Natural isotopes support groundwater origin as a driver of mire type and biodiversity in Slitere National Park, Latvia

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SUMMARY

Slitere National Park in Latvia is home to rich fens with many endangered and threatened plant species. This study aims to address how the hydrological systems affect vegetation biodiversity (cf. Wolejko *et al*. 2019) in the mire systems of the National Park: the base-rich inter-dune mires and extremely base-rich calcareous fens. Groundwater samples from these areas were collected for measurements of ion composition and natural isotopes of C, H and O. Also, we simulated groundwater flow paths from the highest local topographical point (a nearby sandy plateau) to the sea, and calculated the residence times of these groundwater flows. The results show that the inter-dune mires are supplied by a mixture of local and regional groundwater systems. The groundwater supply at one of the inter-dune mires was dominated by local groundwater flow from adjacent dunes, but we also detected a small input of calcareous water. This dominance of local groundwater may have resulted from the presence of drainage ditches and a small stream that drains into the Baltic Sea. In contrast, the extremely base-rich fens were found to be solely dependent on regional groundwater which is likely to discharge at the plateau foothills due to the presence of fault structures. Thus, the mires in Slitere National Park are not as undisturbed as was previously believed. Drainage may have affected the original hydrological flow paths. Further research on the extent of these changes is recommended to preserve the endangered species and high biodiversity of these fens. Also, in order to trace the origin of groundwater flows, further investigation into the larger landscape beyond the plateau might be required.

KEY WORDS: base-rich fens, ecohydrology, groundwater system analysis

INTRODUCTION

Peatlands are wet landscapes with water tables sustained at or near the surface for extended periods of time (Joosten & Clarke 2002). When these sustained water tables allow for active accumulation of peat, the resulting peatlands are called mires (Mitsch & Gosselink 2000, Joosten & Clarke 2002). Peat is formed through accumulation of senescing vegetation that does not completely decompose, with organic matter constituting about 30 % or more of the total volume (Clymo *et al*. 1998). Hence, mires act as important carbon sinks in the carbon global cycle. Furthermore, mires provide refuge to rare and endangered wetland species (Pakalne & Kalnina 2005).

Slitere National Park is part of the coastal lowland region of northwestern Latvia, stretching along the Baltic Sea coastline (Pakalne & Kalnina 2005). Its wetlands range from an active raised bog (Bažu mire) to inter-dune fen complexes and calcareous fens (Figure 1). These mires developed in former Littorina Sea lagoons, where seawater regression and high groundwater levels allowed the infilling of inter-dune depressions around 4700 years ago (Kalnina *et al*. 2014). A high proportion of the landscape in Slitere National Park consists of protected (Natura 2000) habitat types, representing Europe's most valuable dune forests and mires. This classification indicates that the landscape structure is considered to be untouched, and it is used as a reference area for conservation and restoration purposes at international scale (Wolejko *et al*. 2019).

Hydrology plays an important role in sustaining the functions of mires and, therefore, their biodiversity (Gilvear & Bradley 2009). Wolejko *et al*. (2019) showed that one of the inter-dune mires (Kuksuspes) is dependent on exfiltration of base-rich groundwater flowing from south of the mires to the north. This type of base-rich groundwater flow is

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important for sustaining high vegetation biodiversity (Grootjans *et al*. 1993). Furthermore, Wolejko *et al*. (2019) hypothesise that these inter-dune mire systems also depend on exfiltration of base-rich groundwater flowing from other parts of the area, i.e. the bordering plateau.

The study described here aimed to describe the groundwater systems that sustain the mire landscapes, and to follow up on the recent vegetation biodiversity assessment in Slitere National Park (Wolejko *et al*. 2019). Specific objectives were to (1) determine the groundwater flow systems and origins and (2) assess whether the mires are indeed in pristine state. An ecohydrological approach was used, involving a quick scan to analyse the groundwater flows in the area that sustains the natural wet landscapes of the National Park (Grootjans & Jansen 2012). We measured natural isotopes of C, H and O, together with macro-ions, to verify the water quality types associated with each mire type; and coupled this with groundwater simulation.

METHODS

Study area

Slitere National Park is bordered by the Baltic Sea and the Gulf of Riga to the north and east, respectively, and by agricultural and urban landscapes to the south and west. The area to the south is located on the plateau of the former Littorina coastline (Figure 1). As this plateau represents the highest point in the local topography, the upper reaches of the groundwater flow are found here. Below the plateau's cliffs, a gentle downward slope continues for a few kilometres landwards forming the middle reaches, and this is where calcareous fens are currently present (LEGMC 2018). The northern parts of the National Park are home to sand-dune ridges that extend in the east–west direction. Between the ridges, there are inter-dune valleys that have accumulated peat over the years, depending on groundwater supply (Kalnina *et al*. 2014). Some of these fens have expanded laterally over the ridges,

