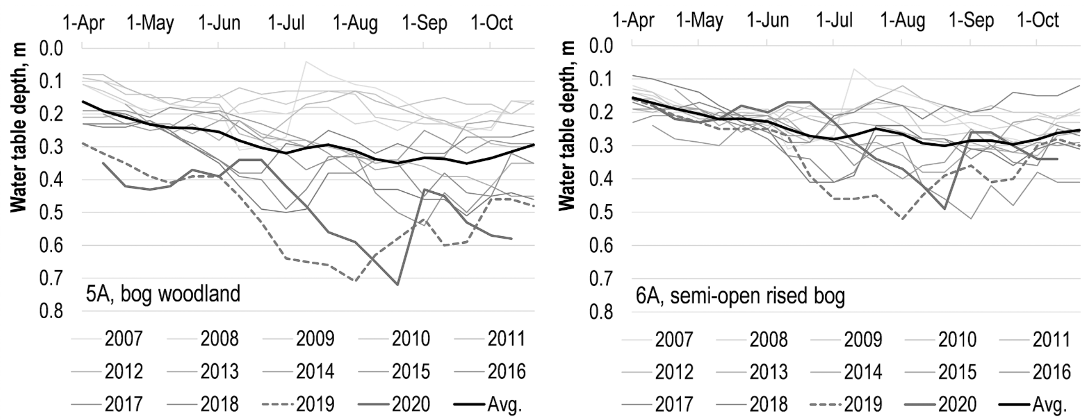

Fig. 3. Seasonal water table depth fluctuation in the long-term observation wells of the Čepkeliai raised bog in 2007–2020.

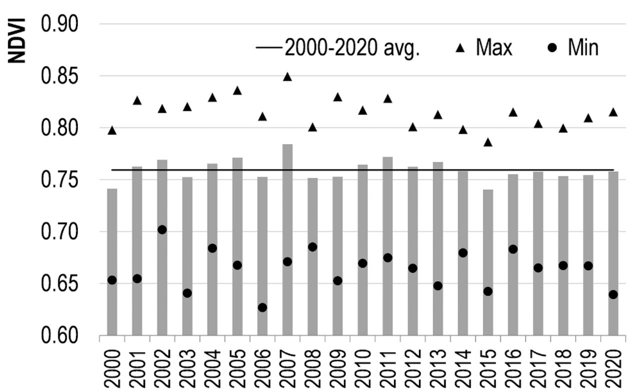

Fig. 4. Change of NDVI values in Čepkeliai raised bog (according to MODIS data).

the values of 45 trial plots were used to assess the relationships between NDVI/NDWI and water table depth (excluding trial plots with no water table depth or NDVI/NDWI data).

To analyse the chronological relationship between the water table depth and the spectral indices NDVI and NDWI, the measurements of the nearest dates of these indicators were selected (the difference in measurement dates ranged from 1 to 5 days). For each trial plot, 10 (study plot A, where water table measurements were taken every 10 days) or six (study plots B–E, where water table measurements were taken once a month) pairs of simultaneous data were obtained, and correlations analysis between water table depth and NDVI and water table depth and NDWI were performed.

3. Results

3.1. Raised bog vegetation

The trial plots (1–57) were divided into three groups according to raised bog habitat type (see Table 1). Vegetation met semi-open raised bog habitat criteria in 25 trial plots (at least two criteria out of three; see Table 1), bog woodland habitat criteria in 23 trial plots, and open raised bog habitat criteria in 9 trial plots. Study plot B comprised bog woodland and study plot C, semi-open raised bog. Study plot E was divided clearly into two sections: an open raised bog appeared in the western part after the 1992 fire (its growth was also disturbed by animals destroying new shoots), while a bog woodland formed in the eastern part (which was unaffected by the fire). Trial plots assigned to both bog woodland and semi-open bog habitats were found in study plots A and D (Table 2).

The percentage cover of different vegetation layers varied greatly across the 57 trial plots: tree cover ranged from 8–77 %, shrub cover 1–67 %, grass 2–47 %, green moss 1–63 %, and *Sphagnum* 30–90 %. Of the five study plots (A–E), trial plots B and C had the greatest average tree cover (Tables 2 and 3). They also have the highest average percentage of green moss cover and the lowest of *Sphagnum* cover. The other three study plots (A, D, and E) had lower average tree cover, lower green moss cover, and higher *Sphagnum* cover. A similar relation was found in the shrub and grass layers: as the cover of the shrubs increased, the cover of grass decreased, and vice versa. Study plot C had a particularly low shrub cover and a high grass cover (Tables 2 and 3).

The *Sphagnum* layer has the largest percentage cover in all types of raised bog habitat (Table 3). The percentage cover of other vegetation layers revealed differences between the raised bog habitats. The trial plots assigned to the bog woodland habitat had the greatest percentage of tree and green moss cover. When compared with the other types of raised bog, the semi-open raised bog trial plots had a greater grass and *Sphagnum* percentage cover. By contrast, shrub layer percentage cover was greatest in the open raised bog trial plots (Table 3).

Differences in the species composition were also evident in the vegetation layers. Tree layer in the bog woodland trial plots comprised various ecological forms of pines. *Rhododendron tomentosum* prevailed in shrub layer; grass layer were dominated by *Eriophorum vaginatum*; moss layer were dominated by *Pleurozium schreberi*; and *Sphagnum magellanicum* prevailed in the *Sphagnum* layer.

Young pines (1–5 m height) predominated in the tree layer of semi-open raised bog trial plots. *Calluna vulgaris* and *Vaccinium oxycoccos* were the most common in the shrub layer. *Andromeda polifolia* was most abundant in the shrub layer of semi-open raised bog, compared to other raised bog habitat types. In the grass layer, *Eriophorum vaginatum* was accompanied by *Molinia coerulea* and *Carex nigra*, and in study plot C, which was characterised by a thin peat layer (≤40 cm) and was periodically flooded, *Drosera rotundifolia* and *Carex rostrata*. *Polytrichum strictum* predominated amongst green mosses, while *Acutifolia* predominated amongst *Sphagnum*. Lichens were also common in the semi-open raised bog trial plots.

