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SPECIFIC FEATURES OF GROUNDWATER CIRCULATION IN THE BOGGED BASIN OF RĖKYVA LAKE

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Abstract. Two mathematical models using MODFLOW software were developed to estimate water losses from the bogged Lake Rėkyva watershed which are happening due to the groundwater recharge and to evaluate the influence of peat deposit development on the lake and the natural belt of a raised bog protecting the lake. The modelling data lead to the following conclusions: (1) groundwater exploitation in the Šiauliai waterworks would increase the water losses from the boggy basin negligibly (from 7 to 9 mm/a when the total runoff is over 150 mm/a (2) the annual and long-term runoff and water level regimes in the raised bog, that separates the peat deposit from the lake as a 3 km long and 0.26 to 0.8 m wide belt, are rather variable. Depending on the season, from 80 to 95% of the runoff from it is formed in the 0.3–0.5 m thick top layer (acrotelm) distinguished by anomalously good filtration properties and porosity; (3) at the end of the peat deposit exploitation, the discharge from the protective bog to the lake presumably will reduce by 0.2–0.4 l/s (about 1% of the total lake runoff) and that from the bog to the peat deposit will increase by about 0.5 l/s (depending on the season, 1–15% of the total runoff from the bog); and (4) seasonal recharge of acrotelm is capable of counterbalancing the loss therefore the status of protective bog will remain close to the actual one.

Keywords: raised bog, peat bog, groundwater, modelling, Lake Rėkyva basin, Lithuania.

1. Introduction

Rėkyva is the largest watershed lake in Lithuania. It is situated in the watershed of the Nevėžis, Dubysa and Mūša rivers in the East Žemaičiai Plateau. The present-day area of this large proglacial lake is 11.85 km^2, the average depth is about 2 m, the altitude of the water horizon is about 130.6 m and the basin area including the lake is only 21.7 km^2. According to different data, in the last 70 years the lake area changed inconspicuously (from 11 to 11.85 km^2) (Kolupaila 1933; Bieliukas 1961; Gailiušis *et al.* 2001). Raised bogs occupy almost the entire basin area. A small area on the eastern bank of the lake, occupied by basal moraine, is an exception. The altitude of water horizon has been increasing with the expansion of raised bog (Bumblauskis 1979). The location of Lake Rėkyva and its basin is best illustrated by lithology and genesis of surface rocks (Fig. 1) (Kvartero geologinis… 1999).

The Lake of Rėkyva is characterised by a small basin, which has reduced even more during the last hundred years. The lake has no natural tributaries and effluents, yet it is a very important recreational site for the Šiauliai city and the region. Lake environs include preserved territories and valuable habitats. The water from the outflow canal on the north-eastern shore of the lake is taken to replenish water resources of Lake Talkša and the Kulpė River. There is an exhausted peat deposit situated about 200–250 m north-east of the lake in the Piktamiškis raised bog. At present, intensive digging of peat takes place in the peat deposit which is situated in the south of the lake on the area of about 540 ha of the Rėkyva raised bog. The remaining smaller area of the natural bog (about 160 ha) separates the exploitable peat deposit from the Lake of Rėkyva and protects the lake from the possible negative impact of peat extraction. The drainage is the main factor of peat bog exploitation impact on the water regime in the Rėkyva Lake basin. The current altitude of water horizon in the limiting drain is about 130.4 m. The expected one at the end of peat bog exploitation is 126.0 m.

Lake Rėkyva and the adjacent areas of the East Žemaičiai Plateau represent the regional groundwater recharge area. At present the water horizon is regulated by a spillway set up in the canal through which the excessive water is drained into the Lake of Talkša. Its altitude observed in 2008 is 130.67 m. In the environs of Lake Rėkyva the altitude of the natural piezometric levels of the first confined compact Upper Permian aquifer is 100–110 m a. s. l. Due to groundwater withdrawal by the Šiauliai waterworks in Lepšiai, it may drop to the altitude of 80 m and the downward filtration from the Lake Rėkyva basin may strengthen (Gedžiūnas, Zuzevičius 1994).

Many practical and scientific research works have been devoted to the issues of formation and development of the lake and surrounding bogs, their current state and water formation (Kolupaila 1933; Bumblauskis 1979; Tamošaitis, Grigelytė 1979; Ramonas 2004; Gaigalas *et al.* 2008; Šimanauskienė *et al.* 2008; Gailiušis *et al.* 2009).