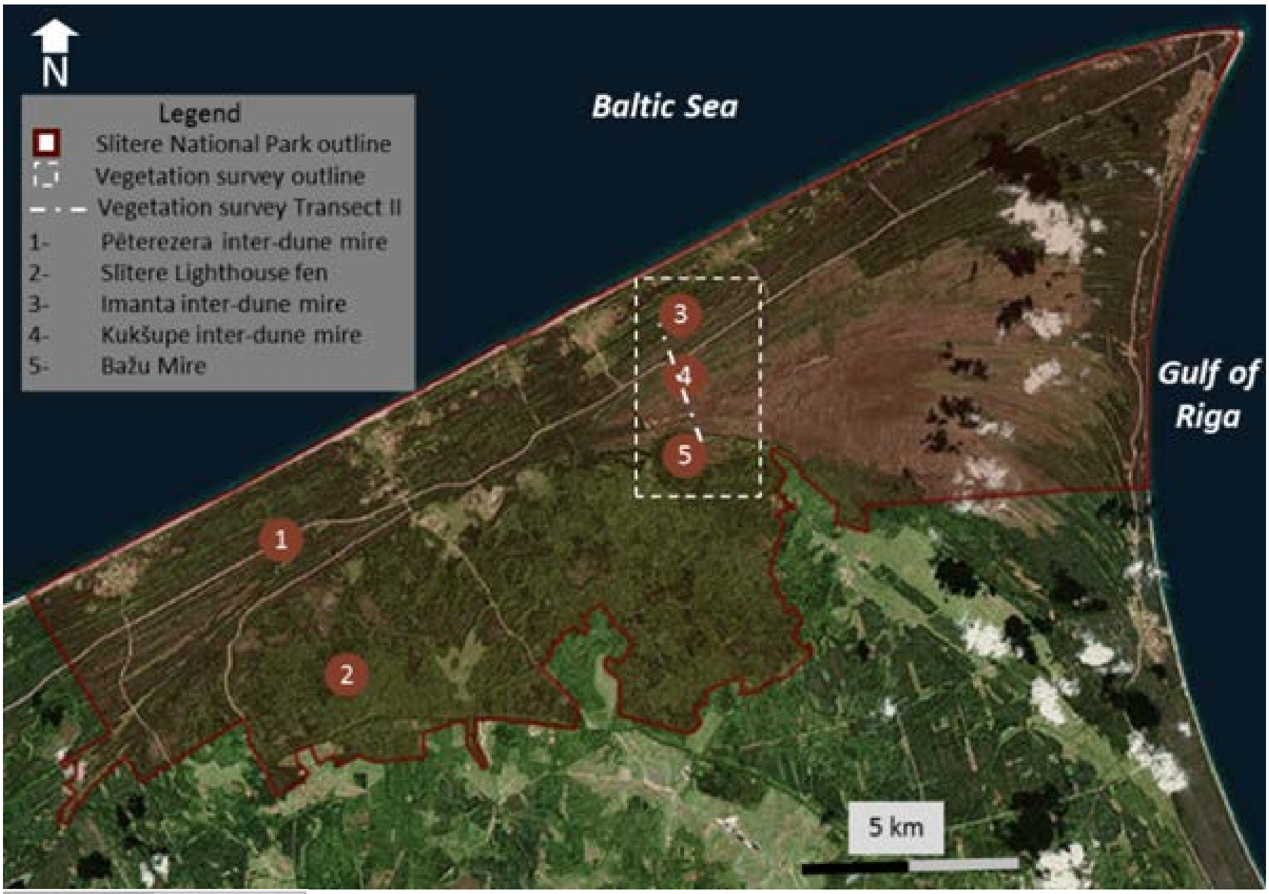

Figure 1. Study area land cover and distribution of study sites in Slitere National Park (adapted from Wolejko *et al*. 2019). Map source: GIS_Latvija10.2., LiDAR DEM, LU ĢZZF.

thus becoming dependent mainly on rainwater, e.g. Bažu bog (Pakalne & Kalnina 2005, Kalnina *et al*. 2014).

Precipitation in Slitere National Park averages around 600–700 mm yr^{-1}, with the highest amount occurring during autumn (Remm *et al*. 2011). Evaporation is estimated at about 455 mm yr^{-1}, with an average precipitation surplus of at least 150 mm yr^{-1} in the Baltic Sea region (Omstedt *et al*. 1997), however site data are not available with regards to evapotranspiration. Glacial sand deposits form the underlying unconfined Quaternary aquifer (Juodkazis 1994, Virbulis *et al*. 2013). This unconfined aquifer is intercalated with a series of inter-spaced clay and clay/sand mixtures (moraine sediments), which form aquitards at different depths (Zelčs *et al*. 2011, Saks *et al*. 2012, Virbulis *et al*. 2013). A regional aquifer is present below the unconfined sands, and it consists of sedimentary sandstone rocks (D2ar# aquifer, see Table A1 in Appendix; Virbulis *et al*. 2013).

Site selection and sampling

Fourteen sites were selected to collect groundwater samples (Figure 2). Four of these sites were established along a south–north transect within a single inter-dune fen, the Peterezera mire (Pe.ID1 to Pe.ID4). Four other sites were established to the south (Pe.IDS1 and Pe.IDS2) and north (Pe.IDN1 and Pe.IDN2) of the Peterezera mire, with two in each cardinal direction. One site was established in the Kuksupes mire (Ku.ID), which intersects the area studied by Wolejko *et al*. (2019). This site was established in the southern part of mire where we hypothesised that groundwater exfiltration is taking place. Two sites were established in the calcareous

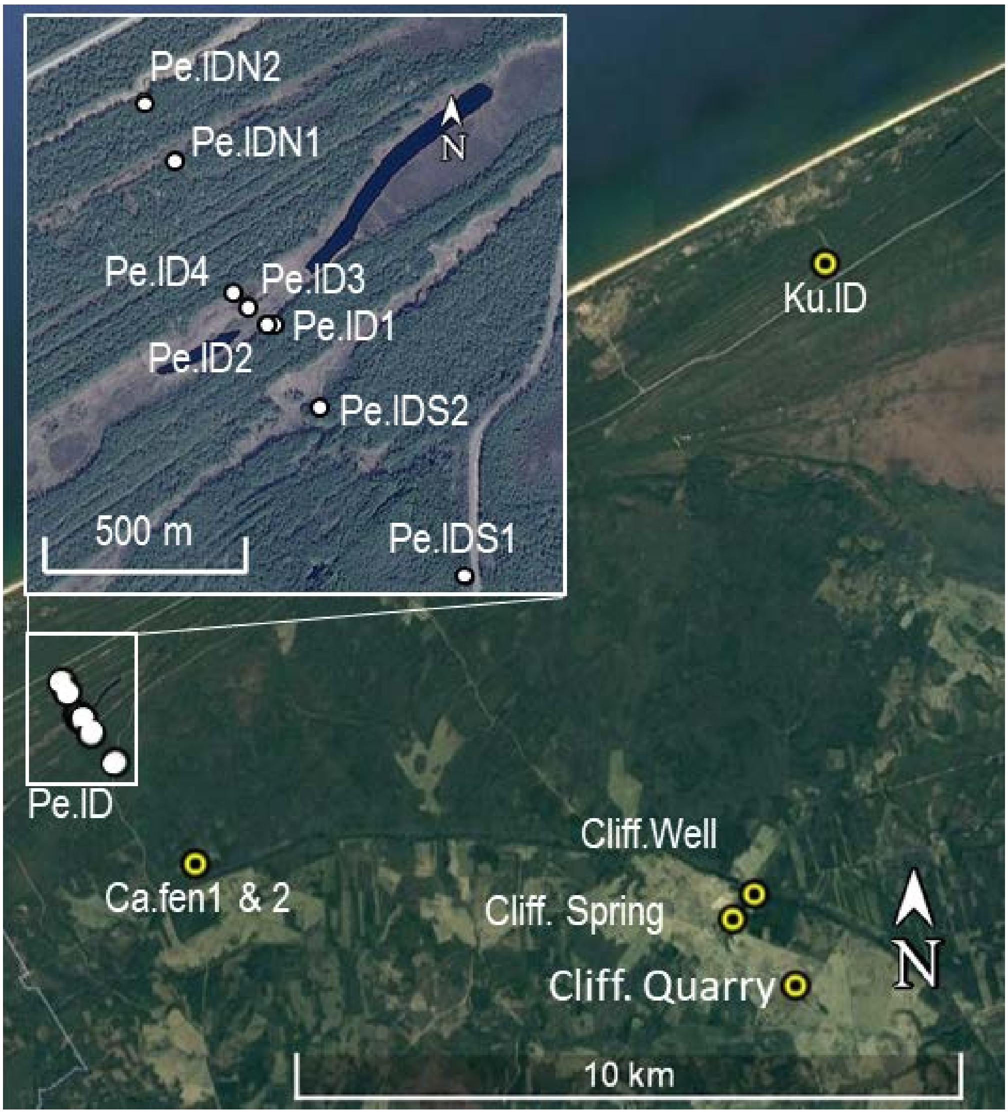

Figure 2. Water sampling sites in Slitere National Park.

fen near the old coastline of the Littorina Sea (Ca.Fen 1 and 2). Three sites were selected along the cliffs that are remnants of the old coast line: a spring mire on the cliff (Cliff.Spring), an open waterhole resulting from excavations in a sand quarry on top of the cliff (Cliff.Quarry) and a well that supplies groundwater to a household on the cliff (Cliff.well).

