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Prediction of change in wetland habitats by groundwater: case study in Northeast Lithuania

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Abstract. The main aim of this article is to assess changes in important waterfowl habitats – protected wetlands situated in the impact zone of proposed dolomite mining. The changes in the waterfowl habitats are evaluated according to changes in the area of sub-wetlands that compose the principal basis of the waterfowl habitat. The sub-wetlands were selected according to vegetation structure of Lake Čedasas and its riparian zone (northern Lithuania). The open water, hydrophyte, helophyte, open grass and mire scrub sub-wetlands were distinguished.

According to the simulation results, the decrease in groundwater level between 6 and 7 m in the dolomite quarry would not produce a decline of the water level of Lake Čedasas and groundwater level in the riparian zone, but the lowering of the groundwater level in the dolomite quarry and predicted climate change will produce a decline of groundwater level of as much as 10 cm in the surroundings of the investigated lake. The water level of Lake Čedasas would also decrease by about 10 cm. Even these minor water level changes will influence the ecosystems of Lake Čedasas. The following changes are predicted: open water territory will diminish by about 25%, the area covered by hydrophytes will increase by about 15% and the area covered by helophytes will decrease by about 17%, the area of the open grass sub-wetland will decline by about 5%, whereas the area of the mire scrub sub-wetland will increase even by as much as 28%.

The research results showed that the selected mathematical model could be employed to produce a useful simulation of surface water resources and understand the wetland habitats response to disturbances in the water regime.

Key words: wetland habitats, wetland hydrology, water resources, groundwater flow modelling, ecohydrology.

INTRODUCTION

Wetlands are important systems of water environment, significantly contributing to sustainable river basin management and maintaining good ecological quality of water bodies (EC 2000). The importance of these landscape elements and the need to protect them are also emphasized in other international documents. For example, one of the main purposes of the Ramsar convention is to stop the decline of palustrine, riverine and lacustrine aquatic ecosystems as well as to ensure the protection of these valuable natural complexes (Convention... 1971).

Farming activities and climate change (Acreman et al. 2009; Kovarova & Pokorny 2010) are among the most critical contemporary issues that affect the water quality and quantity of aquatic ecosystems. These changes influence the structure of aquatic habitats that are important for waterfowl as breeding, nursery and protective areas. One of the main threats to these ecosystems is extraction of natural resources (for example, dolomite) in their surroundings. The water level changes caused by such anthropogenic activities could negatively affect the structure of aquatic habitats.

The influence of water level changes in aquatic ecosystems is a well-studied issue. Many relevant studies deal with the responses of aquatic ecosystems to natural and artificial water level changes (Riis & Hawes 2002; Schmieder 2004; Chow-Fraser 2005; Coops & Havens 2005; Hudon et al. 2005; Connor & Gabor 2006; Desgranges et al. 2006; Wilcox & Xie 2007). According to various research results, the fluctuations of water level greatly influence the area of waterfowl habitats as well as the rate of biomass accumulation in aquatic ecosystems (Casanova & Brock 2000; Van Geest et al. 2005; Paillisson & Marion 2006). Additional research indicates considerable biological changes in the shallow ecosystems and littoral zones, where even small fluctuations of water level cause fundamental habitat changes (Blindow et al. 1993; Coops et al. 2003; Beklioglu et al. 2006; Leira & Cantonati 2008). Other studies suggest that waterfowl are very sensitive to changes in their habitat area, especially during the breeding season (Hake et al. 2005; Connor & Gabor 2006).

The idea of predicting water regime changes in aquatic habitats arose during the environmental impact assessment for a dolomite mining project (Environmental… 2008). According to this assessment, there were no reliable data that could confirm a likely influence of the proposed dolomite mining on the changes of the Lake Čedasas level. Therefore an independent investigation was initiated. A unique methodology for evaluation of the optimal habitat structure for waterfowl was created, which afterwards was applied to the particular case of Lake Čedasas.

Understanding the optimal aquatic habitat structure for waterfowl and its possible alteration after water level changes is a fundamental ecohydrological question. Moreover, a negative influence of dolomite mining could play a crucial role in the NATURA 2000 sites – the protected habitats of European importance. Therefore, it was hypothesized that the decline of groundwater level in the dolomite quarry and the predicted climate change would affect the water level in the lake, situated in the surroundings of the quarry. Change in the hydrological regime of the lacustrine aquatic ecosystem would result in a rapid succession of changes in vegetation, leading towards the destruction of waterfowl habitats. The water level determined by groundwater inflow from aquifers is of crucial importance for waterfowl habitats. Thus a decrease in the water level in these aquifers would cause a dangerous lowering of the lake water level during a dry season.