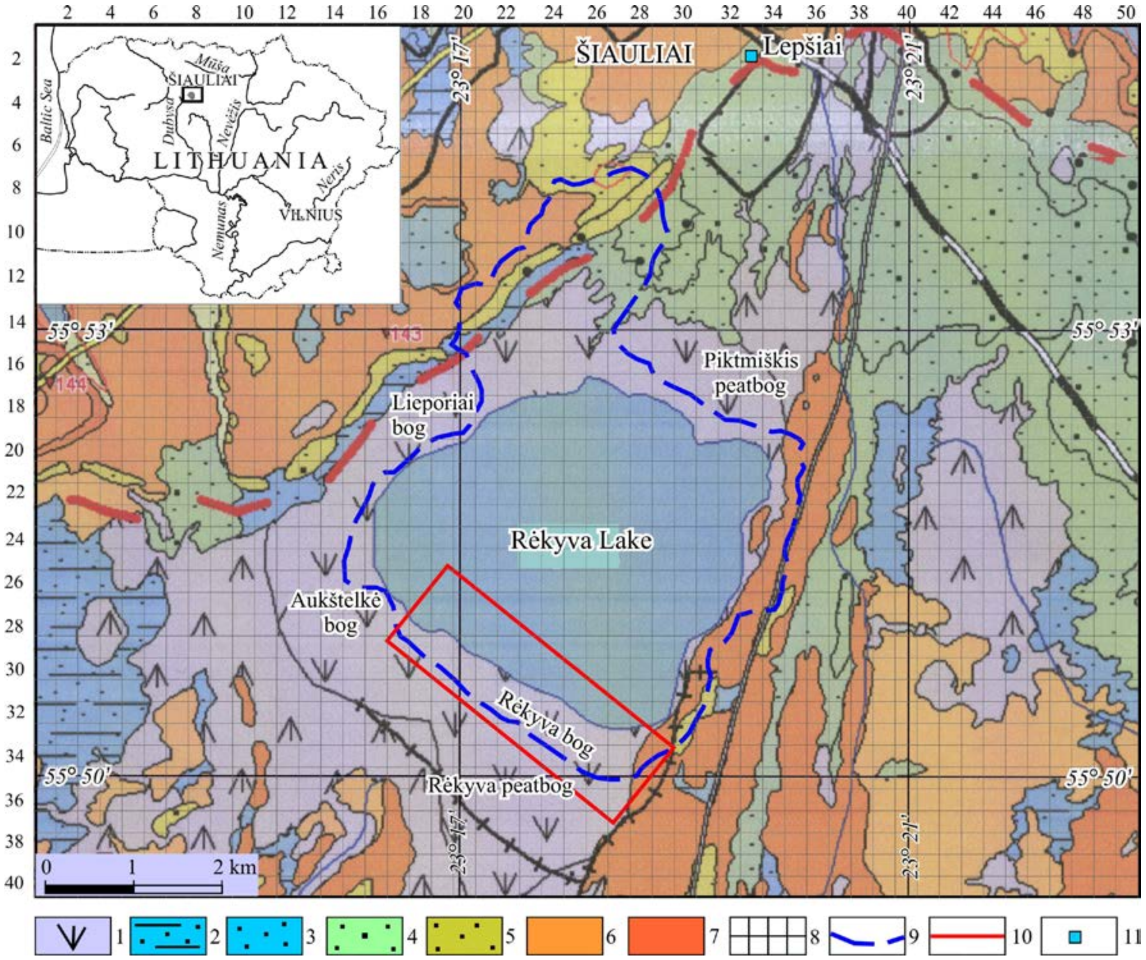

Fig. 1. Lithology of unconfined aquifer in the modelled region (According to Kvartero geologinis... 1999): 1 – peat of raised bogs; 2 – glacio-lacustrine deposits (clayey sand); 3 – lacustrine deposits (very fine sand), 4 – glaciofluvial deposits (sand); 5 – marginal glaciofluvial formations (fine-grained sand); 6 – basal moraine (morainic loam and sandy loam), 7 – marginal glacial formations (morainic loam and sandy loam), 8 – grid of the regional model; 9 – boundary of the Lake Rėkyva basin; 10 – boundary of a detailed Rėkyva raised bog model; 11 – waterworks

Yet the importance of the lake for the water economy, recreation of Šiauliai city and region, as well as the changing economic and climatic situation demand repeated and detailed investigations.

There are some issues which still need objective studies: (1) water losses from the lake basin to recharge deep groundwater aquifers; (2) scale and seasonal variations of water runoff from the raised bog into the lake and the drains; (3) possible impact of exploitable peat deposit drainage on water regime in the adjacent raised bog and the lake. The present investigation is devoted to evaluation of the mentioned aspects of groundwater formation.

The purposes of the present study are: (1) to create a mathematical model reflecting adequately the regularities of groundwater and surface water circulation in the Lake Rėkyva basin; (2) to evaluate the groundwater and surface water circulation patterns under the natural and affected by water intake conditions; (3) evaluation of regularities in formation of the runoff from the raised bog and the influence of peat deposit drainage during exploitation on the water regime of the raised bog and lake. Due to the differences in the scale of the studied objects and specific characteristics of the set tasks, separate models of groundwater formation were created for the region and the Rėkyva bog (more detailed).

2. Methods

The MODFLOW software created by the U.S. Geological Survey was used for modelling of groundwater filtration in the Lake Rėkyva basin and Groundwater Vistas 5.0 software was used for designing and calibration of the models and interpretation of obtained results (McDonald, Harbaugh 2000; Rumbaugh, Rumbaugh 2007).

MODFLOW determines the hydraulic head with the governing equation (1)

$$\frac{\partial}{\partial x}(K_x\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial}{\partial z})\pm Q=S\frac{\partial h}{\partial t}. \quad (1)$$

Where h is the hydraulic head, m; K_x, K_y, K_z is the hydraulic conductivity in the x, y, and z directions, m/d; Q is the flux into or out of the system due to sources or sinks (also recharge/discharge), m^3/d or m/d; S is the storativity, 1/m; t is the time, d. Equation (1) is solved using a block-centred finite-difference approach based on calculations of water budget at chosen discrete time points in the interrelated rectangular blocks, into which the groundwater filtration region is divided, under the boundary and initial conditions typical for the modelled object.

The role of the Lake Rėkyva basin in recharging deep aquifers was evaluated by modelling the shallow and deeper Upper Permian aquifers and semi-permeable layer of loam isolating them in an area of 125 km^2. The modelled filtration region is bounded below by the Upper Permian aquifer because the intensity of water exchange in the deeper aquifers is low to vanishing, if compared to the rates of shallow groundwater recharge (Gedžiūnas, Zuzevičius 1994). As the piezometric level depends on the operation of Šiauliai waterworks, two variants were modelled: with the natural and dropped water levels in the Upper Permian aquifer.

Water filtration in the natural part of the raised bog separating the lake and the exploited peat deposit was analysed in more detail. The modelled territory occupies about 1.8 km^2. In the north-west it is bounded by the groundwater flow line running at about 200 m from the edge of the peat deposit and in the south-east by a ditch surrounding the bog. The peat bed of the raised bog is composed of two parts very different in terms of water exchange: the upper part (acrotelm) that usually is up to 0.5 m thick and the lower part (catotelm) represented by the remaining larger half reaching the mineral base of the bed (Ingram 1978). For a more detailed reflection of the variation of peat bed properties with depth and the effect of drain on the bog water regime, the peat bed with maximum thickness reaching 8 m was divided into 5 layers and the bog area was divided into blocks of 20×50 m.

The boundary conditions of the model are the following: (1) Lake Rėkyva and the bounding ditches (drains) meet the 1st type boundary condition $H = f(t)$; (2) the north-western boundary coinciding with the flow line meets the 2 d type boundary condition ($Q = 0$); (3) the upper boundary of the model is represented by the surface of shallow (unconfined) aquifer with time-varying recharge/discharge ($Q_{w-} = f(t)$) and, due to negligible loss of water for deep aquifer recharge, the lower one, represented by morainic loam layer underlying the peat, is impermeable ($Q = 0$). It should be pointed out that at present the depth of the drain separating the peat deposit from the raised bog exceeds 2 m and it drains the lower peat layer (catotelm) (Figs 2 and 3).