Tree layer of open raised bog trial plots were dominated by pine trees up to 1 m in height. *Betula pendula*, *Betula pubescens* were more common there than in the other types of raised bog habitats. *Picea abies* occurred in open raised bogs trial plots. However, it should be stressed that the trial plots were located in an open raised bog that appeared after the fire in 1992, so tree species composition was influenced by the higher content of nutrients in the soil. No spruces were found in the other open raised bog areas of Čepkeliai. *Calluna vulgaris* and *Vaccinium uliginosum* were more abundant in the shrub layer of open raised bog than the trial plots of other habitat types. Grass layer were sparse, with *Eriophorum vaginatum* being the most common. *Aulacomnium palustre* prevailed

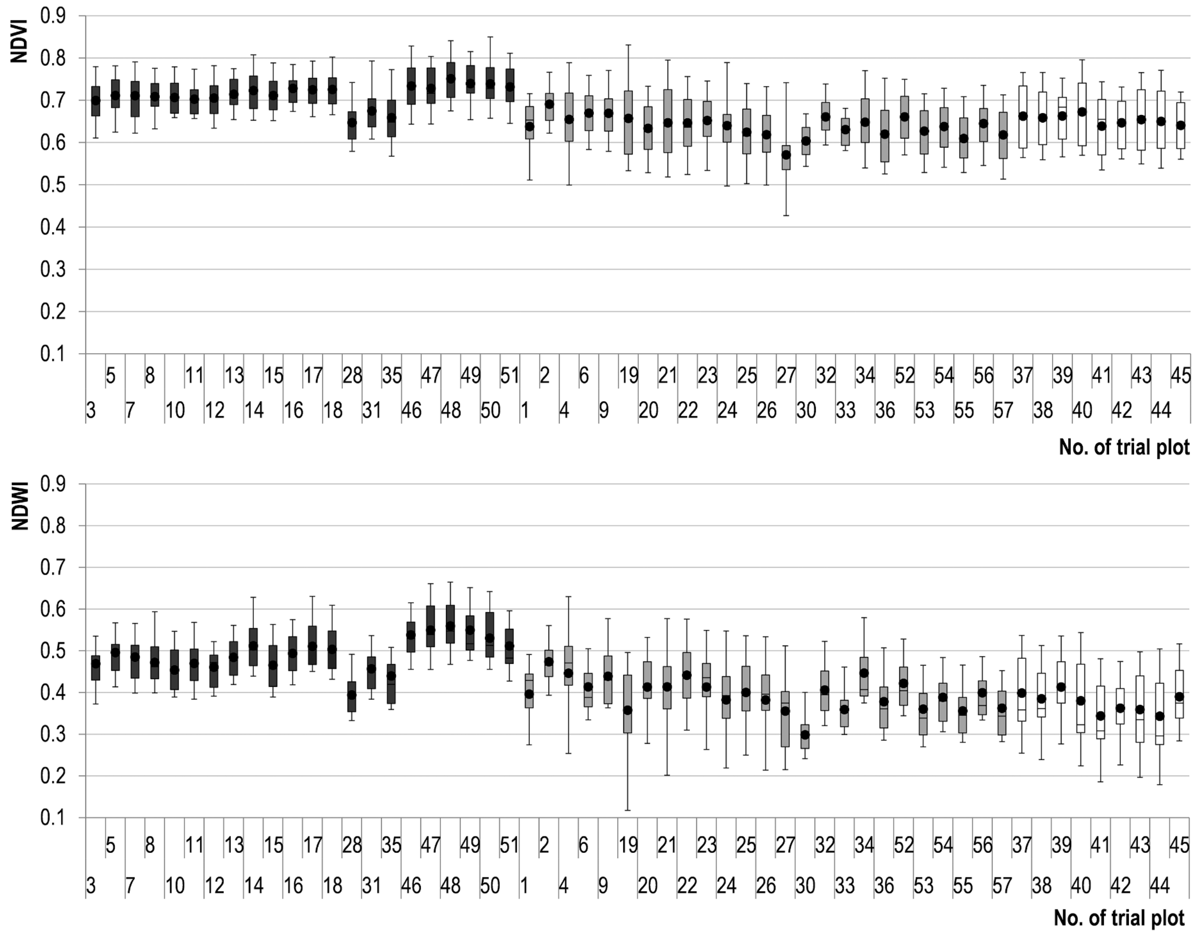

Fig. 5. Distribution of NDVI and NDWI values of 57 trial plots in different raised bog habitat types (2019–2020, open raised bog – white, semi-open raised bog – light grey, bog woodland – dark grey).

Table 2
Distribution of raised bog habitat types in the Čepkeliai raised bog study plots (A–E) and trial plots (1–57): open raised bogs – O (white), semi-open raised bogs – SO (grey), bog woodland – W (black).

A					*B*			*C*			*D*			*E*				
1 SO	2 SO	3 W	52 SO	53 SO	10 W	11 W	12 W	19 SO	20 SO	21 SO	28 W	29 W	30 SO	37 O	38 O	39 O	46 W	47 W
4 SO	5 W	6 SO	54 SO	55 SO	13 W	14 W	15 W	22 SO	23 SO	24 SO	31 W	32 SO	33 SO	40 O	41 O	42 O	48 W	49 W
7 W	8 W	9 SO	56 SO	57 SO	16 W	17 W	18 W	25 SO	26 SO	27 SO	34 SO	35 W	36 SO	43 O	44 O	45 O	50 W	51 W

amongst green mosses, while *Cuspidata* predominated amongst *Sphagnum*.

3.2. Raised bog hydrology

The years 2019–2020 were classified as dry. According to data from the Lithuanian Hydrometeorological Service, precipitation in Varėna WS, located 27 km to the north of Čepkeliai, reached 489.2 mm in 2019, 524.5 mm in 2020, which was 70–75 % of climate normal (701 mm). Growing season precipitation was 64–69 % of climate normal. The first half of the growing season was particularly dry in 2019: precipitation in April was only 1 % and in May–June, 24–28 % of climate normal. April was the driest month in 2020 (when precipitation was 21 % of the climate normal); July and September were also dry (22 and 34 %, respectively).