Moreover, the Little Crake (*Porzana parva*) and the Black Tern (*Chlidonias niger*) species are preserved in the study area. The quality of habitats of these birds is directly related to the hydrological regime of the aquatic environment. Therefore the main goal of this article is to assess changes in wetlands serving as important waterfowl habitats, situated in the impact zone of proposed dolomite mining.

The objectives of this study were to (1) evaluate the water regime and the vegetation cover on a selected territory in the problematic region, (2) determine the hydrological indicators whose change could threat the existence of sub-wetlands in the NATURA 2000 area (a shallow lake and its riparian zone), (3) simulate the anticipated changes in the lake and the groundwater level in the riparian zone according to the FEFLOW 5.0 program and (4) determine the expected changes of sub-wetland types according to the simulated groundwater level and lake depth.

METHODS

Study area

Lake Čedasas, situated in a sub-watershed of the Vyžuona River (3rd-order river in the Lielupė watershed), was chosen for this study. The length of the Vyžuona River is 34.1 km and its watershed area is 32 090 ha. The Minava Stream, flowing from Lake Čedasas to the Vyžuona River, enters it about 23 km from the river source. The proposed dolomite mining site is situated near this section of the river, only at a distance of about 0.4 km, near Čedasai settlement. Lake Čedasas is a shallow eutrophic lake, with an area of 49.9 ha mostly overgrown with helophytes and hydrophytes. The area of the lake watershed is 2580 ha (Gailiušis et al. 2001), 65% of which is situated in Lithuania, while the rest belongs to Latvia (Fig. 1). The average depth of the lake is 0.86 m, maximum depth 1.85 m and the water turnover rate is 23 days.

The only inflow of the lake, the Minava Stream with an agrarian watershed (2420 ha), enters Lake Čedasas in its eastern part. The same stream flows out of the southern part of the lake (Fig. 1). A solid weir (i.e. non-regulated solid concrete construction) occurs 250 m downstream from the lake, therefore there is no discharge from the lake at very low water levels.

The absolute height of the wetland habitat is about 86 m a.s.l. The height of the Earth's surface in the proposed mining area is similar and varies in the range of 86–88 m a.s.l. The groundwater levels of the wetland area (about 85 m a.s.l.) and the mining area (84.5–86.4 m a.s.l.) are similar in the conditions of the natural groundwater regime, however, they will differ after the opening of the dolomite quarry affecting the groundwater regime (possible drawdown to less than 80 m a.s.l. in the mining area). According to the existing project, the water pumped out of the quarry will be directed to the Vyžuona River, which is not connected with the wetland water system.

There was no net discharge from Lake Čedasas till the end of the 19th century (Report... 2007). The amplitude of lake water level fluctuations was about 0.6 m. Later on, after partial drainage of the riparian zone and watershed of Lake Čedasas, its outflow became seasonal. Water discharge took place only when the lake level was very high and the sub-wetlands in the riparian zone were submerged at the southern end of the lake – normally in spring and autumn. The riparian zone sub-wetland accumulated a depth of about 200 mm of water during the floods and protected the lake from serious declines of water level during the dry season. However, the water surplus during the first half of the period of vegetation growth influenced the formation of wetlands in the riparian zone. The water turnover rate increased (especially during the flood periods) and the water resources of the riparian