The calibration of the model included analysis of hydrodynamic role of boundary conditions and variants of parameters. It was based on the comparison of simulated and factual (measured) groundwater level in different parts of bog and it fluctuations; because the data of direct measurements of groundwater discharge into drains are scanty and the data about groundwater discharge into the lake is lacking. The closest congruence between fluctuation of computed and measured groundwater levels was taken as the quality index of the model. The time span from January (2007) to July (2008) with detailed measurements of precipitation, evaporation and water levels in Lake Rėkyva and the bog was the most useful for calibrations of hydraulic conductivity and storativity of peat.

In order to model statistically different humidity years (medium humid, humid and dry), it was assumed that: (1) the bog does not receive atmospheric precipitation and there is no evaporation in winter (December–February); (2) precipitation in winter months and March (without evaporation) is infiltrated during the March; (3) for other seasons the atmospheric recharge/discharge corresponded with such for years of different humidity.

3. Natural conditions and their schematization for modelling

The information necessary for modelling and prognostic calculations includes: hydrogeological conditions of the object (bedding conditions of aquifers and semipermeable layers, conductivity parameters, storativity, and hydrodynamics), climate factors (precipitation and evaporation), current and predicted parameters of natural (lakes and rivers) and artificial (waterworks and drainage ditches) and their level or discharge regimes (boundary and initial model conditions). The information necessary for modelling of the role of Upper Permian aquifer in the Rėkyva basin has been collected during the survey of Šiauliai waterworks and the estimation of their resources at different years (Gedžiūnas, Zuzevičius 1994).

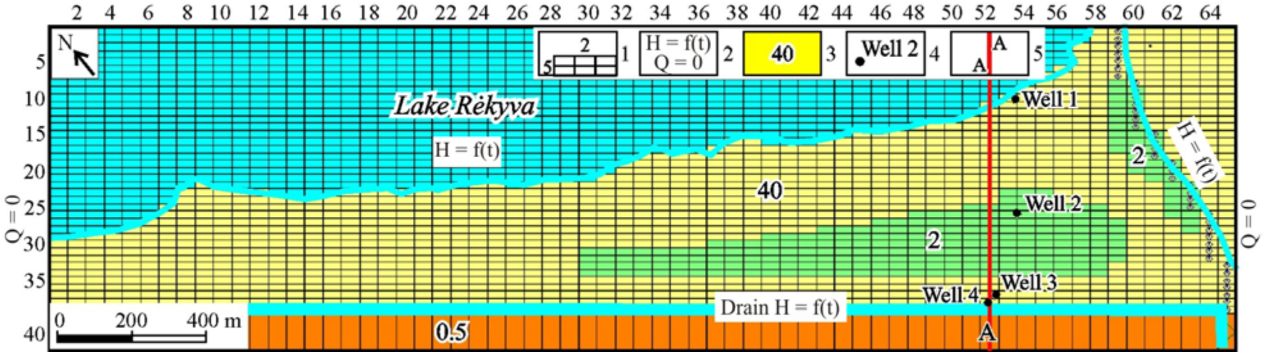

Fig. 2. A scheme of the Rėkyva bog model: 1 – grid; 2 – boundary conditions; 3 – hydraulic conductivity of the acrotelm, m/d; 4 – observation well; 5 – direction of section (Fig. 3)

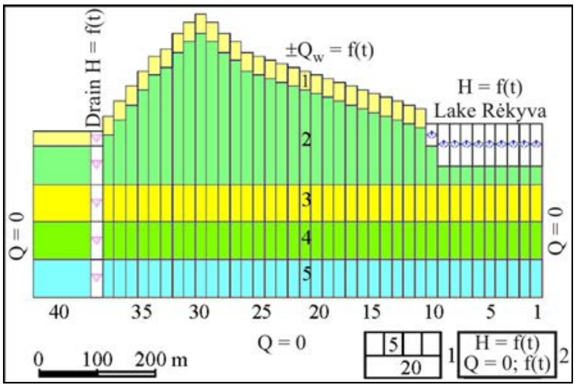

Fig. 3. A section of the Rėkyva bog model: 1 – grid of blocks and their numbers (vertically: 1 – acrotelm, 2–5 – catotelm); 2 – boundary conditions

The part of the Rėkyva bog lying between the peat deposit and the lake preserved all features of a raised bog. The total thickness of the peat layer reaches 8 m and the altitude of the base of the bed is about 126 m. The top 0.3–0.5 m thick layer of the raised bog, called acrotelm, is composed of non-mineralized bog plants (5–10%) and water (90–95%). The water movement in the acrotelm is a transitional case between filtration in the porous medium and surface water flow in channel distinguished for high resistance. Taken that the water flow in the acrotelm follows the main pattern of groundwater flow through porous medium (Darcy's Law), the values of flow parameters are extremely high. The values of hydraulic conductivity range within a wide spectrum – from 1–10 to a few hundred m/d, the value of storativity is 0.35–0.9 1/m and the value of porosity is 0.9–0.95 (Rycroft *et al.* 1975; Chrzanowski 1999; Van der Shaaft 1999; Reeve *et al.* 2000; Holden *et al.* 2001; Zaidelman *et al.* 2005; Hogan *et al.* 2006; Schwärzel *et al.* 2006; Price *et al.* 2008).

It is hard to measure the conductivity of acrotelm technically and methodologically. This kind of data from the Rėkyva bog is lacking. Consequently, the comparable acrotelm parameters established in Ireland were taken as the input data for modelling (Van der Schaaft 1999). They were revised by model calibration. The hydraulic conductivity values chosen by modelling and generalized for the whole peat stratum including acrotelm range within 0.1–0.5 m/d and the average value of annual storativity is 0.05 1/m (Ramonas 2004). The reported data about peat parameters obtained by other authors during special field and laboratory investigations show that hydraulic conductivity of acrotelm is much higher. Conductivity of catotelm is highly dependent on mechanical load and reduces with depth from 10 to 100 times every 1 m. Their values in horizontal and vertical directions may differ by 2–5 times (Van der Schaaft 1999).