The water table for 2019–2020 was impacted by particularly dry years. The elevation of the average annual water table in wells used for long-term measurements reached its lowest point since measurements began. In addition, the water table was the lowest or one of the lowest in 14 years (Fig. 2). In some wells (19–25, 27, 43–45, and 50), the water table dropped below the well's bottom. These data could not be used for analysis.

The measurements in 2019–2020 revealed the characteristics of water table fluctuations in a greater number of measuring wells spread across the entire Čepkeliai peatland. Water table elevation in the wells studied ranged between 129.85 and 133.33 m ASL (with an average of 131.42 m). However, it was also affected by peatland surface elevation. Therefore, the wells in study plot A, which were located at the highest elevation in the peatland's western area, were distinct from the others: the water table ranged from 132.78 to 133.33 m ASL. In the remaining

Table 3
Distribution of vegetation species in the Čepkeliai raised bog trial plots in 2019 (%).

Trial plot No.	**Tree layer**	*Betula pendula*	*Betula pubescens*	*Picea abies*	*Pinus sylvestris* f. *litwinowii*	*Pinus sylvestris* f. *uliginosa*	*Pinus sylvestris* f. *willkommii*	*Pinus sylvestris* (1-7 m high)	*Pinus sylvestris* (up to 1 m high)	**Shrub/dwarf shrub layer**	*Andromeda polifolia*	*Calluna vulgaris*	*Empetrum nigrum*	*Rhododendron tomentosum*	*Vaccinium myrtillus*	*Vaccinium oxycoccus*	*Vaccinium uliginosum*	**Grass layer**	*Carex nigra*	*Carex rostrata*	*Drosera rotundifolia*	*Eriophorum vaginatum*	*Molinia coerulea*	**Moss layer**	**Green moss**	*Aulacomnium palustre*	*Dicranum polysetum*	*Pleurozium schreberi*	*Polytrichum strictum*	***Sphagnum* L.**	Section *Acutifolia* Wilson	Subgenus *Cuspidata* Lindb.	Subgenus *Sphagnum*	**Lichen**
Open raised bog																																		
37	**13**	10	1						2	**67**		15		20		7	25	**4**				4			**18**	10		5	3	**65**		60	5	
38	**12**	4	2						6	**40**		10		15		5	10	**5**				5			**9**	5		2	2	**70**		60	10	
39	**13**	3			4				6	**32**		15		10		5	2	**6**				6			**11**	3		6	2	**81**	1	40	40	
40	**17**	10	3	1					3	**65**		20		20		10	15	**4**				4			**21**	15		3	3	**60**	5	45	10	
41	**20**	12	2						6	**29**		17		7		3	2	**5**				5			**12**	5		5	2	**70**		50	20	
42	**20**	9	2						9	**26**	<1	12		8		5	1	**6**				6			**15**	10		3	2	**70**		40	30	
43	**17**	9	2						6	**60**		30		10		10	10	**8**				8			**30**	20	<1	5	5	**55**	5	40	10	
44	**24**	15	6						3	**62**		25		15		2	20	**4**				4			**38**	15		20	3	**50**	10	40		
45	**14**	4	4						6	**56**	1	25		12		3	15	**5**				5			**35**	15		15	5	**50**		50		
Avg.	***17***									***49***								***5***							***21***					***63***				
Semi-open raised bog																																		
1	**12**	6			6					**58**	3	2		3		50		**20**				20			**3**			1	2	**85**		70	15	
2	**23**				4	8		10	1	**35**	3	5		15		10	2	**10**				10			**9**	2	2	3	2	**85**	5	20	60	
4	**8**		4		4					**46**	2	1		10		25	8	**25**				25			**6**	2		3	1	**85**		60	25	
6	**32**				20			10	2	**48**	2	15		15		8	8	**8**				8			**9**	3		3	3	**85**	5	15	65	
9	**34**				12			20	2	**33**	3	15		5		10		**20**				20			**14**	5		6	3	**75**		20	55	
52	**24**				6			16	2	**34**	3	14		6		10	1	**10**				10			**7**	3		1	3	**87**	7	30	50	
53	**18**	1			2			5	10	**30**	3	20				7		**16**			1	15			**3**				3	**85**	5	15	65	
54	**33**	1			6			20	6	**33**	5	10		10		8		**15**			0.1	15			**11**	5		1	5	**85**	5	30	50	
55	**30**				10			10	10	**39**	2	15		10		10	2	**10**				10			**27**	10	3	7	7	**60**	10	30	20	**<1**
56	**29**							25	4	**30**	5	15		3		7		**18**			0.1	18			**15**	5		5	5	**70**	10	30	30	
57	**32**				6			20	6	**27**	5	10		5		7		**17**			2	15			**15**	5		5	5	**75**	5	30	40	
19	**36**		10					18	8	**23**		1			7	10	5	**47**	2			5	40		**8**	3			5	**80**		80		
20	**44**		10					24	10	**18**	3					5	10	**22**	2			20			**20**	5			15	**70**		60	10	
21	**34**	6	6					12	10	**5**	3					2		**35**	5			5	25		**30**	15			15	**60**		40	20	
22	**62**	6	6					30	20	**17**						15	2	**31**	3	<1		25	3		**15**	5			10	**73**		70	3	
23	**56**							36	20	**26**	5	1		1		18	1	**15**			<1	15			**20**	5			15	**70**		30	40	
24	**52**	2						30	20	**<1**					<1	<1	<1	**20**	3			10	7		**31**	10		1	20	**60**		60		
25	**53**	3						40	10	**31**	10			1		20		**30**				30			**20**	5			15	**75**		60	15	
26	**51**		1					30	20	**42**	10					25	7	**30**				30			**35**	5			30	**60**		55	5	
27	**45**	2	3					20	20	**1**						1		**27**	2			20	5		**40**	5			35	**58**		55	3	
30	**21**		1					14	6	**47**	2	40				2	3	**7**				7			**6**	3			3	**75**	70		5	**4**
32	**18**							14	4	**52**	1	45				1	5	**5**				5			**7**	3		1	3	**80**	75		5	**1**
33	**27**		1		10			12	4	**45**	2	40			2	1		**7**				7			**18**	5	1	5	7	**73**	70		3	**3**
34	**24**							20	4	**41**	2	10		3		25	1	**25**			<1	25			**6**	2		1	3	**88**		25	63	
36	**28**				6			16	6	**48**		40				5	3	**5**			<1	5			**7**	2			5	**85**		15	70	
Avg.	***33***									***32***								***19***							***15***					***75***				
Bog woodland																																		
3	**63**				12			50	1	**42**	1	5		25		3	8	**5**				5			**1**				1	**90**		25	65	
5	**60**				12	2		46		**40**	1	3		25	3	3	5	**7**				7			**30**	2		25	3	**60**		10	50	
7	**37**		20		15			2		**32**	2	1		10		15	4	**20**				20			**11**	2	2	5	2	**85**		60	25	
8	**42**	4	6		8	10		12	2	**50**	3	5		15	2	5	20	**5**				5			**26**	2	2	20	2	**60**		10	50	
10	**52**	2				30		20		**48**		10		30		5	3	**5**				5			**63**	10	10	35	8	**30**		10	20	
11	**35**					30		3	2	**33**		10		20			3	**5**				5			**35**	5	5	20	5	**55**		15	40	
12	**30**					30				**66**	1	10		30		20	5	**10**				10			**38**		3	25	10	**50**		20	30	**<1**
13	**40**					30		10		**43**		10		25		5	3	**6**				6			**35**	5	10	15	5	**55**		10	45	
14	**72**					30		40	2	**31**	1	5		15		5	5	**7**				7			**50**	10	5	30	5	**40**		10	30	
15	**35**		2			30	2	1		**56**	1	10		15		10	20	**15**				15			**53**		2	50	1	**38**		35	3	
16	**70**	5	10			15		40		**43**		8		30		3	2	**3**				3			**51**	8	5	35	3	**40**		15	25	
17	**77**	6	4			25		40	2	**51**		7	4	30	2	5	3	**8**				8			**33**	3	8	20	2	**50**		30	20	
18	**62**	2				20		40		**57**	1	8		40	3	5		**5**				5			**17**	1	5	10	1	**65**		50	15	
28	**70**					10		40	20	**36**	1	20		10		2	3	**10**				10			**9**	2	2		5	**75**	45	20	10	**2**
29	**46**	2						40	4	**44**	3	30		5		3	3	**7**				7			**12**	2	7		3	**80**	60	20		**1**
31	**52**	4			8			40		**26**	1	7		10	<1	3	5	**10**				10			**5**	2			3	**85**	70	5	10	
35	**50**							48	2	**57**	2	15		15		20	5	**15**				15			**5**	2			3	**88**		25	63	
46	**22**	2			10			10		**39**	1	4		20		12	2	**10**			<1	10			**20**	3		15	2	**70**		40	30	
47	**32**				18			14		**26**	1	1		15		8	1	**8**				8			**11**			10	1	**80**		30	50	
48	**35**	4	1		10			20		**40**	1	2		20		10	7	**7**				7			**22**	5		15	2	**70**		30	40	
49	**40**	1	1		26			12		**22**	<1	<1		12		5	5	**7**				7			**12**	1	<1	10	1	**80**		40	40	
50	**30**	1	2		16			10	1	**30**	1	5		15		4	5	**7**				7			**5**	3		1	1	**85**		65	20	
51	**41**		1		24			16		**35**	<1	<1		30		5	<1	**2**				2			**12**	1		10	1	**78**		40	38	
Avg.	***48***									***41***								***8***							***24***					***66***				