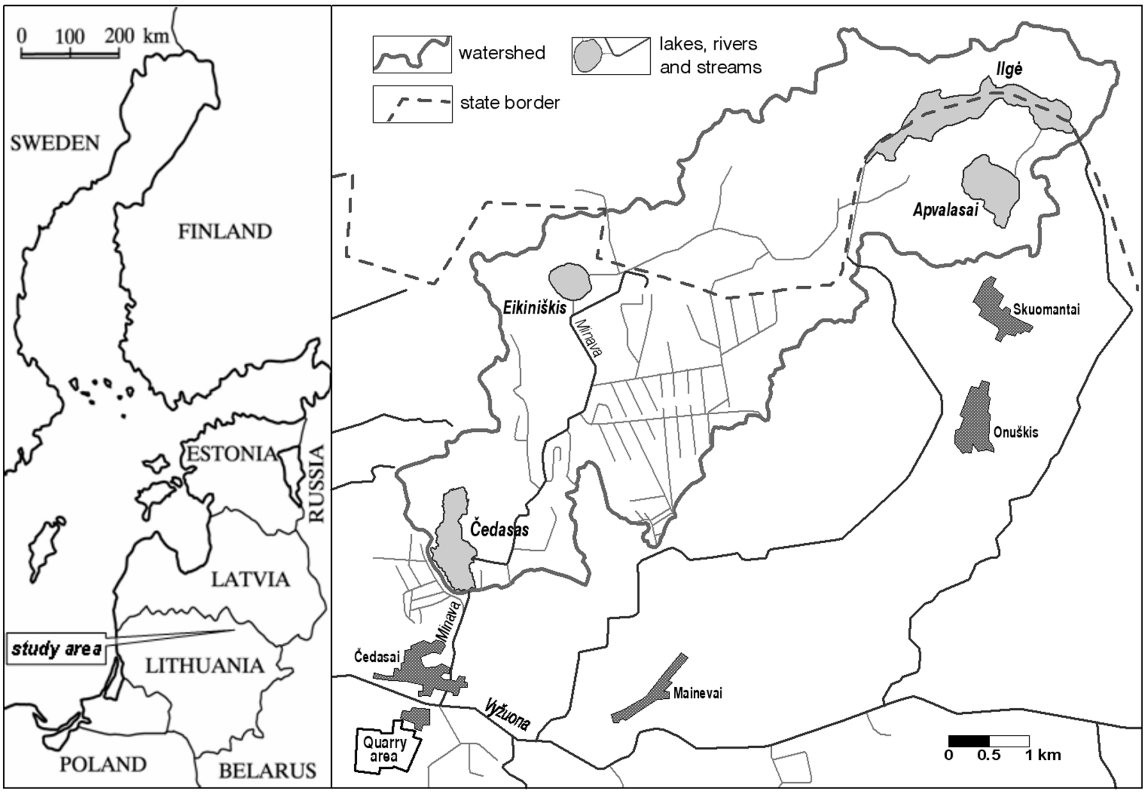

Fig. 1. Study area: the Lake Čedasas watershed and its surroundings.

zone decreased after the deepening of the lake outflow, the construction of the weir and the installation of the drainage system of open ditches in the western part of the riparian zone in 1977 (Fig. 1).

The effect of such reconstructions is obvious during the dry summer periods – there is no outflow from the lake and the evaporation from the lake surface contributes to rapid decline of its water level. Nowadays the input of water to the lake exceeds the loss only during the period from March to June; the water balance of the lake is negative during the rest of the year. A large amount of water enters the lake with the surface inflow; the amount of water entering directly the lake surface from precipitation is roughly similar to the groundwater inflow (Table 1). The greatest part of surface outflow takes place during March–May – more than 62% of annual outflow. During the warm season, the inflow to the lake can be smaller than both evaporation and outflow from the lake. If the lake water level is declining to the weir level, the outflow from the lake stops. Net seasonal discharge is typical of this lake. However the lake water level can increase by up to 1 m during the flood periods.

Table 1. The present (Gailiušis et al. 2001) and future (according to the trends of climate change) water budget of Lake Čedasas

Time	Dimension	P	S_{in}	Gr_{in}	E	S_{out}	Gr_{out}
Present	10^3 m³	374	7 642	348	266	8 088	10
	% (inflow/outflow)	4.5	91.4	4.2	3.2	96.7	0.1
	mm	750	15 315	697	533	16 249	20
Future	10^3 m³	359	7 392	174	274	7 645	10
	% (inflow/outflow)	4.5	93.3	2.2	3.5	96.4	0.1
	mm	720	14 813	348	550	15 321	20

P, precipitation on the lake surface; S_{in}, surface inflow to the lake; Gr_{in}, groundwater inflow; E, evaporation from the lake surface; S_{out}, surface outflow from lakes; Gr_{out}, groundwater outflow from lakes.

It is proposed that during the drainage of the quarry, groundwater could be used for the technological processes, and its surplus could be discharged to the drainage ditches nearby. The quantity of discharged water could reach up to 42 L s^{-1}– this is the approximate inflow of groundwater in the quarry. During the environmental impact assessment, a marginal groundwater level decrease of 0.5 m from the initial level was estimated in the drainage area. Such a decrease should not affect the surrounding groundwater users, the groundwater layer or the bodies of surface water. However, it was recognized that groundwater level decrease could be higher and have a negative influence upon the lake water level and habitats. On the other hand, this earlier assessment contained no data on how the protected waterfowl habitats would respond even to a smaller groundwater decrease.

The amount of precipitation has decreased and the air temperature increased in the watershed of Lake Čedasas and the surrounding region. If this tendency persists, the water budget will change (Table 1) and the water level of the lake will decrease by about 10 cm in future.