Investigations of groundwater regime in the wells in the Rėkyva bog were carried out in 1997, 2001, 2003, and, on a regular basis, since 2006. The measurements were carried out in July–November. Only in the years of implementation of the project in 2007–2008, the winter fluctuations of groundwater levels in the bog were observed (Fig. 4^a).

The winter of 2007–2008 (December–February) was distinguished by an untypically high air temperature. According to the data of Šiauliai hydrometeorological station, there were only 30 days with a negative mean daily temperature. The March of 2008 was colder than the long-term norm. (Fig. 4^b). The groundwater levels were high and close to surface throughout the winter and dropped only in April. Presumably, at certain time intervals of the winter, the bog was recharged with water. The best correlation of factual and model bog water levels in 2007–2008 was observed when a half of precipitation permanently reached the underground. Since the June of 2008, the drop of model levels has exceeded the ones measured in wells (Fig. 4^a). This is predetermined by poorer conductivity of the lower part of the acrotelm, where the groundwater flows through when the level is dropped.

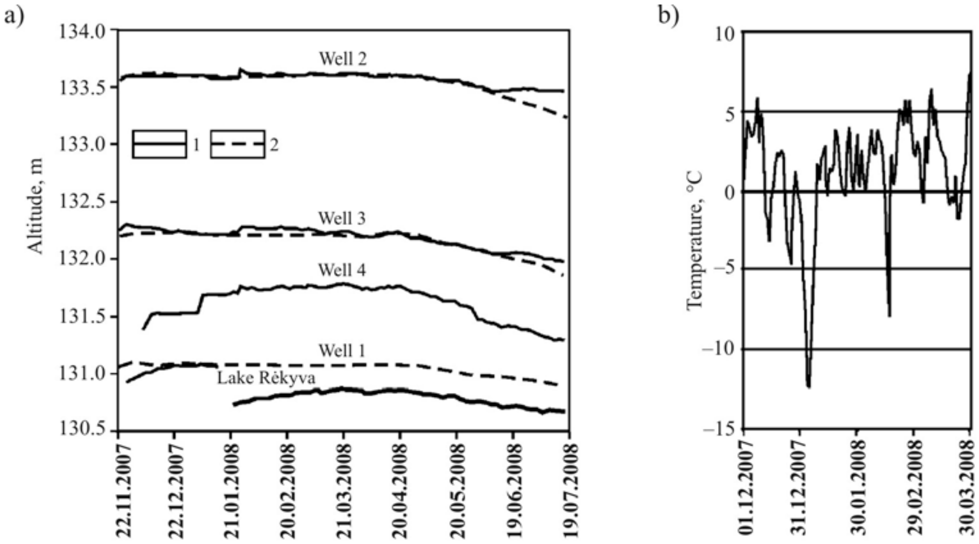

Fig. 4. The water levels in Lake Rėkyva and its bog in 2007–2008 (a) and the mean daily air temperature in December–March (b): 1 – measured level; 2 – modelled level

The data about the winter groundwater levels of other years and presumable maximal groundwater levels of early spring are lacking. The highest groundwater levels were measured in May. Minimal levels usually were observed in September or (in rarer cases) in August. At the time of investigation, the minimal annual bog water level fluctuation amplitude was 7–10 cm and the maximal one was 30–49 cm. The maximal amplitude was recorded in 2007–2008 in the well-4 close to the drain. This might have been caused by water abundance in the drain in winter and abrupt water draining before peat exploitation. As the model grid (50×20 m) is too large for precise reconstruction of water level at the drain side (boundary condition of the 1st type), the model groundwater level of well-4 is not shown in Fig. 4^a. The depth of water table, measured in the dry September of 2008, was close to the ground surface throughout the entire area of the bog (0.1–0.5 m). The best correlation between computed and measured water levels in wells 1, 2 and 3 (residual mean 0.015 m, residual standard deviation ±0.044 m or 1.6% of the overall gradient) was obtained for peat parameters shown in Table 1.

Table 1. Model parameters of the peat bed

Layer	Conductivity, m/d	Porosity	Storativity, 1/m
Acrotelm	0.5–40	0.9	0.3–0.4
Catotelm	0.01	0.8	0.01–0.2

The Lake Rėkyva basin is distinguished by small values of precipitation (less than 600 mm per year) and small surface (about 5 l/s from km^2) and groundwater (0.2–0.4 l/s from km^2) runoff (Lietuvos… 1981). It should be pointed out that here the bog runoff is incorporated into the surface runoff. The evaporation from water surface is close to evapotranspiration from raised bog surface. The long-term values of precipitation and evaporation from water surface of different probability in the Lake Rėkyva basin, calculated using the data from the closest Šiauliai meteorological station and measuring data obtained *in situ* in 2007–2008, are given in Table 2. The reconstruction of seasonal distribution pattern of precipitation and evaporation is a result of statistical generalization of long-term measuring data. As can be seen, in the years of statistically medium humidity the recharge of bog groundwater amounts to 153 mm/a and in humid years to 253 mm/a (or about 4.8 and 8 l/s km^2 respectively). In dry years, the bog loses about 200 mm or about 6.3 l/s km^2 through evaporation alone. In humid years evaporation exceeds precipitation only in May–July, in the years of medium humidity this time span lasts from April till July and in dry years from April to October (i.e. 3, 4 and 7 months respectively). As the alternation of annual humidity does not follow any regular pattern, the evaluation of bog groundwater exchange in years of statistically different humidity is based on the assumption that they were preceded by a year of medium humidity. A seasonal distribution pattern of precipitation-evaporation of a concrete year is more complicated than the long-term statistical distribution pattern. In 2007, which according to precipitation and evaporation was close to a statistically humid year, the time spans of April–May and August–September stand out for evaporation values exceeding the precipitation values. Though evaporation in the September–December of 2008 was not measured, judging from the total precipitation and its seasonal distribution pattern this year was presumably close to medium humid one. The water level in Lake Rėkyva in 2008 ranges within 130–130.9 m and in the peat bog drain it was about 130.40 m a. s. l.