Table 4
Values of water table depth in the Čepkeliai raised bog study plots (2019–2020, m below surface).

Value	*A*	*B*	*C**	*D*	*E*
Minimum	0.06	0.15	0.16	0.13	0.15
Maximum	0.63	0.77	0.79	0.67	0.67
Average	0.33	0.41	0.50	0.38	0.38
Average amplitude in the well	0.34	0.46	0.63	0.47	0.38

* Data from well No. 26 only.

study plots, these values were closer, ranging between 129.85 and 130.99 m ASL.

Water table depth values allowed us to compare the data from wells located at different elevations, making it better suited for comparing individual study plots. The minimum water table depth in the wells was recorded in April–June and the maximum in August. The depth decreased again in early autumn. According to the assessment of seasonal variations based on long-term monitoring of the wells, 2019–2020 differed from previous years by having a deep water table and a high annual fluctuation amplitude (0.32–0.42 m), while average amplitude was 0.22–0.25 m and the lowest amplitude was 0.10–0.11 m (Fig. 3).

The water table was highest in study plot A, ranging between 0.06 and 0.63 m below the surface (average: 0.33 m). Water table was lowest in the study plot C wells—eight had dried out —and 0.79 m below the surface (0.5 m on average) in the remaining well. The amplitude of water table depth fluctuations was lowest in the study plot A wells—0.34 m—and highest in the study plot C wells – 0.63 m (Table 4). The average for all wells was 0.42 m. However, the differences in depth between the wells during the same measurement were significant, ranging from 0.20 to 0.52 m (with the average being 0.36 m).

The correlation matrix revealed that the fluctuations of water table depth in the wells were not identical. The Pearson correlation coefficient ranged from 0.59 to 1.00. Even wells 50–200 m apart in the same study plot had different water table fluctuations. According to the correlation matrix data, the water table depth fluctuated most evenly in the study plot B wells and most unevenly in the study plot A wells (Table 5). The difference in water table depth during the same measurement in the wells of study plot B was 8–24 cm (an average of 14 cm), whereas the difference in the study plot A wells was 18–30 cm (an average of 23 cm). The water table depth fluctuations in the study plot A wells correlated least with the fluctuations in the other study plots (with the exception of study plot C, where only one of the nine wells remained undried).

3.3. Remote sensing indices NDVI and NDWI

Long-term data (MODIS, 2000–2020) analysis shows that the interannual variation of average annual NDVI for the entire Čepkeliai peatland after 2016 became smaller and closer to the 2000–2020 average (0.76). However, the amplitude of intra-annual variations of NDVI increased, one of the largest being in 2020. It was concluded that the status of raised bog vegetation changed significantly during the growing season (Fig. 4).