Terminology

Wetlands are heterogeneous landscape elements. According to their vegetation structure and other characteristics, they can be divided into several groups, types or subtypes. Usually the main classification features of such systems are watershed characteristics, including land-use or land-cover type (Detenbeck et al. 2000), hydro-geomorphological differences (Brinson 1993), vegetation type (Grossman et al. 1998) or some combination of these features (Cowardin et al. 1979). The nature of the problems to be solved will determine what kind of classification is the most useful. Therefore, according to the main goal of this paper, a modified Cowardin classification system of lacustrine aquatic ecosystems is used.

According to the Ramsar Classification System for Wetland Type (Information... 2009), Lake Čedasas is considered as one wetland type – permanent freshwater pools. However, the differences in vegetation cover and hydromorphological parameters enable distinction of several sub-wetlands, among those forming the entire habitat for protected waterfowl. In order to evaluate the effect of water regime changes, five sub-wetlands were distinguished based on the vegetation structure of Lake Čedasas and its riparian zone: open water, hydrophytes, helophytes, open grass and mire scrub (Table 2). All water areas without vegetation were considered as **open water** sub-wetland. Such areas are important to various protected bird species. For example, the Black Tern tends to nest at a site with 50 : 50 vegetation cover : open water (Cuthbert 1954; Hickey & Malecki 1997; Mazzocchi et al. 1997; Naugle et al. 2000). Nesting occurs

Table 2. Aquatic ecosystem complex: types of sub-wetlands, their present and predicted area

Sub-wetland	Hydromorphological indicator	Present sub-wetland area, ha		Coincidence according to sub-wetland area, %	Coincidence according to sub-wetland location, %	Predicted sub-wetland area, ha	Predicted area changes (–/+), %
		Data from the orthophotograph and satellite image	Data from the bathymetrical plan				
Open water	Depth >1.05 m	19.80	19.67	99.4	74.3	14.45	–27
Hydrophyte wetland	Depth <1.05 m >0.4 m	17.48	17.45	99.8	55.0	20.44	17
Helophyte wetland	Depth <0.4 m	11.34	11.59	97.8	68.7	9.62	–15.6
Grass wetland	Groundwater depth <0.2 m	17.42	21.07	79.1	85.1	15.80	–9.3
Mire scrub	Groundwater depth <0.2 m <1 m	24.64	26.09	94.1	74.5	30.85	25.2
Total:		90.68	95.87			91.16	

at water depths ranging from 0.5 to 1.2 m (Dunn 1979). **Hydrophyte** sub-wetland consists of areas covered with floating vegetation such as spatterdocks (*Nuphar lutea*), white waterlilies (*Nymphaea odorata*), floating-leaf pondweed (*Potamogeton natans*), etc. This sub-wetland could be considered as a transitional one between the open water and overgrown sub-wetlands. **Helophyte** sub-wetland consists of territories covered with water plants with only the underpart submerged, so that their stems with blooms emerge from the water: bulrushes (*Scirpus* spp.), cattails (*Typha* spp.), etc. Cattails or bulrushes are characteristically dominant in Black Tern colonies (Dunn 1979). **Open grass** sub-wetland consists of territories that are covered with emergent riparian grass vegetation for the greater part of the year. Here the same plant species grow that can be found in helophyte sub-wetlands. However, the predominance of lower herbaceous plants is obvious here. **Mire scrub** sub-wetlands are characterized as temporarily (during floods) submerged territories overgrown with scrubs. The most common plants of these areas are white willows (*Salix alba*), bird cherries (*Prunus padus*), etc.

It is supposed in this work that the complex of these sub-wetlands composes a necessary environment for protected waterfowl. Elimination or drastic reduction of only one sub-wetland could disturb the whole of the Lake Čedasas ecosystem. The main factor influencing the formation of these sub-wetlands is the level of water in the lake and its surroundings. The changes in this parameter will induce changes in the sub-wetland areas (Table 2).

Remote sensing analysis

The limits of the areas covered by the above-mentioned sub-wetlands were determined according to the orthophotographical map (M 1 : 10 000, 2005–2006) and *LANDSAT 7* satellite telemetric data (*LANDSAT ETM* imagery). The *ERDAS IMAGINE* program was used to work with *LANDSAT ETM* data. Interpretation and analysis of remote sensing data involved both multispectral *ETM* imagery (with 1, 2, 3, 4, 5 and 7 spectral channels) with the resolution of 28.5 m and imagery with increased resolution of 14.25 m. Statistical filtering (one of the spatial enhancement operations that enables improving image pixel values) and image contrast enhancement operations were made in order to extract as much information as possible. Sub-wetlands were classified using one of the unsupervised training algorithm methods – *RGB* clustering. A thematic raster layer of the investigated territory was formed. A combination of the information found in both remote sensing data was used to form the whole picture of Lake Čedasas sub-wetlands.