Table 2. Groundwater recharge or discharge (–) in the years of different humidity in the Lake Rėkyva basin (mm) (unpublished data obtained by B. Gailiušis and J. Taminskas in 2008)

Years	Index	Months												Annual
		1	2	3	4	5	6	7	8	9	10	11	12	
Medium humidity (p. 50%)	Precipitation	32	27	29	37	49	59	79	75	60	57	49	40	593
	Evaporation	4	11	25	50	69	81	80	60	33	19	6	2	440
	Recharge	28	16	4	–13	–20	–22	–1	15	27	38	43	38	153
Humid (p. 5%)	Precipitation	46	42	40	47	63	79	99	96	79	66	60	52	769
	Evaporation	–	–	–	44	89	88	104	74	56	39	22	–	516
	Recharge	48	42	40	3	–26	–9	–5	22	23	27	38	52	253
Dry (p. 95%)	Precipitation	30	27	25	31	41	52	65	63	52	43	39	34	502
	Evaporation	–	–	–	61	121	120	142	112	71	52	30	–	709
	Recharge	30	27	25	–30	–80	–68	–77	–49	–19	–9	9	34	–207
2007	Precipitation	95	36	19	25	58	79	159	45	55	91	61	20	743
	Evaporation	0	8	17	42	67	73	85	88	56	43	26	20	525
	Recharge	95	28	2	–17	–9	6	74	–43	–1	48	35	0	218
2008	Precipitation	50	38	46	48	23	46	73	125	16	84	46	40	635
	Evaporation	0	6	23	59	80	74	90	98	na	na	na	na	na
	Recharge	50	32	23	–11	–57	–28	–17	27	na	na	na	na	na

na – not analysed (no data)

4. Results and discussion

The water losses suffered by Lake Rėkyva basin due to recharge into the Upper Permian aquifer were evaluated through a regional modelling. Under natural conditions, the losses amount to about 7 mm/a, when the total average long-term groundwater runoff (including raised bog part) is 153 mm/a (Table 2). As the water lost for recharge of the Upper Permian aquifer is not reflected in the measured lake runoff, the actual average recharge of the basin by precipitation should be higher by the 7 mm/a (about 160 mm/a). The losses of water from the basin through filtration into deeper layers could increase by 2 mm/a (up to 9 mm/a) if the Lepšiai waterworks (Šiauliai) situated 6 km from the lake is exploited with maximal permissible yield. This means that the possible increase in the loss of the runoff from the basin would account for about 1% of the total and would have no significant influence on the bog water regime. Small losses due to deep groundwater recharge also are proved by an abundance of bogs in the entire region that plays the role of a groundwater recharge zone (Reeve *et al.* 2000).

The patterns of the runoff formation in the Rėkyva bog and the influence of peat deposit drainage on the water regime of the bog and the lake were investigated in a detailed model. It was established that the groundwater regime of the bog is subject to seasonal variations, yet its dependence on precipitation is complicated. The water, which accumulates in the upper peat layer (acrotelm), when precipitation exceeds the sum of evaporation and discharge, and maintains outflow when evaporation exceed precipitation, complicates it. A significant role of precipitation-evaporation in the seasonal water regime of the raised bog also was determined during the investigation of the Kamanos bog (Lithuania) (Ruseckas, Grigaliūnas 2008). Model variants of the Rėkyva bog water regime showed that (applying of constant average annual recharge values and boundaries, i.e. steady-state) it is impossible to reconstruct the actual seasonal fluctuation pattern of groundwater levels and discharge into drains regime. This is preconditioned by frequent and very noticeable (up to the negative sign) seasonal fluctuations of water budget elements. In order to reconstruct a model of the actual fluctuation pattern of water levels, it is necessary to take into account the seasonal atmospheric recharge/discharge values and the properties of the acrotelm, i.e. to reconstruct real transient process. From mineral soils the acrotelm is distinguished by an especially high effective porosity (0.9–0.95) and related gravitational storativity (0.3–0.6). Thus notwithstanding the very intensive water circulation in the acrotelm, its filling detains the penetration of atmospheric water into the drains and into the lake. The sources of Rėkyva bog water formation at different time moments of 2007–2008 are shown in Table 3.

The distribution of groundwater levels in the Rėkyva bog reconstructed by the calibrated model at typical time moments of medium humid years is shown in Fig. 5. The sources and budget of groundwater formation at typical times of humidity (as well as at the end of peat bog exploitation) are given in Table 4.

The minus sign in Tables 3 and 4 indicates the water loss by the bog. The water accumulated in the layer (storage) makes an exception: the minus sign shows the water accumulated in the layer manifesting through water level rise. The plus sign shows the loss of water by the pores followed by the drop of water level. The numerical values of water formation sources derived by modelling were not rounded as is required by the rules in order to show their relative portion in the water budget and possible change as a result of drainage. The unbroken dynamics of the different elements of seasonal regime of the Rėkyva bog with the beginning of a hydrological year in March 1 is illustrated by diagrams in Fig. 6.

The water levels in the Rėkyva bog observed in wells-2, 3 and 4 during the period of 2007–2008 were close to maximal and rather stable throughout winter. This implies that recharge was not intermitted completely.

Table 3. Sources of Rėkyva bog water formation at different times of 2007–2008 (m^3/d) (modelling data)

Layer	Source or boundary	March 31, 2007	July 31, 2007	November 30, 2007	February 29, 2008
Acrotelm	Atmosphere	8320	2040	2200	620
	Lake	–1074	–720	–643	–473
	Other boundaries	–168	–133	–122	–98
	Catotelm	–680	–137	–155	–21
	Storage	–6398	–1050	–1280	–28
Catotelm	Acrotelm	680	137	155	21
	Drain	–322	–106	–105	–55
	Storage	358	–31	–50	34
Total in the bog	Atmosphere	8320	2040	2200	620
	Lake	–1074	–720	–643	–473
	Drain	–322	–106	–105	–55
	Other boundaries	–168	–133	–122	–98
	Storage	–6756	–1081	–1330	6