Twelve groundwater piezometers were installed. The piezometers were made of polyvinylchloride (PVC) tubes with a 20-cm screen at the bottom. A Russian hand auger was used to drill the holes to insert the piezometers. Two sites at Peterezera had the screens installed at two depths: one in the mineral soil (Pe.ID2 and Pe.ID3) and one in the peat layer at around 20 cm from the surface (Pe.ID2sh and Pe.ID3sh). We did not install piezometers at two sites: Cliff.Quarry and Cliff.Well. At these sites, water samples were collected from a drinking water well and an open waterhole, respectively. Table A1 lists the sampling points, their codes and screen depths. All the piezometers were flushed three to four days before sampling, which took place during July 2017. The sampling was conducted using a hand pump. Sixteen samples were collected in 100- and 50-ml polyethylene bottles for cation and anion composition analysis, respectively, and in 30-ml dark glass bottles for stable isotopes analysis. Eleven samples were collected in 500-ml dark glass bottles for carbon isotopes. All the bottles were filled to the brim and kept in a refrigerator at 4 °C.

Ion composition

Analysis of the ion composition was conducted at the Laboratory of Environmental Ecology at the University of Radboud in Nijmegen, the Netherlands. Sample pH and total alkalinity were measured by titration. Bicarbonate values were derived from the total alkalinity. Ions (Ca, Fe, K, Mg, Mn, Al, P, SO_4, Si, Zn) were measured using an inductive coupled plasma mass spectrometer (ICP-MS). Nutrients (PO_4, NO_3 and NH_4), chloride and sodium contents were measured using an atomic absorption spectroscopy (ASA) auto-analyser (Skalar, Breda, the Netherlands).

Stable isotopes

Measurements of the $\delta^{18}O$ and $\delta^{2}H$ in the water samples were conducted at the Laboratory for Isotope Research (CIO) at the University of Groningen, the Netherlands. The CO_2 gas in the samples was trapped after combustion. The gas was then analysed by Dual Inlet Isotope Ratio Mass Spectrometry (DI-IRMS) following Meijer (2009). The results were calibrated using the Vienna standard mean ocean water reference (V-SMOW), and reported as an isotopic ratio of the reference material (δ) in permil (‰) (Mook 2006). The global meteoric water line (GMWL) to plot the data was obtained from the international atomic energy agency (IAEA/WMO 2017).

Radiocarbon dating

The carbon isotopes were also analysed at the CIO laboratory. The samples' dissolved inorganic carbon content (DIC) was extracted from the CO_2 gas in the samples and turned into graphite sheets. Radiocarbon (^{14}C) contents were then counted using the atomic mass spectrometer (AMS), while the stable carbon isotope $\delta^{13}C$ was analysed using the DI-IRMS. The ^{14}C results were reported as uncorrected values in percent modern carbon (pMC) with respect to reference material V-PDB (Mook 2006). Meanwhile, $\delta^{13}C$ results were reported in respect to the V-SMOW reference material in permil (‰).

Groundwater simulation

A groundwater model was constructed using the software program Processing Modflow for Windows (PMWIN) (Chiang & Kinzelbach 2001). The model covered a surface area of 25 km by 18 km, which was able to replicate the main topographic characteristics of our study area. The grid design consisted of a matrix of 173 by 181 cells of three types (Figure 3). The first type comprised 40 m by 40 m square cells, representing the area of the inter-dune wetlands (top left corner). The second type of cells (top right and bottom left) were rectangular representing the areas of the plateau and the Bažu bog (250 m by 40 m). The remaining cells were of larger square cells (250 m by 250 m), which represented an area of low interest (in the bottom right corner). This model was oriented in the NW–SE direction instead of N–S for the sake of convenience.

Boundary conditions

The bottom boundary of the model was set as an open boundary at a depth of 20 m below sea level. This depth was defined taking into consideration the available geological data, which shows constant lithologic variation with depth. The lithology corresponded mainly to sandstone. The top boundary condition was defined by a map of vertical fluxes (rainwater infiltration) calculated and provided by the Environmental Modeling Center (VMC) at Riga Technical University. A value for infiltration or evapotranspiration was assigned to each active cell of the model according to the map fluxes. The north and east faces, which are bound by the Baltic Sea and the Gulf of Riga, were defined as closed boundaries. At the coastline, the topography reaches its lowest level;

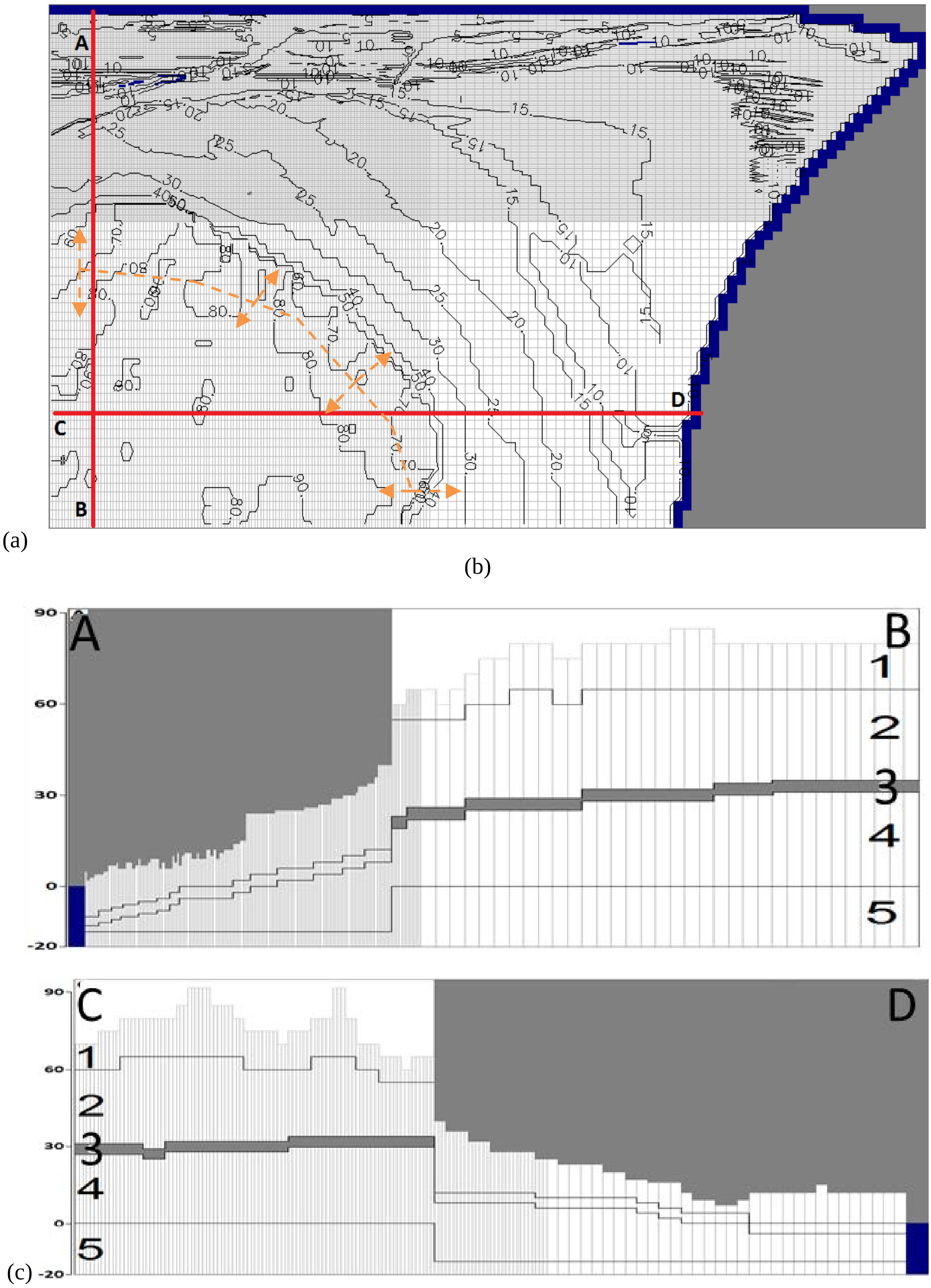

Figure 3. (a) Plan view of the model with contour lines representing the major topographic characteristics of the area, also the fault zone at the plateau. The dashed orange line marks the plateau area. The white and light grey boxes represent active cells; blue boxes represent cells with constant hydraulic heads, i.e. sea level. Finally, dark grey boxes represent inactive cells, where no flow can take place. (b) South [B] to north [A] cross-section showing the main characteristics of the model, and (c) west [C] to east [D] cross-section.