The status of vegetation differed significantly from a spatial perspective, according to higher-resolution images from Sentinel 2. The differences in NDVI values of trial plots calculated from one satellite image range from 0.15 to 0.30. The amplitude of NDVI in each trial plot ranged from 0.3 to 0.4 in 2015–2020. The differences in the values of NDWI, corresponding to plant moisture content, were even greater: differences between the trial plots ranged between 0.2 and 0.4 in one satellite image, whereas the change amplitude in each trial plot was 0.2–0.5 over the study period (2015–2020). However, even though we could not estimate the temporal variability of the satellite indices in detail due to the limited set of existing values and their uneven distribution over time, the spatial variability in NDVI and NDWI trends was clear and served as the basis for spatial grouping of the trial plots across the different study plots (Table 6). The highest average NDVI and NDWI values and the lowest amplitudes were observed in study plot B. Study plot C was distinguished by the lowest average values and the greatest amplitudes. There were two distinct areas in study plot E: western, with lower NDVI and NDWI values and wider variation, and eastern, with high values (with the values even higher than those in study plot B) but smaller variation (Table 6). A similar but less pronounced difference could be seen in study plot A: the eastern part had lower NDVI and NDWI values, while the highest NDVI and NDWI values and lowest variation were observed in the western part, excluding trial plots No. 1, 4, and 7 (which were located in raised bog lagg). The same trends were observed in previous years (2015–2018).

A summary of the trends in NDVI and NDWI values according to raised bog habitat types shows that bog woodland had the highest values but the lowest variation in both. Average values and variation in amplitude for semi-open and open raised bog habitats were similar. However, a similar distribution in all trial plots was observed in open raised bog, whereas wide distribution in values among separate trial plots prevailed in semi-open raised bog (Table 6, Fig. 5).

Variations in NDVI values in the trial plots of some study plots were simultaneous, while in others, the state of vegetation changes differently even in neighbouring trial plots. According to the correlation matrix, the lowest correlation coefficients (when comparing the trial plots of the same study plot and the trial plots of other study plots) were found for the trial plots No. 1, 4, 56, and 27, and were determined by local (hydrological) conditions. The generalised data of the correlation matrix (Table 7) show that in study plot B, NDVI variation was even in all trial plots, as well as in study plots E' and E". In other study plots (including the entire study plot E), the correlation between the individual fields was weaker. Study plots B and E were characterised by exceptionally high NDVI correlation: all coefficients were >0.9 (Table 7).

Lower correlations were observed in the NDWI correlation matrix (Table 7). Variation in the vegetation water content of trial plots No. 1 and 4, situated in the bog's lagg, was weakly correlated with the same index values of the other trial plots (the Pearson correlation coefficient

Table 5
Pearson correlation coefficients ($p < .05$) between water table depth in the wells in study plots A–E (avg. [min.–max.]).

	A	*B*	*C**	*D*	*E*
A	0.92 (0.74–0.99)				
B	0.88 (0.59–0.97)	0.98 (0.93–1.00)			
*C**	0.81 (0.68–0.92)	0.75 (0.65–0.81)	–		
D	0.89 (0.62–0.98)	0.95 (0.85–0.99)	0.76 (0.66–0.87)	0.95 (0.81–0.99)	
E	0.90 (0.69–0.99)	0.95 (0.87–0.99)	0.85 (0.72–0.89)	0.94 (0.83–0.99)	0.97 (0.89–1.00)

* Data from well No. 26 only.

Table 6
NDVI and NDWI values in study plots A–E and different raised bog habitat types (2019–2020).

Study plot		*A*	*B*	*C*	*D*	*E*	*E'*	*E"*	*Bog wood-land*	*Semi-open raised bog*	*Open raised bog*
Trial plot No.		1–9, 52–57	10–18	19–27	28, 30–36	37–51	*37–45*	*46–51*			
NDVI	***Avg.***	0.66	0.72	0.63	0.64	0.69	0.65	0.74	0.71	0.64	0.65
	Max.	0.79	0.81	0.83	0.79	0.85	0.80	0.85	0.85	0.83	0.80
	Min.	0.50	0.63	0.43	0.53	0.53	0.53	0.64	0.57	0.43	0.53
	Avg. ampl.	0.18	0.13	0.26	0.17	0.19	0.20	0.17	0.15	0.21	0.20
NDWI	***Avg.***	0.43	0.48	0.40	0.40	0.44	*0.37*	*0.54*	0.49	0.40	0.37
	Max.	0.59	0.60	0.61	0.60	0.68	*0.56*	*0.68*	0.68	0.61	0.56
	Min.	0.25	0.38	0.12	0.24	0.18	*0.18*	*0.43*	0.33	0.12	0.18
	Avg. ampl.	0.20	0.16	0.32	0.19	0.25	*0.29*	*0.19*	0.18	0.24	0.29

reached only 0.1–0.6). The NDWI correlation was low or moderate in study plot C, which was characterised by a significant fall in the water table depth (the most of the wells had dried up). A very high NDWI correlation was detected amongst study plot B and study plot E trial plots; the eastern and western sub-sites were assessed individually).

3.4. Relationship between vegetation cover, groundwater table, and remote sensing variables

The relationships between water table depth, NDVI and NDWI indicators, and vegetation cover in individual study points (i.e., wells and trial plots), in many cases the indicators were characterised by a weak and statistically insignificant correlation ($r < 0{,}4$, $p > .05$). Some indicators showed a moderate positive or negative statistically significant correlation (Table 8).

The species more common to open raised bog (*Sphagnum*) appeared in the trial plots where the water table was closer to the surface. The species more common to bog woodland (green moss, *Rhododendron tomentosum*, and trees) were characteristic of the trial plots where a deeper water table was observed. The changes in vegetation state and moisture content were most visible in the trial plots with a higher percentage of grass cover: the values of NDVI and NDWI fell the most, and the amplitude of their variability was larger than in other trial plots. They were also related to water table depth, with the lowest index values more common for trial plots where water was located closer to the surface.