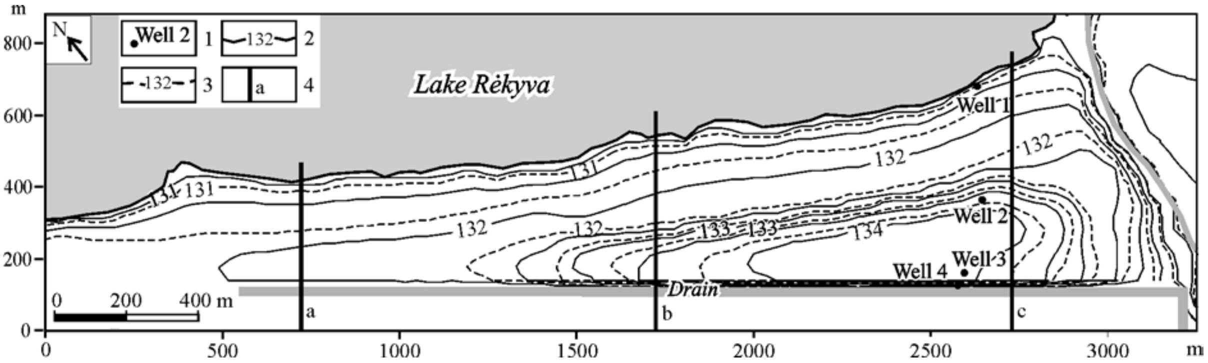

Fig. 5. Groundwater levels in the Rėkyva bog in March and July of medium humid years (model data): 1 – observation well and its number; isolines of groundwater levels, m a. s. l.: 2 – March; 3 – July; 4 – direction of profiles (Fig. 7)

Table 4. The Rėkyva bog groundwater sources (m^3/d): current 1 and predicted at the end of peat deposit exploitation 2 at typical time moments for the years of different humidity (model data)

Layer	Source or boundary	Winter minimum (February 28)		Spring maximum (March 31		Summer (July 31)		Autumn maximum (November 30)	
		1	2	1	2	1	2	1	2
Medium humid year									
Acrotelm	Atmosphere	0	0	4275	4275	–726	–726	1580	1580
	Lake	–369	–338	–732	–695	–264	–237	–534	–504
	Other boundaries	–79	–72	–124	–115	–61	–57	–101	–93
	Catotelm	18	–26	–341	–382	76	33	–122	–166
	Storage	430	436	–3078	–3083	975	987	–823	–817
Catotelm	Acrotelm	–18	26	341	382	–76	–33	124	166
	Drain	–27	–73	–175	–223	–3	–46	–82	–130
	Storage	45	47	–166	–159	79	79	–40	–36
Humid year									
Acrotelm	Atmosphere	0	0	9320	9320	–679	–679	1422	1422
	Lake	–455	–422	–1280	–1238	–452	–417	–653	–617
	Other boundaries	–96	–88	–190	–182	–96	–88	–122	–114
	Catotelm	31	–15	–756	–805	105	56	–89	–134
	Storage	520	525	–7094	–7095	1122	1128	–558	–557
Catotelm	Acrotelm	–31	15	756	805	–105	–56	89	134
	Drain	–30	–77	–353	–405	–5	–52	–80	–129
	Storage	61	62	–403	–400	110	108	–9	–5
Dry year									
Acrotelm	Atmosphere	0	0	5842	5842	–253	–253	474	474
	Lake	–267	–241	–944	–907	–448	–416	–336	–307
	Other boundaries	–65	–59	–157	–147	–97	–89	–76	–69
	Catotelm	14	–30	–464	–512	38	–8	–15	–59
	Storage	318	330	–4277	–4276	760	766	–47	–39
Catotelm	Acrotelm	–14	30	464	512	–38	8	15	59
	Drain	–28	–74	–234	–284	–24	–71	–44	–91
	Storage	42	44	–230	–228	62	63	29	32

The model based on the available data showed that the most intensive groundwater discharge into the lake, drain and other boundaries take place in spring after snow melting, when the recharge in the bog area (about 1.8 km^2) may reach from 4275 (in medium humidity years) to 9300 m^3/day (humid years), i.e. from 27 to 60 l/s km^2. Meanwhile, the discharge into the Lake of Rėkyva in medium humid years may reach 730 m^3/d and in humid years even 1280 m^3/d (8 and 15 l/s); into the peat bog drain 175 and 350 m^3/d (2 and 4 l/s, respectively). Yet during the spring, the discharge accounts only for 20 to 25% of the total recharge at the same time: 14–17% into the lake and 3–4% into the drain. The remaining major part of infiltrated water (from 3000 to 7000 m^3/d) accumulates in the acrotelm followed by the water level rise by 0.2–0.4 m. At the end of the time span, when evaporation including transpiration from the bog surface exceeds precipitation, the discharge into the lake and drains is minimal. For example, in July of the years of medium humidity, the total discharge reduces to 550 m^3/d (3.5 l/s km^2) and becomes lower than evaporation (about 680 m^3/d or 4.4 l/s km^2). Besides, the discharge from the raised bog into drain actually ceases: the model discharge is only 3 m^3/d) (Table 4). The water accumulated in the acrotelm is the source of discharge and evaporation followed by water drop in the bog. Field investigations revealed that actually at the end of dry time span (the middle of September 2008) there was no discharge into the drain. This proves that the model and assumptions reflect the actual water regime in the Rėkyva bog. The main part of the discharge (evaporation and lateral outflow) falls on the acrotelm. This means that deepening of the drain into the lower part of the raised bog (catotelm) does not produce any marked influence on the total discharge from the bog into the lake (Table 5).