therefore, it was considered as the discharge point for fluxes flowing from inland. The recharge in our study area occurs along the highest topographic levels, which in our model corresponds to the southwest side of the cell matrix. The dashed orange line in Figure 3a represents the water divide, showing the place where recharge is present, and arrows represent the flow directions. Since flow directions at a certain point, i.e. near the western and southern boundaries, remain unchanged, we decided to leave these boundaries open, i.e. without a fixed head or no flow boundary.

Hydrogeological setting

The hydrogeological data used to create the model were obtained from the following sources: (i) the Latvian registry of mineral resources belonging to the Latvian Environment, Geology, and Meteorology Center (LEGMC), (ii) the VMC at Riga Technical University, and (iii) a literature review. The wells from the LEGMC database were distributed along the two administrative provinces (parishes) of the Dundaga Municipality: the northern Kolka Parish located next to the coastline, where Slitere National park is located, and in the upper areas of Dundaga Parish. This registry contains data from 48 wells in the study area reaching different depths (see Appendix). Figures 3b and 3c show two cross-sections of the model, where the maximum height was set at 90 metres above sea level and the maximum depth was set at 20 metres below sea level. The model was built using five layers (Table 1). The first layer from top to bottom corresponds to the unsaturated Quaternary sand sediments and it is mainly present on the elevated plateau in the southwest (Figure 3b). The second layer represents saturated Quaternary sand sediments, and the third corresponds to an impermeable layer, depicted as inactive grey cells located between 28 and 34 metres above sea level (Figure 3c). This impermeable layer was observed from well datasets, specifically in higher areas where more boreholes were available. However, at low-lying areas near wetlands where no boreholes had been available, we used the information from two wells drilled during June 2018 and a literature review. The clay glacial deposits were inserted as elongated lenses, which result from the strong influence of glacial and inter-glacial cycles in the region (Sviridov & Emelyanov 2000, Svendsen *et al*. 2004, Zelčs *et al*. 2011, Saks *et al*. 2012). The fourth and fifth layers represent the sandstone layers, which also serve as the base of the model (Zelčs *et al*. 2011).

RESULTS

Ion composition

The samples in the upper (plateau water samples) and middle (Ca.fen1 and 2 and Pe.IDS1) reaches were found to have high calcium and bicarbonate concentrations associated with pH values close to or higher than 7 (Table 2). In the lower reaches, only Ku.ID was found to have high calcium and bicarbonate concentrations associated with a pH higher than 7. Meanwhile, the dune south (Pe.IDS2) of the Peterezera inter-dune mire and the deep sample at its southern edge (Pe.ID2 and Pe.ID3) have intermediate calcium and bicarbonate concentrations and pH values close to 6.5. The rest of the samples in Pe.ID and its surrounding are dominated by silicate ions and generally lower total dissolved salts (TDS).

Table 1. Model dimensions and layer parameters.

Study area				**Model dimensions**	
Length (km)	30			Columns	181
Width (km)	19.8			Rows	173
Depth (m)	120			Layers	5
Model parameters					
Layer	1	2	3	4	5
Lithology	Sand	Sand	Clay	Sandstone	Sandstone
Permeability*	P	P	I	P	P
Horizontal conductivity (Khv) (m day^{-1})	7	4 - 7	-	4	4
Vertical conductivity (Kvv) (m day^{-1})	7	4 - 7	-	4	4
Effective porosity	0.2	0.1 - 0.2	impermeable	0.1	0.1

* P = permeable, I = impermeable

The water collected north of Peterezera (Pe.IDN1 and Pe.IDN2) was more acidic, especially from the northeast dune sample, with pH = 5.64. Notably, iron concentrations higher than 2 mg L^{-1} were observed in the samples taken from the sand layer underlying or close to peat accumulations, e.g. Pe.ID2 and Pe.ID3, Ca.fen1, Pe.IDN1 and 2, and Pe.IDS2.

Ion tracers

The isohypse lines of chloride concentrations along the Peterezera inter-dune transect show a diluted input of water from the dune at point Pe.ID1, while point Pe.ID2 was found to have an input of groundwater with higher chloride content (Figure 4a). The chloride content was found to be slightly diluted further up in the shallow layer at points Pe.ID2sh and Pe.ID3sh, and northwards at points Pe.ID3 and Pe.ID4. Similar patterns were observed for calcium concentrations, which were found to be higher at point Pe.ID2 by a factor of five than in the shallow samples (Figure 4b).

Stable isotopes

Regarding the stable isotope content of the groundwater samples, most of the samples were found to have $\delta^{18}O$ values between -11 and -10 ‰, and ‰ $\delta^{2}H$ values between -80 and -70 ‰ (Figure 5). More than half of the samples in this range are above the GMWL, while only 4 samples from that range are below this line, including most of the samples collected from the southern part of the Peterezera transect (Pe.ID1 and Pe.ID2). Only the sample collected from below the peat at Pe2 is above the GMWL. A linear regression of the samples along the Peterezera inter-dune transect (Pe.ID1 to Pe.ID4) has a slope of about 5.

Radiocarbon dating

The radiocarbon results show that most samples have ^{14}C values above 90 pMC (Figure 6). Different groups were categorised based on the Mook (2006) model for ^{14}C and $\delta^{13}C$ values in groundwater in relation to some geochemical effects. Two samples were found to be below that range, i.e. > 90 pMC: the most northern sample Pe.IDN2, which has a value of about 69 pMC, and the sample collected from the spring in the cliff area of the plateau, Cliff.Spring, which has a value of about 77 pMC. The $\delta^{13}C$ values for those two samples, however, show that the sample from Pe.IDN2 is slightly depleted with respect to $\delta^{13}C$, with values closer to -16 ‰. This sample also has the lowest pH and HCO_3 content of all samples.

Table 2. Ion composition (mg L^{-1}) analysis of 16 groundwater samples from Slitere National Park.