The limit between the open water and hydrophyte sub-wetlands was distinguished from the orthophotograph.

Discerning the differences between the boundaries of the territories covered with hydrophytes and helophytes was the most difficult problem. Field observations during several years in Lake Čedasas show that the limit between hydrophytes and helophytes is quite stable. Therefore, the satellite image taken in early summer (10 June) when the hydrophytes have not yet appeared and the lake is covered with the previous year helophytes (reeds, cattails, etc.) enabled us to distinguish the boundary between these two sub-wetlands.

Later on, the limits of sub-wetlands were examined in relation to the depth of the lake, determined according to the Lake Čedasas bathymetrical map of 1970. Using this map, we could draw the most accurate shoreline. Afterwards, the limits of sub-wetlands, situated in the riparian zone (open grass and mire scrub sub-wetlands), were determined based on satellite imagery and orthophotographs.

The limits of these sub-wetlands were also compared with the groundwater depth, determined from hydrogeological maps (M 1 : 50 000). The vertical precision of the bathymetrical map is 1 cm, the horizontal precision is 10 cm. The average density of the depth measuring points is 71 m. Finally, about 100 depth measuring points were made. Therefore, the precision of the bathymetrical map is 2 measuring points in 1 ha.

The best correlations of sub-wetland limits (distinguished from the orthophotograph and satellite image) with particular depths of the lake or groundwater depth were investigated. The best match of these limits was taken as the parameter characterizing each sub-wetland, i.e. the depth of the lake and the groundwater became the so-called hydromorphological indicators (Table 2). Sub-wetland areas were calculated and compared using SURFER 8 software, which automatically sets the optimal step of the grid (11 m). However, in order to get the best visualization of isolines, the step of the grid of 8.2 × 8.2 m for depth interpolation and 5.7 × 5.7 m for sub-wetland boundaries was chosen. Sub-wetland areas calculated on the basis of the remote sensing data were compared with habitat areas, calculated from the lake and groundwater depth.

FEFLOW 5.0 modelling

The purpose of the following stage, modelling, was to estimate the changes in lake water level and groundwater depth in the riparian zone during the exploitation of the dolomite quarry. For this purpose, the modelling software FEFLOW 5.0 was applied (Diersh 2002). This system has been used for specific hydrological and hydrogeological conditions of the studied watershed and for verification of some other parameters. It has been applied to particular geometrical and hydraulic properties of the modelled area of the Lake Čedasas watershed (Figs 2, 3). For