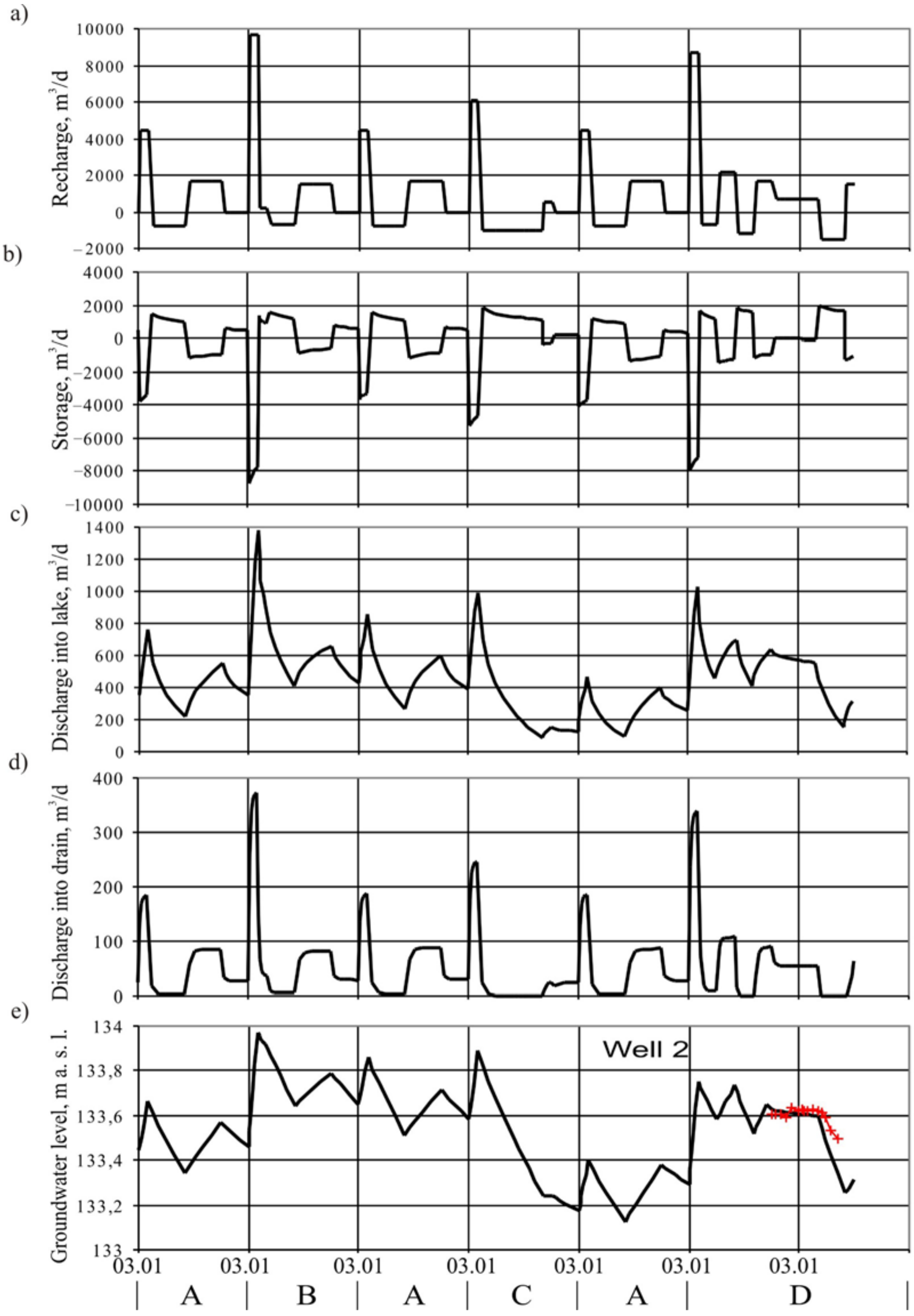

Fig. 6. Groundwater regime of the Rėkyva bog for the years of typical humidity (model data) (A – year of medium humidity; B – humid year; C – dry year; D – 2007–2008. Red graph-measured level)

Table 5. Predicted alteration of groundwater discharge from the bog in medium humidity years at the end of peat exploitation in comparison with the current discharge (m^3/d) (model data)

Discharge boundary	Winter minimum	Spring maximum	Summer minimum	Autumn maximum
Lake	–31	–37	–7	–33
Drain	46	48	43	48
Other	–7	–9	–4	–8
Total	8	2	12	7

The absolute figures of the possible reduction of discharge from the bog into the Lake Rėkyva are small: only 10–40 m^3/d (0.1–0.4 l/s) or 4–9% of the total discharge. The minimal discharge into the drain increases from 3 to 46 and the maximal from 170 to 220 m^3/d or from 20% of the spring maximum to 15-fold value (from 3 to 46 m^3/d) during summer minimum. Yet only during the winter minimum, it reaches 15% of the total bog discharge (73 to 483 m^3/d). In the rest of the year, it ranges within the limits of 1–8%. The part of the Rėkyva bog between the peat bog and the lake accounts for about 5% of the lake basin area. The forecasted loss of 0.4 l/s of its runoff caused by peat bog drainage would only account for 1% of the total runoff of lake basin. The current and forecasted at the end of peat bog exploitation distribution patterns of groundwater levels between the lake and the drain in March and July of medium humid years in different bog areas are shown in Fig. 7.

The predicted impact of peat bog drainage on the groundwater levels may reach the present groundwater divide between the lake and the drain. Yet the absolute drop of the water level at a distance of 50 m from the drain does not exceed 20 cm and 2–5 cm in the divide itself.

It should be pointed out that the information about the parameters of peat bed and seasonal intensity and regime of recharge and evaporation used for modelling is not very precise. The same refers to the preciseness of model values illustrating concrete processes. However, the investigation reveals their relationship and weight in the process of water formation in the Rėkyva basin and the decisive role of the acrotelm. Application of filtration patterns for modelling water movement in the acrotelm allows adequate reflection of its anomalous properties and raised bog water regime.

5. Conclusions

According to the obtained modelling data, the groundwater exploitation in the Šiauliai waterworks may increase the water losses from the Lake Rėkyva basin due to recharge of deeper aquifers by about 2 mm/a (from 7 to 9 mm/a). So the negative impact of water exploitation on the basin runoff, which amounts to more than 150 mm/a, will be negligible.

A detailed modelling of water regime in the Rėkyva raised bog under actual and project conditions of peat bog drainage showed that:

1. Application of the filtration laws for water movement modelling in the acrotelm provides a possibility of adequate reflection of its anomalous properties and water regime in raised bogs. The major part of the groundwater discharge (from 80 to 95%) is formed in the acrotelm which is only 0.3–0.5 m in thickness. Due to extremely good filtration properties, the groundwater regime of the raised bog repeats the regime of recharge from above with a time-lag which is predetermined by water accumulation and the following water level rise in the acrotelm. The rest of the water is accumulated in the lower part of the peat bed (catotelm) which in the Rėkyva raised bog is 6–8 m in thickness.