No.	Code	Depth (cm)	pH	Anions (mg L^{-1})			Cations (mg L^{-1})									TDS (mg L^{-1})
				HCO_3	Cl	SO_4	Al	Ca	Fe	K	Mg	Mn	Na	Si	Zn	
1	Pe.IDN2	185	5.64	10	3.3	8.8	1.5	12	4.2	0.9	3.0	0.13	4.9	26	0.2	76
2	Pe.IDN1	120	6.02	12	5.3	5.5	1.5	16	3.0	1.4	3.0	0.07	6.5	35	0.4	91
3	Pe.ID4	85	6.08	11	4.1	4.9	0.8	17	1.4	0.9	3.5	0.23	6.5	19	0.4	71
4	Pe.ID3	200	6.52	71	3.7	1.0	0.1	48	0.0	0.7	7.8	0.02	5.4	26	0.3	164
5	Pe.ID3sh	20	6.18	37	4.4	3.4	0.4	24	0.3	1.9	6.2	0.00	5.8	26	0.2	110
6	Pe.ID2	355	6.82	117	5.8	6.5	1.8	76	5.9	2.2	19	0.05	6.3	21	0.2	263
7	Pe.ID2sh	20	6.14	23	4.9	8.7	0.2	18	0.2	0.8	5.2	0.00	6.0	19	0.2	93
8	Pe.ID1	190	6.47	15	1.2	1.2	0.2	11	1.4	0.4	2.5	0.67	2.4	10	0.1	47
9	Pe.IDS2	130	6.56	68	5.3	4.5	0.3	46	5.6	1.1	11	0.04	7.2	14	0.2	163
10	Pe.IDS1	85	7.25	365	188	8.8	0.1	249	0.1	4.6	29	1.08	113	17	0.2	976
11	Ca.fen1	65	7.49	219	6.7	3.7	0.1	107	4.1	2.0	25	0.01	6.3	14	0.2	389
12	Ca.fen2	200	7.66	196	9.1	15	0.1	100	0.1	3.0	22	0.00	6.5	6.5	0.2	359
13	Ku.ID	205	7.35	215	6.8	3.1	0.3	110	0.6	2.4	10	0.01	7.2	31	0.3	389
14	Cliff.Quarry	0	7.6	154	3.2	51	0.0	77	0.0	2.6	24	0.00	3.8	3.8	0.1	319
15	Cliff.Spring	20	7.73	318	8.7	41	0.1	182	0.0	1.7	34	0.00	4.4	14	0.1	605
16	Cliff.Well	>400	7.82	274	1.5	31	0.0	111	0.0	0.9	61	0.00	3.9	23	0.1	508

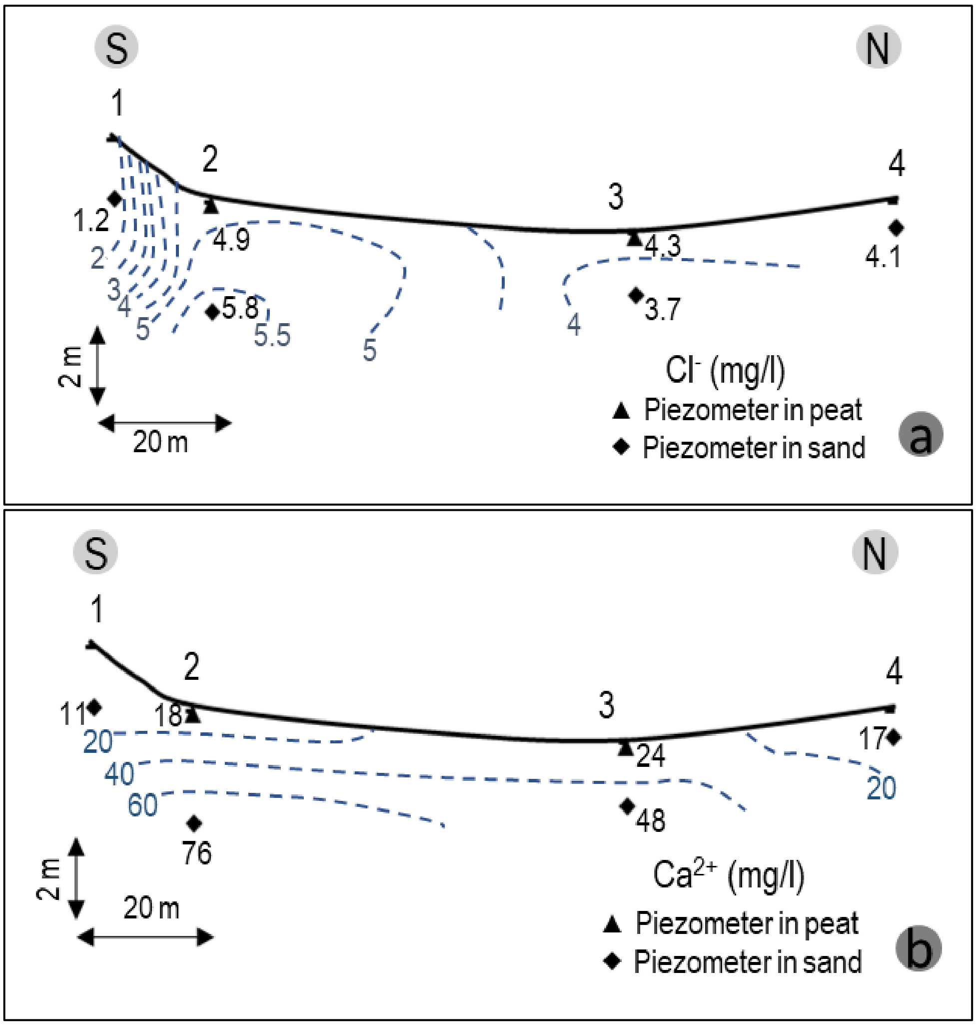

Figure 4. Isohypses of (a) chloride and (b) calcium concentrations in mg L^{-1} along the Peterezera inter-dune transect.

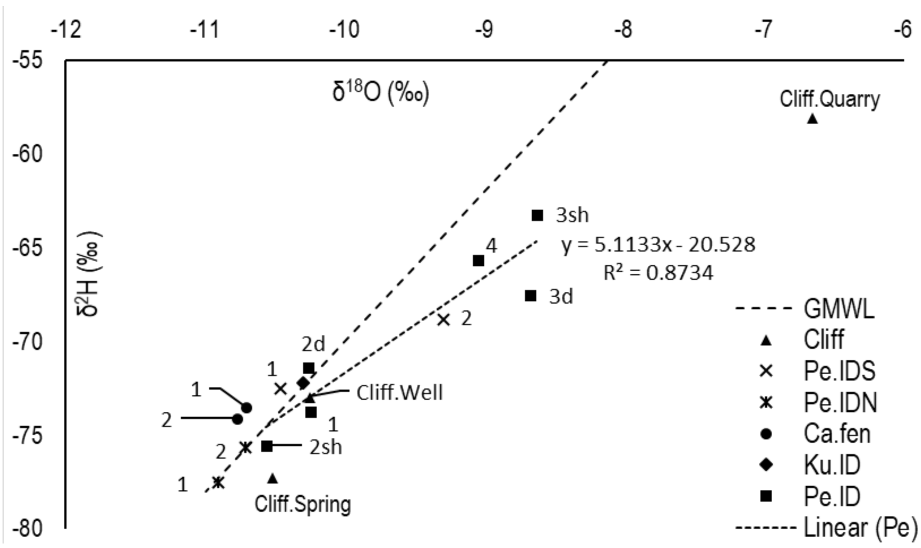

Figure 5. The stable isotope content of $\delta^{18}O$ versus $\delta^{2}H$ (‰) in 16 groundwater samples in relation to the global meteoric water line (GMWL). A trendline was calculated for the samples from the Peterezera inter-dune mire (Pe.ID1 to Pe.ID4).