Seasonal variation is ordinarily reflected in water table depth and NDVI/NDWI indices, so a correlation analysis was performed between simultaneous measurements of these indicators; the difference between the measurements was 1–5 days). The correlation between NDVI and water table depth was found to be very different at individual study points: the Pearson coefficient varied between 0.10 and 0.93 (with an average of 0.57). However, the limited data sets meant that a statistically significant correlation was found in only 25 % of the trial plots. The relationship between NDWI and water table depth was stronger in individual trial plots: the Pearson coefficient attained values between 0.42 and 0.95 (average – 0.77), and 80 % of the coefficient values were statistically significant.

In terms of the relationship between water table depth and NDVI in study plots A–E, statistically significant coefficients were obtained (except for study plot C, where only one well was suitable), showing a moderate correlation in study plots A and E (with a strong correlation in the western part of study plot E and weak one in the eastern part) and a weak correlation in study plots B and D. Meanwhile, the correlation of water table depth with NDWI was strongest in those study plots (B and E") with the weakest correlation with NDVI. Water table depth was strongly correlated with both indices in study plot E' (Table 9).

When the different raised bog habitat types were compared, a strong correlation of water table depth with both indices was found in the open raised bog (Table 9). The highest statistically significant coefficients showing a strong and very strong correlation between water table depth and NDVI/NDWI in individual trial plots were found for open raised bog habitats. A weak correlation between water table depth and NDVI/NDWI was observed in semi-open raised bog habitats, though there was a high correlation in some individual trial plots; NDVI was weakly correlated with water table depth in bog woodland, while there was a moderate correlation between water table depth and NDWI. The correlation coefficients between water table depth and NDVI in individual trial plots in the bog woodland were statistically insignificant in most cases and significant in the case of NDWI in most trial plots.

In all cases, a positive correlation was found between water table depth and NDVI/NDWI, indicating that the deeper water table encouraged vegetative vigour of plants (leaves with high chlorophyll and moisture content). This may also be due to the seasonal patterns of vegetation development – the growth of plant biomass increases during the vegetation period when plants accumulate more moisture in a canopy, and thus, NDVI and NDWI values increase. Meanwhile, the water table depth increases during the warm season as the amount of net precipitation decreases (Taminskas et al., 2018).

Lower water tables were more common in bog woodland; NDVI/NDWI values were highest, but their variation in individual trial plots was the smallest when compared with other raised bog habitat types (Table 10). Semi-open raised bog was characterised by a diversity in water table depth amongst the different wells, although in some individual cases the water table depth varied the least when compared with other raised bog habitat types. Therefore, the local conditions in the semi-open raised bog were the most diverse. Summarising the water table depth measurements of the open raised bog, the opposite distribution was observed: that is, the amplitude of water table fluctuation was the largest at individual wells in comparison with other raised bog habitat types. However, the range of water table depth data measured in the open raised bog was the narrowest. This may have been because the trial plots assigned to the open raised bog habitat were all located in the same study plot, whereas the trial plots of other raised bog habitat types were scattered over several study plots with different peat layer thicknesses and other peatland properties. Semi-open raised bog trial plots had a wider variation in NDVI values, whereas open raised bog habitat had a wider variation in NDWI values (Table 10).

Significant differences were found between raised bog habitat types in terms of the correlation between satellite indices NDVI and NDWI values in the period 2015–2020. The Pearson coefficient showed that there was a weak correlation (0.38) in only two trial plots, whereas a negligible ($r \leq 0.18$) correlation was found in the other 20 trial plots in bog woodland habitats. A moderate correlation between NDVI and NDWI was detected in all trial plots of open raised bog: Pearson coefficient values varied between 0.53 and 0.65. The correlation between NDVI and NDWI was very different in semi-open raised bog trial plots: half of the fields were characterised by a weak correlation, a third of the trial plots by a moderate correlation, and four of the trial plots by a negligible correlation. Thus, fluctuations in vegetation states (expressed

Table 7
NDVI and NDWI correlation matrixes between trial plots of study plots A–E (avg. [min.–max.]).

	NDVI							NDWI						
	A	**B**	**C**	**D**	**E**	**E’**	**E“**	**A**	**B**	**C**	**D**	**E**	**E’**	**E“**
A	0.84 (0.56-0.99)							0.78 (0.20–0.99)						
B	0.82 (0.56-0.95)	0.98 (0.96-0.99)						0.79 (0.09–0.96)	0.97 (0.94–0.99)					
C	0.74 (0.50-0.87)	0.73 (0.54-0.87)	0.86 (0.58-0.98)					0.64 (0.34–0.86)	0.60 (0.29–0.82)	0.80 (0.53–0.96)				
D	0.78 (0.55-0.94)	0.89 (0.73-0.96)	0.78 (0.59-0.88)	0.89 (0.78-0.98)				0.79 (0.18–0.98)	0.89 (0.82–0.94)	0.68 (0.46–0.84)	0.88 (0.69–0.97)			
E	0.83 (0.60-0.97)	0.84 (0.70-0.96)	0.75 (0.56-0.93)	0.83 (0.69-0.94)	0.87 (0.73-0.99)			0.79 (0.02–0.96)	0.87 (0.73–0.97)	0.60 (0.32–0.87)	0.81 (0.64–0.96)	0.85 (0.63–0.99)		
E’	*0.82 (0.67-0.96)*	*0.78 (0.70-0.84)*	*0.77 (0.56-0.93)*	*0.81 (0.69-0.94)*		*0.97 (0.95-0.99)*		*0.80 (0.40–0.95)*	*0.83 (0.73–0.92)*	*0.60 (0.32–0.87)*	*0.77 (0.64–0.93)*		*0.96 (0.90–0.99)*	
E’’	*0.84 (0.60-0.97)*	*0.94 (0.91-0.96)*	*0.73 (0.56-0.85)*	*0.87 (0.75-0.93)*		*0.78 (0.73-0.83)*	*0.98 (0.97-0.99)*	*0.79 (0.02–0.96)*	*0.92 (0.86–0.97)*	*0.58 (0.32–0.80)*	*0.87 (0.64–0.96)*		*0.75 (0.63–0.87)*	*0.96 (0.94–0.97)*

Table 8
Moderate positive (0.6 > *r* > 0.4, **P**) and moderate negative (−0.4 > *r* > −0.6, **N**) statistically significant (*p* <.05) correlations between hydrological, botanical indicators, and spectral indices.