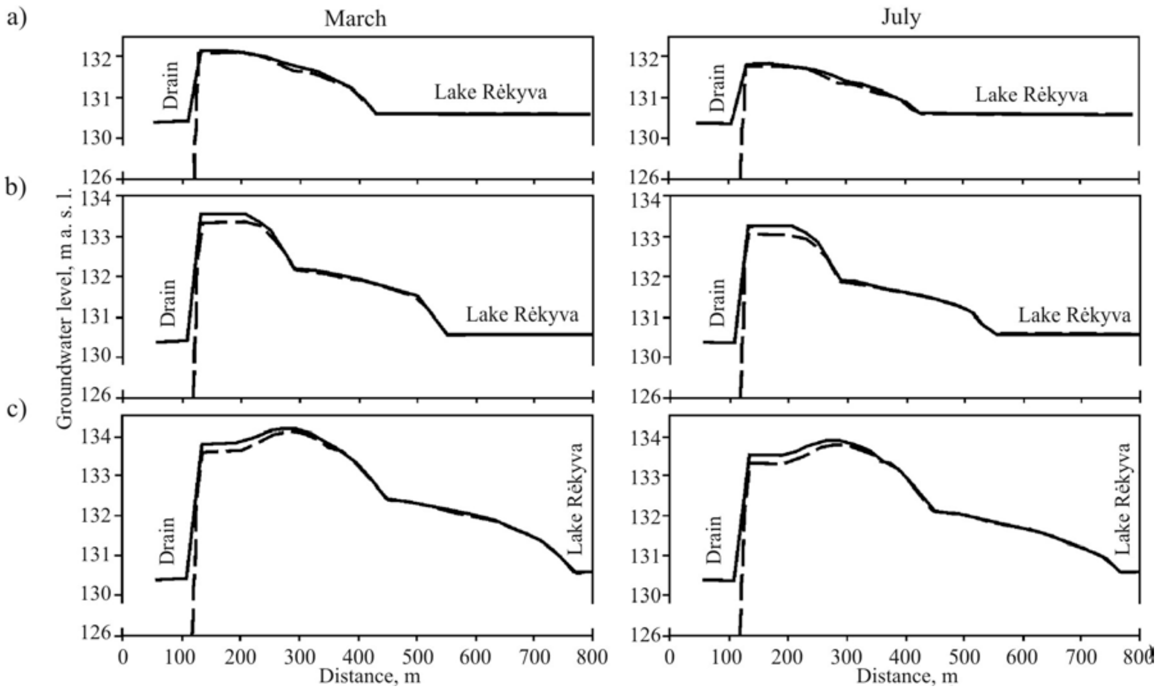

Fig. 7. The current and forecasted at the end of peat bog exploitation (broken line) distribution patterns of groundwater levels between the Rėkyva Lake and the drain (sections a, b, c on Fig. 5) (model data)

2. Most intensive bog groundwater recharge by melt snow water takes place in spring and depending on the humidity may reach from 80 to 180 mm. The major part of the infiltrated water (up to 75%) is temporarily retained in acrotelm where the water level rises by 0.1–0.4 m. The discharge into Lake Rėkyva accounts for 15–18% and into the drain limiting the peat bog about 4%.

3. In summer, when evaporation exceeds precipitation, the total groundwater circulation in the bog reduces by 5 (in medium humid years) to 15–20 times (in dry years). The source of discharge into the lake and the drains is the water accumulated in the acrotelm (about 90%) and catotelm. The lowest discharge occurs in summer and at the end of winter. The minimal groundwater discharge into the lake amounts to about 2.5 l/s. There is almost no discharge into the drains in this time.

4. In terms of precipitation and evaporation intensity, the year 2007 was close to a humid year. Yet the seasonal distribution of precipitation differed from the 5% probability long-term value. An untypical groundwater recharge and high water level in the bog were recorded in June–July. Moreover, due to anomalously high air temperature the recharge into the bog may have taken place in the winter of 2007–2008 (December–February).

5. At the end of peat bog exploitation (30–40 years later), the discharge from the Rėkyva bog into the drain may exceed the actual one by about 40–50 m^3/d (about 0.5 l/s). So, the loss may reach about 1% of the total runoff from the Lake Rėkyva basin.

The recharge into the lower peat layer (catotelm) would increase respectively yet even under these conditions it would account only for 1 to 15% of the total water circulation in the bog (depending on the humidity of the year and season).

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POŽEMINIO VANDENS APYKAITOS PELKĖTAME RĖKYVOS EŽERO BASEINE YPATUMAI

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Santrauka

Didžiausio Lietuvoje 11,85 km^2 ploto vandenskyrinio Rėkyvos ežero baseino nuostoliams, jam maitinant požeminius vandenis, bei piečiau eksploatuojamo durpyno poveikiui ežerui ir apsauginei aukštapelkės juostai vertinti *MODFLOW* priemonėmis sudaryti du matematiniai modeliai. Nustatyta: 1 – dėl požeminio vandens gavybos Šiaulių miesto vandenvietėse baseino nuostoliai gali padidėti nežymiai (nuo 7 iki 9 mm/a, kai bendras nuotėkis yra per 150 mm/a); 2 – metinis ir daugiametis nuotėkio bei vandens lygių aukštapelkėje režimas yra labai kaitus; pagrindinė aukštapelkės, kuri 3 km ilgio ir 0,26–0,8 km pločio juosta skiria durpyną nuo ežero, nuotėkio dalis (nuo 80 iki 95 % – priklausomai nuo sezono) formuojasi 0,3–0,5 m storio viršutiniame sluoksnyje (akrotelme), šiam sluoksniui būdingos anomaliai geros filtracinės savybės ir poringumas (iki 0,95); 3 – eksploatacijos pabaigoje, pasiekus durpyno klodo dugną, nuotėkis iš pelkės į ežerą gali sumažėti 0,2–0,4 *l*/s (apie 1 % bendrojo ežero nuotėkio), o į durpyną – padidėti apie 0,5 *l*/s (pagal sezoną – 1–15 % bendrosios pelkės vandens apykaitos); 4 – sezoninis akrotelmo maitinimas yra pakankamas, kad kompensuotų šiuos nuostolius, ir apsauginės pelkės būklė išliktų artima dabartinei.

Reikšminiai žodžiai: aukštapelkė, durpynas, požeminis vanduo, matematinis modeliavimas, Rėkyvos ežero baseinas, Lietuva.

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