Groundwater simulation
Figure 7 shows a profile running along the transect from point A to B, ending at the Peterezera mire. Four particles at different levels were tracked using PMPATH (Chiang & Kinzelbach 2001). The shallower particles above the impermeable layer (red and orange) infiltrate at the plateau, while the two deeper particles below the impermeable layer (green and pink) are able to reach the southern boundary of the model. The trajectory of the shallow particles is similar to surface delineation, while the deeper particles follow a horizontal trajectory over almost their entire flow path. All four particles show a vertical anomaly, in the shape of a “step” between 10 and 15 metres long, when they reach the cliffs. Further, Figure 8 shows the flow paths of water infiltrating at the plateau and arriving at the calcareous fen. It also shows an input of groundwater flow from the sandstone aquifer, which originates from outside the study area.

Residence time estimation
The recharge areas were not found to be restricted to a specific place. Looking specifically at the inter-dune mire complex, a great part of the recharge was found to occur in the upper plateau and the dunes, while the discharge zones were identified as the ocean and local water bodies. The simulated residence time is between 40 and 45 years for a particle originating from the unconfined aquifer in the plateau to reach the sea, and 25 years to reach the inter-dune mire complex. For a particle located in the same layer in the plateau and discharging in an easterly direction, it takes 100 years to reach the output. For particles located in the sedimentary rock layer following travel paths similar to those shown in Figure 7 (green and pink particles), residence times were found to be 200 years, which is actually the minimum value as the particles originated from outside the study area. Finally, particles coming from the dunes through infiltration reach the mire system within a period of 1 or 5 years, depending on the distance of the dune from the mire.

DISCUSSION

Analysis of the water quality data indicated the presence of different groundwater systems that feed the mire systems (Figure 9). There are three gradients of groundwater systems (regional, local and their mixtures) that have different ranges of TDS and $^{14}C/\delta^{13}C$ values (Toth 1963). The first groundwater system (regional) was observed in two samples: Cliff.Well and Cliff.Spring samples, with TDS ranges 500–600 mg L^{-1}. They were found to be distinctly more base-rich than the other samples. Also, the $^{14}C/\delta^{13}C$ content of the Cliff.Spring water sample indicates a discharge of groundwater flow that has a residence time longer than 1000 years (Geyh 2000, Mook 2006). This is in line with the data from the groundwater flow simulation, which

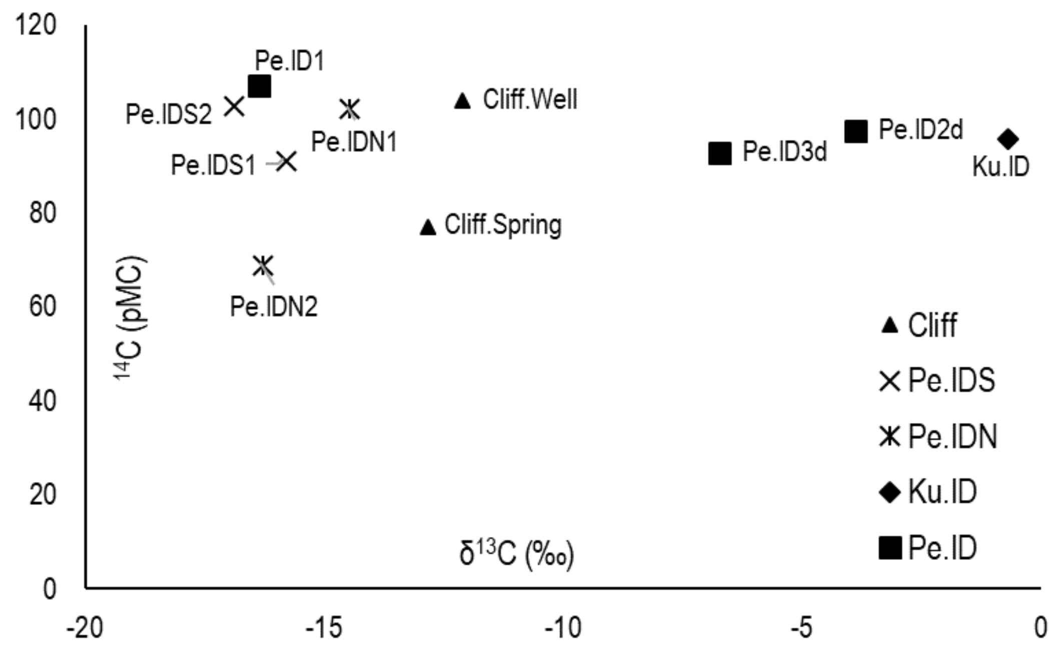

Figure 6. Radiocarbon ^{14}C (pMC) content plotted against the stable carbon isotope $\delta^{13}C$ (‰) content in eleven groundwater samples from Slitere National Park.

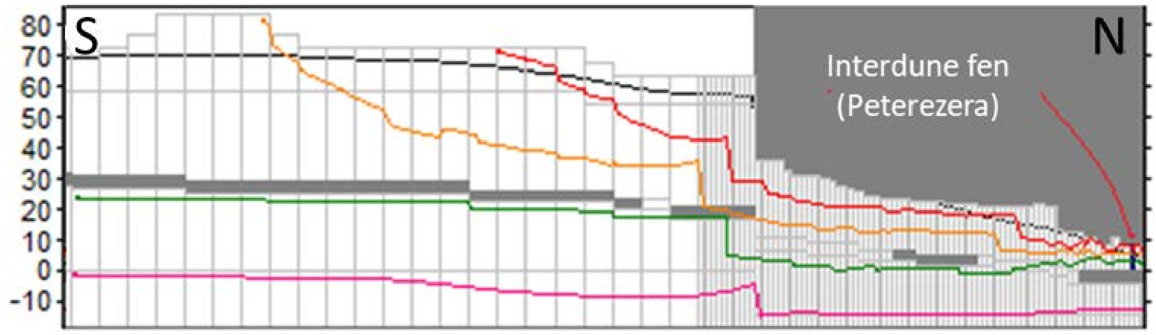

Figure 7. Cross section of the model tracking groundwater particles from the plateau to the inter-dune mire complex (Peterezera Mire): (i) infiltrating at the plateau (red and orange) and (ii) groundwater flow from the sandstone aquifer (green and pink).

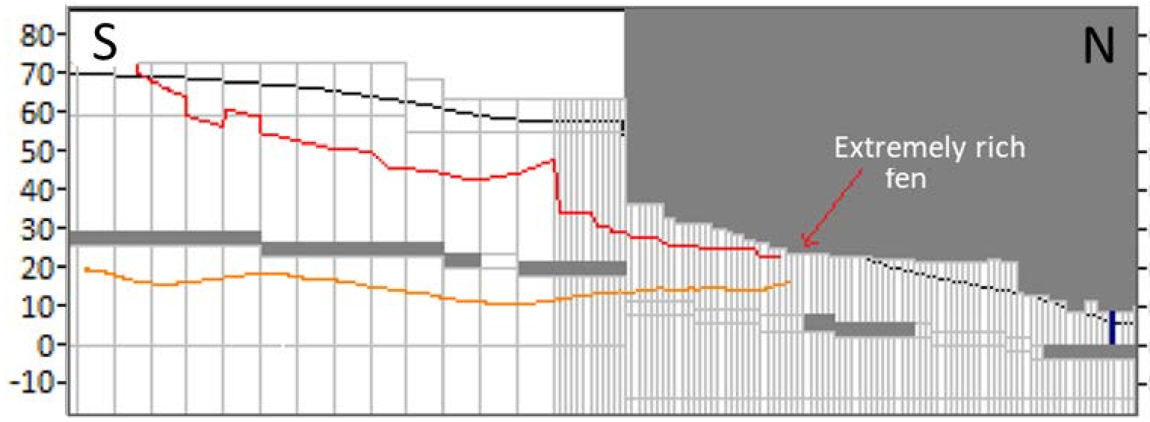

Figure 8. Path lines of two groundwater particles reaching the extremely-rich fens at the foothill of the plateau: (i) infiltrating at the plateau (red) and (ii) from the sandstone aquifer below the clay lenses (orange).