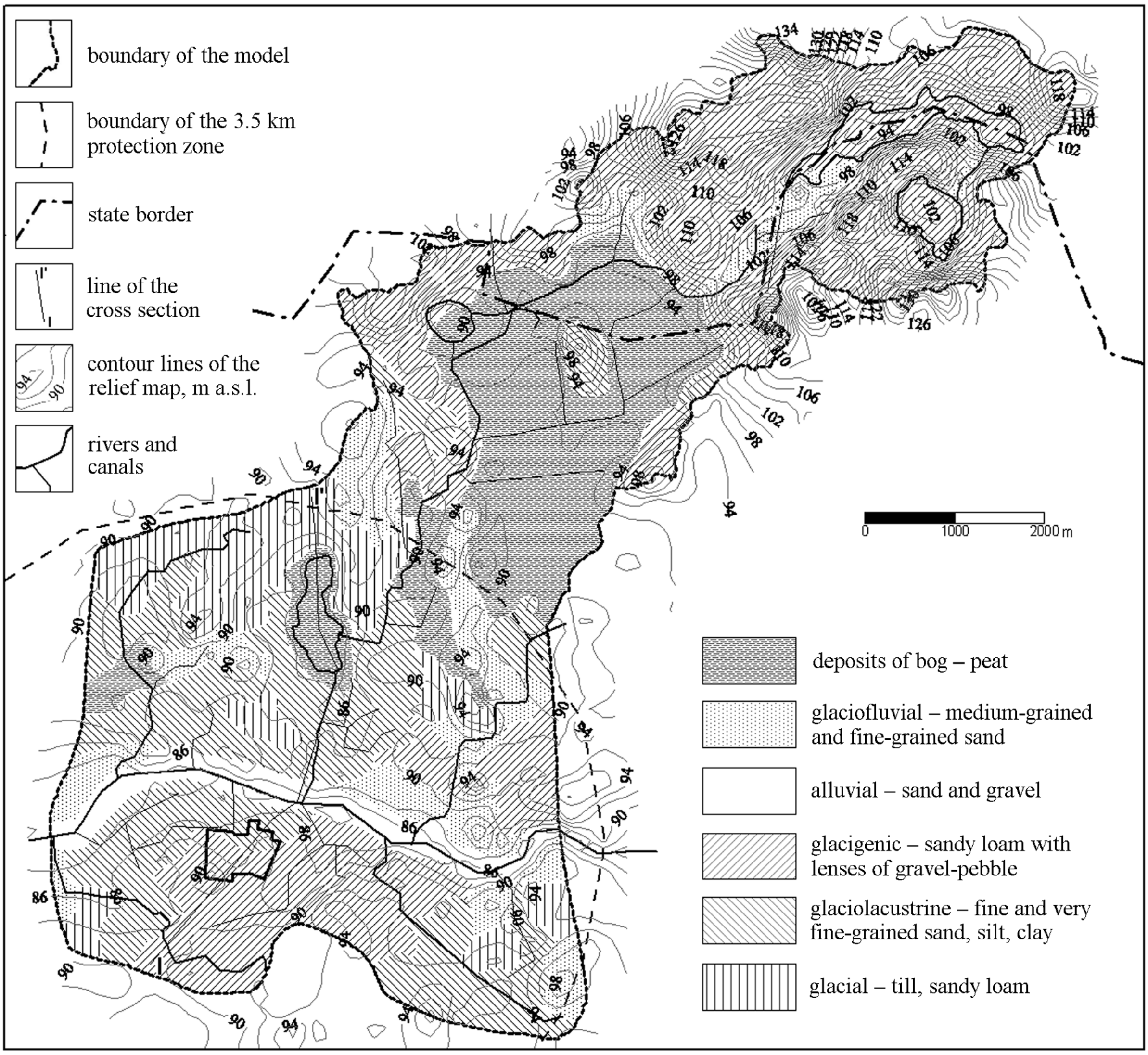

Fig. 2. The Čedasai modelling area and lithological scheme of the top layer – Quaternary deposits.

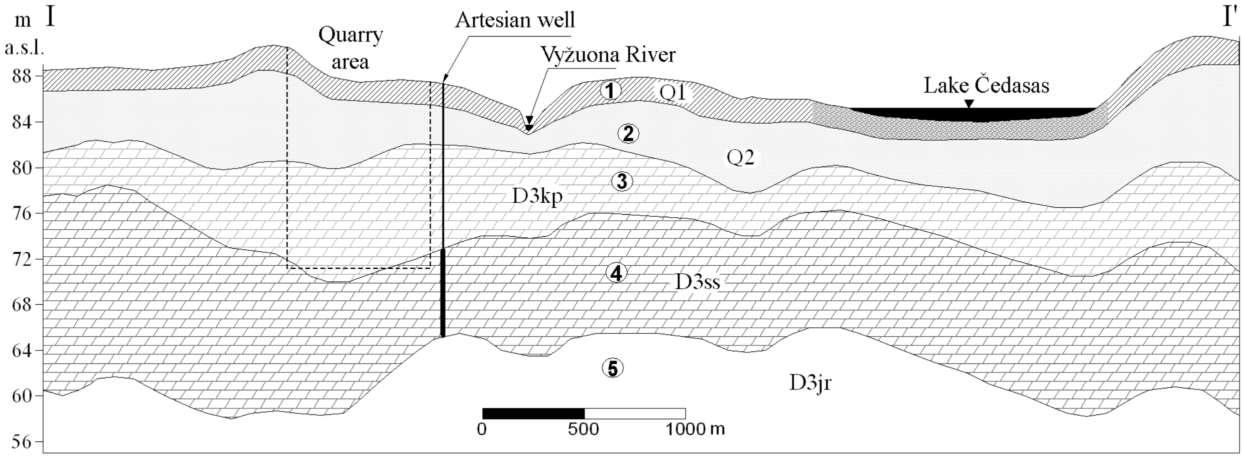

Fig. 3. Geological–lithological cross section along line I–I′ (Fig. 2) of the site adjusted to the layers of the groundwater flow model. Numbers in circles (1–5) – layers according to Table 4.

calibration and validation of the model, the materials of geological investigation from the Lithuanian Geological Survey (Gasiūnienė & Gasiūnas 1973; Report ... 2007) for the area of the planned quarry and investigated lake watershed were used.