			Hydrologic indicators			Botanical indicators					Spectral indices					
			Water depth			Percentage cover					NDVI			NDWI		
			Average	Minimum	Maximum	Tree layer	Grass layer	Green moss	Sphagnum	*Rhododendron tomentosum*	Average	Minimum	Amplitude	Average	Minimum	Amplitude
Hydrologic indicators	Water depth	Average														
		Minimum														
		Maximum														
Botanical indicators	Percentage cover	Tree layer	**P**	**P**	**P**											
		Grass layer														
		Green moss	**P**													
		Sphagnum	**N**													
		Rhododendron tomentosum		**P**												
Spectral indices	NDVI	Average		**P**												
		Minimum	**P**	**P**			**N**									
		Amplitude					**P**									
	NDWI	Average		**P**												
		Minimum		**P**			**N**									
		Amplitude					**P**									

Table 9
Pearson correlation coefficients, comparing simultaneous water table depth and NDVI/NDWI data (*p* <.05).

All trial plots	***Study plots***							***Raised bog habitat types***		
	A	***B***	***C****	***D***	***E***	***E'***	***E''***	***Bog woodland***	***Semi-open raised bog***	***Open raised bog***
Correlation between water table depth and NDVI										
0.50	0.62	0.37	*0.71*	0.48	0.61	*0.84*	*0.47*	0,43	0,38	0,87
Correlation between water table depth and NDWI										
0,57	0.63	0.78	*0.51*	0.52	0.62	*0.87*	*0.76*	0,64	0,36	0,84

* Statistically insignificant, data obtained from one trial plot.

Table 10
Water table depth and NDVI and NDWI values in different Čepkeliai raised bog habitat types (2019–2020).

Indicators		*Raised bog habitat type*		
		Bog woodland	*Semi-open raised bog*	*Open raised bog*
Water table depth (m)	Avg.	0.40	0.34	0.38
	Min.	0.13	0.06	0.15
	Max.	0.77	0.79	0.67
	Ampl.	0.43	0.39	0.45
NDVI	Avg.	0.71	0.63	0.65
	Min.	0.57	0.43	0.53
	Max.	0.85	0.83	0.80
	Ampl.	0.15	0.21	0.20
NDWI	Avg.	0,49	0,40	0,37
	Min.	0,33	0,12	0,18
	Max.	0,68	0,61	0,56
	Ampl.	0.18	0.24	0.29

by NDVI) and moisture content in plants (expressed by NDWI) in the open raised bog (where lower layers of vegetation were prevalent), were simultaneous and reflected seasonal growth patterns. Fluctuations in these indices were only marginally interconnected in the bog woodland, where a tree layer predominated. Local (hydrological and botanical) conditions for each trial plot determined the relationship between spectral indices in semi-open raised bog.

4. Discussion

Remote sensing offers an affordable, alternative approach for studying sensitive and difficult-to-assess areas such as wetlands. High-resolution and long chronological data sets enable a reliable analysis of these vast territories' response to anthropogenic climate change and other impacts, as well as a more accurate evaluation of the importance of raised bog for the stability of hydroclimatic systems. However, to apply and interpret remote sensing data, special attention should be paid to understanding the relationships between processes taking place in the raised bog and spectral reflections recorded from space. Moreover, the raised bog itself is a combination of two closely related and interacting elements – water and vegetation. Frequently, the interaction between these elements is significantly supplemented by anthropogenic factors (e.g., drainage, forestry, and peat mining). Thus, large peatland complexes that have been protected for many decades (such as the Čepkeliai peatland) provide a unique opportunity to examine the relationships of natural processes and refine the interpretation of spectral indices.

Vegetation succession, especially the expansion or decline of woody vegetation, is often the clearest indication of long-term trends in peatland ecosystem change. The specific raised bog environment forces pines to adapt to constantly changing groundwater tables, low minerals and oxygen levels, and large temperature fluctuations in the root zone (Sinkevičius, 2001). The roots of raised bog plants are concentrated in the upper layer of peat (up to 20–30 cm deep), sometimes even in the living *Sphagnum* layer. As a result, raised bog pines are more sensitive to changes in groundwater table than those growing in mineral soils. As a result of climate change, drainage, and the disappearance of traditional extensive agricultural activities in peatlands, the colonisation of Lithuanian raised bogs by woody vegetation have been observed during the last decades (Edvardsson et al., 2015). Tree expansion has also been observed in other boreal peatlands (Berg et al., 2009; Cedro and Lamentowicz, 2008; Čugunovs et al., 2016). According to data from forest management projects carried out in the Čepkeliai State Nature Reserve, the areas of open raised bog steadily declined in the last decades of the 20th century: 400 ha of new forests were inventoried in 1988 and 1,600 ha in 2002, whereas open raised bogs remain only in 2,500 ha (i.e., 43 % of the raised bog area; Stončius et al., 2004). The trend of increasing forested areas continued at the beginning of the 21st century as well.

On the other hand, amplifications of seasonal and interannual variations of temperature and precipitation (Hannah et al., 2002; Rimkus et al., 2020; Valiukas, 2017) and drought events put peatlands under even greater stress and provided ideal conditions for fires. They also served to shape post-fire patterns of shrub expansion in burnt peatland and assumed great ecological importance in preventing the extensive expansion of forest. Therefore, open raised bog habitats increased in area (Manton et al., 2022). The structure and species composition of the vegetation in our study plots confirmed that this open raised bog habitat (study plot E') was the product of 1992 fire; it has been transformed due to the establishment of shrubs, birches, and spruces, which appeared after the fires provided nutrients in an otherwise nutrient-poor environment (Guêné-Nanchen et al., 2021; Kelly et al., 2018).

Semi-open raised bog habitat may be considered to be an indicator of tree expansion that begins at the ecotone between forested and open peatlands, with changes presaging landscape-level responses (Ratcliffe et al., 2017). An increase in the area of such a habitat reveals a trend towards the formation of bog woodland.