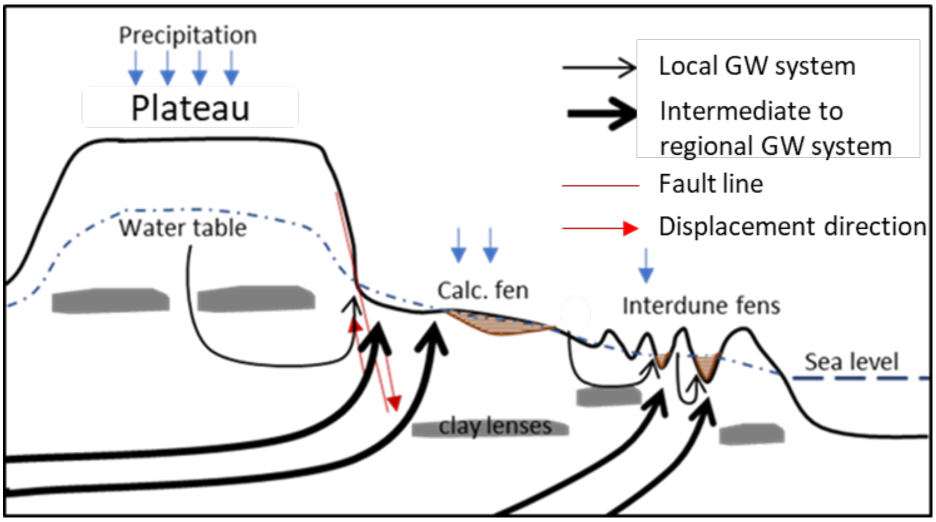

Figure 9. A hypothetical sketch illustrating the origins of the groundwater systems sustaining the biodiversity in Slitere National Park. The regional groundwater enters the study area from external sources and their mixture with local systems creates a different hydrological condition, which could have results in the vegetation gradient from the extremely (calcareous) rich fens to the rich and poor fens that have higher water input from local dune recharge (cf. Wolejko *et al*. 2019).

indicates that the regional groundwater flow would have a residence time that is higher than 400 years if the flow path started under the cliff. Also, the groundwater particle tracking shows that the flow paths from the regional systems would exfiltrate at the inter-dune mires; however, this depends on the water budget of each system. The water quality data indicate that species-rich fens are likely to be fed mostly by the regional groundwater system. The highest discharge of this regional groundwater flow occurs at the foot of the cliff area, where a vertical flow is likely to originate from the semi-confined sandstone aquifer. This vertical flow could have resulted from a fault line stemming from the Baltic basin subsidence (Virbulis *et al*. 2013).

The second TDS range (mixed regional and local), around 350 mg L^{-1}, includes the samples from the middle reaches, Ca.fen1 and 2, Pe.IDS1 and the sample from the Kuksupes inter-dune mire. Also, the water sample from the piezometer screen in the sand at Pe.ID2 has a TDS value close to this range, around 260 mg L^{-1}. This TDS range probably reflects groundwater discharge from the regional system mixing with the local groundwater system recharging from the surrounding dunes. The groundwater simulation model indicates that the presence of clay lenses closer to the mires limits parts of the regional groundwater flow (Virbulis *et al*. 2013). This mixing of the local and regional groundwater systems leads to the observed lower pH and ion composition. The radiocarbon values for such a mixing process would be in the range 90–100 pMC and the $\delta^{13}C$ values would be close to 0 ‰ (Figure 10). This mixing process could be the result of groundwater flows similar to that of Cliff.Spring, ^{14}C = 77 pMC, with infiltration water from the local dune, ^{14}C > 100 pMC (Mook 2006). The mixture of these systems has led to the presence of the extremely rich calcareous fens and the rich inter-dune fen systems (Wolejko *et al*. 2019). It is likely that Kuksupes and Peterezera have similar groundwater flow systems with a discharge of base-rich groundwater flow, which we observed at their southern edges (Wolejko *et al*. 2019). Also, the $\delta^{18}O$ and $\delta^{2}H$ values of the samples taken at the southern edge in Peterezera (Sample Pe.ID2d) and the sample from Kuksupes (Ku.ID) show no interaction with the evaporation processes near the surface of the peat layer. This supports our hypothesis that the regional groundwater discharges at the inter-dune mires, with a contribution from the local systems, which creates an intermediate mixed system.

The third range of TDS (locally dominated) was measured in the water samples collected at depths less than 2 m in the Peterezera inter-dune mire. Despite the discharge of the mixed regional and local groundwater systems, the samples from Peterezera mostly have a TDS range around 100 mg L^{-1}. Two inter-dune mire systems, Kuksupes and Peterezera, had a similar input of groundwater flow discharge at one side, which then results in water flowing from one dune to the next following the discharge (Stuyfzand 1993). Within each valley, the water flows as a through-flow in one valley, influencing the vegetation patterns (Van Loon 2009). Wolejko *et al*. (2019) indicated the dominant effects of base-rich groundwater on the vegetation in the Kuksupes and Peterezera mires, which were identified as rich fens. In Kuksupes the groundwater was more alkaline

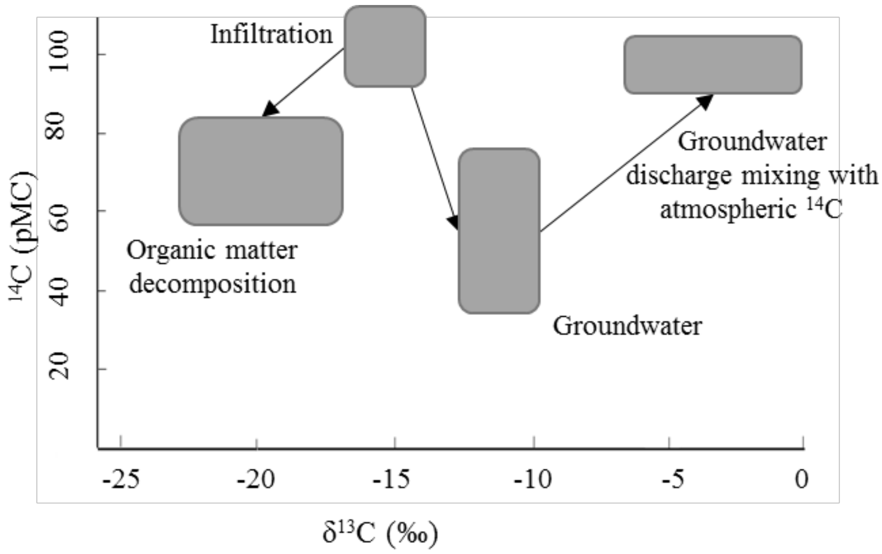

Figure 10. The $^{14}C/\delta^{13}C$ relationships with the possible origins and mixtures of groundwater from infiltration to discharge (adapted from Mook 2006).