Hydrogeological setting

Two layers of the Upper Devonian period (D_3kp, D_3ss) occur under lacustrine and glacigenic Quaternary deposits (Q1, Q2) (Fig. 3) in the dolomite mining area and its vicinity. They are composed of fine-crystalline, solid, in places porous, cracked and cavernous water-bearing dolomite which stratigraphically is dated as the Kupiškis-Suosa aquifer (D_3kp-ss) containing two layers. The general average thickness of the aquifer reaches about 13 m. The top of the aquifer on the territory of the quarry lies at a depth of 3.5–9.6 m or 78.2–83.7 m above sea level. During the geological survey, the depth of appearance of this water and levelling-off in all boreholes has been measured. The piezometric level of water was achieved in the range 83.7–85.2 m a.s.l. The pressure head of water varies from 1.9 to 4.4 m, on average 3 m, above the top of the aquifer. In this way, the water is sub-artesian, whereas the lower part of morainic loam (Q2) is an obvious aquitard. On the other hand, the water of Quaternary formations is theoretically associated with the D_3kp-ss aquifer. This should be taken into consideration when assessing the environmental impact of quarry drainage, because vertical leakage of water may reduce the distances of potential impact.

The D_3kp-ss aquifer occurs above the Upper Devonian layer (D_3jr) which consists of about 10 m thick clay and clayey-carbonaceous deposits of low water permeability (hydraulic conductivity 10^{-3}–10^{-5} m day^{-1}). The D_3jr layer can be considered as a regional aquitard which essentially complicates vertical groundwater exchange between the underlying terrigenous Midddle–Upper Devonian aquifer ($D_{3\text{-}2}$šv-up). It was considered (Report ... 2007) that, because of the rather small quarry area and rather weak permeability of the aquitard, leakage of water from the underlying aquifer will not have any practical significance.

Lake Čedasas lies on a shallow lowland and is surrounded by drained wetland. The thickness of till in the vicinity of the lake is 5.5–6.5 m. In the wetland situated in the northwestern part of the lake, the average thickness of the turf layer is 2.7 m, in the southern part 1.55 m. Under the turf and at the bottom of Lake Čedasas, there occurs a sapropel layer approximately 1.8 m thick. These layers are characterized by extreme resistance to water release and low conductivity, so leakage of water through the sapropel layer practically does not take place at all. In addition, these layers overlie the 5–6 m thick low-permeable floor of loam.

The geological-hydrogeological characteristics of the Čedasai modelling area are presented in Figs 2 and 3 and Table 3.

Structure of the groundwater model

The main feature of the model of groundwater flow is three-dimensional (3D) steady or transient (non-steady) flow. The area of the model includes the entire lake watershed and the territory between the lake and the planned dolomite quarry (Fig. 2). The geometry of the model contains five layers, the lowermost of which is a regional aquitard (layer 5; Fig. 3). The groundwater flow in all aquifers in a numerical model is attributed to five layers (six slices) and is represented by the 3D finite-element grid of mesh elements (Table 3). The geometrical discretization of the model area and the set of boundary conditions after the model calibration are presented in Fig. 4. The total modelled area is 5.0618×10^7 m^2 (Fig. 3), the number of triangle elements (mesh) is 32 908, the number of units (mesh node) is 21 350, the minimal step of the grid (mesh) which was used for the area around the dolomite quarry and the investigated lake is 14–20 m and the minimal area of the element is accordingly ~240 m^2.

Layer 1 (1–3 m thick) corresponds to Upper Quaternary deposits: marsh (bog), alluvial and glaciolacustrine deposits, basal and marginal till (Report … 2007). It is composed of mixed sand, loam, sandy loam, clay and peat (Table 4).

Table 3. Features of the numerical model FEFLOW 5.0 for the Čedasai site

Problem class: transient flow model
Type of problem: saturated (groundwater)
Time stepping scheme: Forward Adams–Bashforth/ backward trapezoid (AB/TR)
Number of time steps: automatic time step control
Length of time step: automatic time step control (increasing new step size)
Error tolerance: 1×10^{-3}
Adaptive mesh error: 1×10^{-2}
Solver: iterative equation solver
Maximum of iterations per time step: 12
Vertical exaggeration: 1 : 1
Problem measure (width of working window): 21 456 m
Dimension: three-dimensional
Number of layers: 5
Number of slices: 6
Element type: 6-noded triangular prism
Mesh elements: 32 908
Mesh nodes: 21 350
Aquifers: unconfined(phreatic); other aquifers are unspecified