There is no single clearly defined central section in the Čepkeliai peatland. It is a complex peatland with four main peat formation cores and an undulating bottom (Kibirkštis, 2002). Previous studies (Taminskas et al., 2018) have shown that water exchange is not uniform across the Čepkeliai peatland, but rather manifests in several open or closed drainage sub-basins. In the present study, the groundwater measurements network located in various study plots in the Čepkeliai raised bog revealed that the water table depth was unevenly distributed between different raised bog parts as well as between neighbouring wells located at a distance of 50–200 m. Water table depth differences between wells in one study plot varied between 0.08 and 0.31 m during the same measurement. The uneven distribution of raised bog water table depth has been confirmed in other studies (Howie and van Meerveld, 2013, 2019). In the present study, continuous water table measurements were carried out during two warm seasons. Correlation analysis of these longer data sets allowed us to compare simultaneous water table differences as well as synchronic changes in water tables in different raised bog study plots. The correlation matrix shows that the water table depth fluctuations in the wells were not identical (the Pearson correlation coefficient varied between 0.59 and 1.00). Thus, measurements at one point could not represent the water regime of even a small raised bog – this requires an optimal research network that reflects water regime characteristics of different raised bog habitat types.

The distribution of water tables and differences in raised bog vegetation are closely related and interacting processes. A fall in the water table in the raised bog influences favourable environmental conditions for woody vegetation establishment (Bönsel and Sonneck, 2012; Jarašius et al., 2015; Matulevičiūtė and Rašomavičius, 2007; Sinyutkina, 2021). Trees, due to rainfall interception and soil water transpiration, promote further falls in the water table (Van Seters and Price, 2002). Increases in woody vegetation are observed not only in drained peatlands but also in pristine peatlands such as Čepkeliai. This shift is triggered by both: direct anthropogenic impact and natural changes in more complex systems. For example, changing peatland tree cover is likely to be an important feedback between peatlands and climate (Ratcliffe et al., 2017). The present study revealed statistically significant relationships between vegetation and water table depth in different raised bog habitat types. In areas with deeper water tables, bog woodland vegetation (trees, green mosses, and *Rhododendron tomentosum*) prevailed and vice versa in areas with higher water tables open raised bog plants (*Sphagnum*) occupied the surface. Thus, by observing an increase in forested areas, we can predict a long-term lowering of raised bog water tables.

The spatial and temporal regularities of spectral indices in three raised bog habitat types indicated in the present study suggest that high-resolution satellite imagery data can be used to identify raised bog habitat types and to study their succession (especially when long time series of such data are collected). This accords with previous studies showing that remote sensing provides invaluable information to characterise and measure the conditions of wetlands and their functioning (Bhatnagar et al., 2018). Indeed, remote sensing provides a robust and spatially explicit means to assess not only vegetation structure and function but also their relationships with climatic variables (Eamus et al., 2015). Determining the connections between raised bog water table depth, vegetation types, and NDVI/NDWI provides an opportunity to assess changes in hydroclimatic conditions and their effects on regional hydrology according to spectral indices. The future application of spectral indices in loss and succession of peatlands influenced by climate change and human activities require more similar research in wider territorial and temporal context. In addition, simultaneous data of water table depth and spectral indices reveal that seasonal cycles may influence long-term trends in variation or spatial regularities. The results, which have shown positive correlations between water table depth and spectral indices, lead us to the conclusion that the status of raised bog plants and their moisture content is higher when the water table is deeper–especially in the open raised bog habitat, where the correlation is strongest. This conclusion is inconsistent with the spatial patterns of water table depth and vegetation distribution found in previous studies and the present one. The explanation for this contradiction might be explained by the seasonality of water table depth and vegetation change. At the beginning and the end of the growing season, when the temperature and evapotranspiration are lowest, the water table is closest to the surface in the raised bog. In the middle of the growing season, as temperatures and evapotranspiration rise, the water table decreases. Meanwhile, the greening of vegetation and the peak of plant biomass occurs in the middle of the growing season, when temperatures are warm enough for normal enzyme activity and photosynthesis (D'Acunha et al., 2018). The cycles of water table and vegetation change are most pronounced and more strongly correlated in open raised bog habitats, where lower-layer vegetation is common. In the bog woodland habitat, the seasonal water table cycle is better reflected by NDWI, which shows the amount of water in the vegetation cover, thus the increasing volume of such cover during the growing season. The seasonal variation of chlorophyll content in trees (particularly pines) reflected by NDVI is less pronounced. In semi-open raised bog habitats with a mosaic of hydrological and botanical features, the correlation between simultaneous indicators is weak. On the other hand, the present study was conducted in dry years (2019–2020), a factor that might have led to exclusive patterns of water table depth and variations in spectral indices. In such dry years, even in a healthy peatland, the water table in wells can drop below 1 m. All of these aspects are important in planning both *in situ* measurements and the use of remote sensing data. The assessment of raised bog habitat type distribution and the boundaries of sub-basins before the installation of water measurement networks would be useful in evaluating water table variation intervals and variety. From a chronological point of view, it is important to know the period of remote sensing and *in situ* data in terms of seasonal and long-term water cycles and assess the potential impact of these seasonal variations on data interactions.

5. Conclusions

1. To obtain representative results, raised bogs should be regarded as heterogenous areas that are marked by spatial and temporal changes in hydrological and botanical indicators and related spectral indices.
2. Similarities in water table depth and spectral indices fluctuations depend more on raised bog habitat types than on the propinquity of measuring points.
3. Correlations between certain botanical and hydrological indicators and spectral indices allow the application of high-resolution remote sensing data as an additional instrument for raised bog measurements.
4. Close relationships between hydrology and the botany of raised bogs suggest that changes in vegetation cover and related spectral indices may become hydroclimatic indicators.

CRediT authorship contribution statement

Rita Linkevičienė: Methodology, Formal analysis, Writing – original draft, Visualization. **Rasa Šimanauskienė:** Formal analysis, Investigation, Writing – review & editing. **Gintautas Kibirkštis:** Investigation. **Onutė Grigaitė:** Investigation. **Julius Taminskas:** Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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