(pH ~ 7) and had higher calcium and bicarbonate content. However, the flow within the top 2 metres of the Peterezera mire did not have the same level of water quality as observed in Kuksupes and in the south of Peterezera. Furthermore, the stable isotopes and the ion composition profiles indicate that the increase in chloride values in the shallow layer resulted from through-flow which is subject to evapotranspiration processes (Gat 1996, Appelo & Potsma 2005). This indicates the dominance of the local groundwater system recharging at the adjacent dunes in these mires, despite the discharge of mixed regional and local groundwater systems.

It is likely that these observed changes in the hydrological systems resulted from the presence of former agricultural drainage channels to the north of Peterezera (Wolejko *et al*. 2019). This was strongly indicated in the Pe.IDN2 sample, which is close to these drainage channels and a small river draining to the northeast. This sample showed an increase in acidity, depleted $\delta^{13}C$ values and lower ^{14}C values, which are probably related to the groundwater passing through an upstream mire and becoming exposed to the release of organic matter from the peat soil (Schot *et al*. 2004, Mook 2006). Such a process leads to the wetland vegetation becoming mainly dependent on the shallow, base-poor groundwater supply from the dunes recharged by the surplus of water budget, which takes over from the base-rich seepage flow (Schot *et al*. 2004). Another possibility is that the presence of interglacial clay layers at some locations limits the access of regional groundwater to the wetlands, which could also hinder the recovery of previously drained systems, such as Peterezera.

CONCLUSION

Slitere National Park is a protected area and thought to be in an almost pristine state, however, this may not be the case for all of the systems within it. The mires in Slitere National Park are not only fed by groundwater systems that recharge at neighbouring dunes or at the plateau. The groundwater flows originating at the plateau could be considered as mixed intermediate systems. It is possible that a regional groundwater system, with a larger spatial extent, recharges farther inland. For instance, the inter-dune systems in Slitere National Park depend on groundwater discharge at the southern edge of the dunes, which originates from a mixture of groundwater flows including regional groundwater systems. While the original groundwater flow is base-rich, some areas seem to have their groundwater flow affected by base-poor flow from adjacent dunes. Furthermore, the groundwater possibly follows cascading systems similar to other inter-dune wetlands in northwest Europe. The change in hydrological regime could also have resulted from activities draining the water table outside the park or the small river system near some of the inter-dune valleys. Further study is needed to determine and understand the role that impermeable clay layers play in controlling the different groundwater supply systems. Also, the effect of remnant drainage ditches on the groundwater flows needs to be assessed and quantified.

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Appendix: Information on and data from groundwater wells

Table A1. List of the groundwater sampling locations, screen depths, analysed aspects of groundwater composition, and volumes used for each analysis.

No.	Code	Depth (cm)	Radiocarbon isotopes (500 ml)	Stable isotopes (30 ml)	Ion composition (100 ml for cations and 50 ml for anions)
1	Pe.IDN2	185	1	1	1
2	Pe.IDN1	120	1	1	1
3	Pe.ID4	85	-	1	1
4	Pe.ID3	200	1	1	1
5	Pe.ID3sh	20	-	1	1
6	Pe.ID2	355	1	1	1
7	Pe.ID2sh	20	-	1	1
8	Pe.ID1	190	1	1	1
9	Pe.IDS2	130	1	1	1
10	Pe.IDS1	85	1	1	1
11	Ca.fen1	65	1 (failed in lab)	1	1
12	Ca.fen2	200	-	1	1
13	Ku.ID	205	1	1	1
14	Cliff.Quarry	0	-	1	1
15	Cliff.Spring	20	1	1	1
16	Cliff.Well	>400	1	1	1

Database of drilled wells in the study area

Information on the geological units in the study area was obtained from the database of the Latvian Environment, Geology, and Meteorology Centre (LEGMC 2018), which contains data from 48 wells in the study area reaching different depths (Figure A1). Wells give indications of soil properties, the presence of groundwater levels, impermeable layers and characteristics of the drilling itself (Figure A2). Furthermore, two wells were drilled at the Peterezera and Kuksupes inter-dune mires to depths of 13 and 20 metres, respectively (blue points 01 and 02 in Figure A1). Additional data were obtained from the LEGMC website, such as horizontal conductivity, effective porosity; others were estimated based on the soil characteristics. Hydrological information was obtained from the Environmental Modelling Centre (VMC), e.g. hydraulic conductivity, recharge and evapotranspiration rates. VMC has a larger-scale groundwater model for Latvia and the Baltic states, i.e. LAMO (Virbulis *et al*. 2013).

Figure A1. Study area with the location of the wells existing in the LEGMC database: (i) red dots indicate wells drilled near the sea, (ii) yellow dots indicate wells drilled on the cliff of the former Littorina coastline, and (iii) blue dots indicate wells drilled at the Kuksupes and Peterezera inter-dune mires.

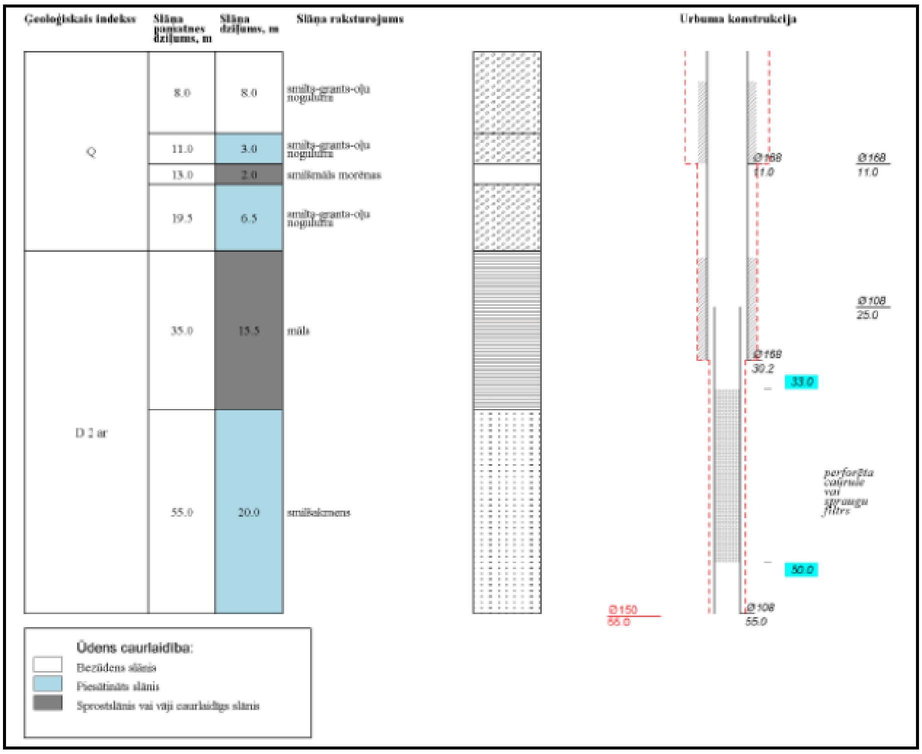

Figure A2: Example of the information obtained from the wells in the LEGMC database.