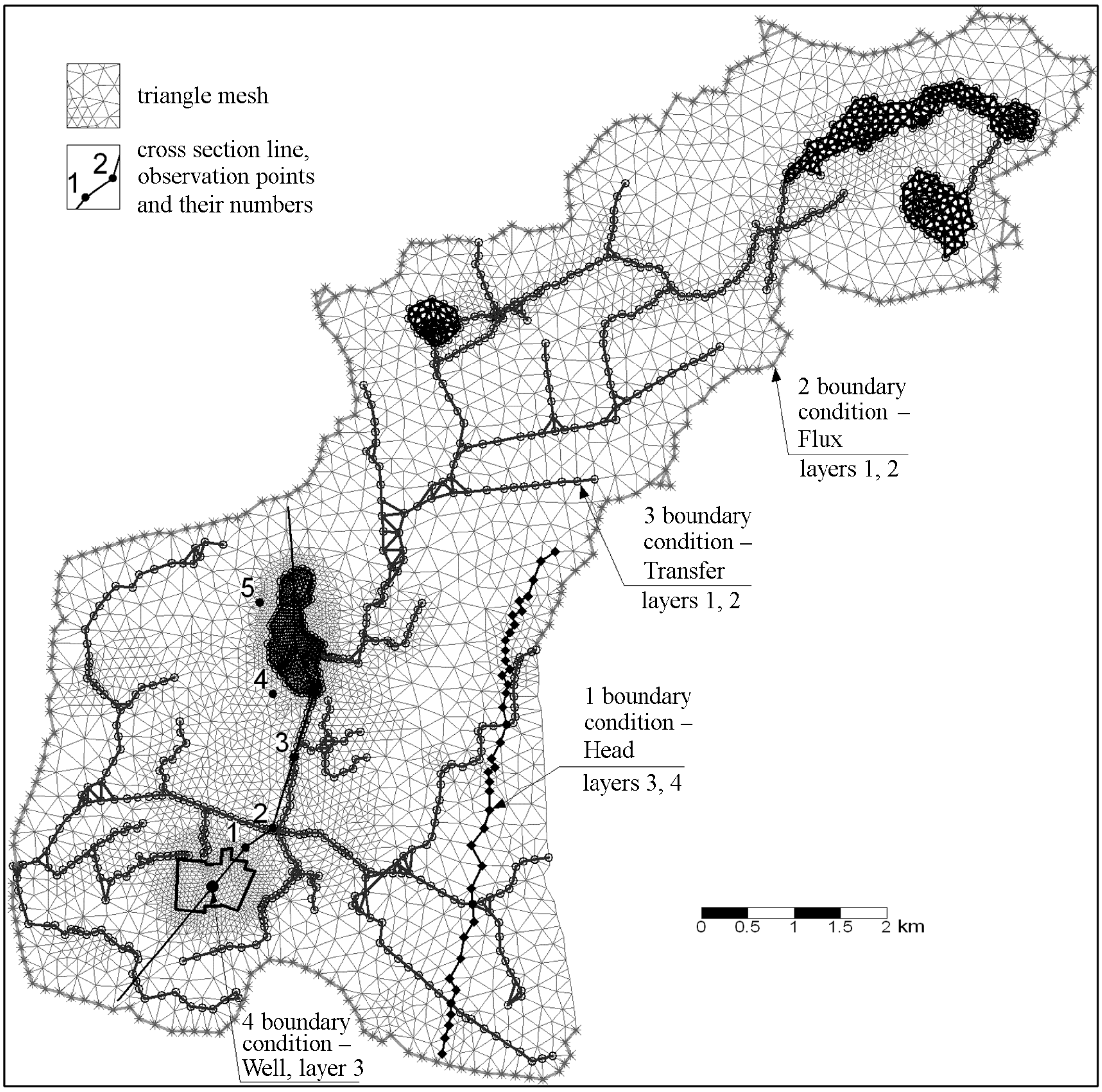

Fig. 4. Mesh geometry and boundary conditions for the FEFLOW finite element model of the Čedasai area.

Layer 2 (2–13 m thick) is composed of glacial loam (till) of low water permeability, which can be considered as a relative aquitard located above the underlying aquifer. Layers 3 (2–13 m thick) and 4 (2–13 m thick) consist of dolomite that corresponds to the Upper Devonian aquifers (D_3kp, D_3ss). The last layer 5 (10 m thick) includes clay and clayey-carbonaceous deposits.

The hydrogeological parameters after the model calibration – hydraulic conductivity, recharge and storativity – are presented in Table 4. They were used for simulation of the distribution of the groundwater flow, representing the real water balance. For this purpose, the published results of field investigations or archive data bases were applied (Gasiūnienė & Gasiūnas 1973; Juodkazis 1979).

The following boundary conditions were used in the model (Fig. 4): the 1st-kind condition, constant head – piezometric level of the Upper Devonian aquifer (the pressure head 3–4 m above the top of the aquifer) (layers 3 and 4); the 2nd-kind condition – constant groundwater flow at the edge of the limitary watershed (layers 1 and 2); the 3rd-kind condition – constant water exchange between rivers, lakes of the watershed and adjacent computational blocks, transfer rate 5000/20 000 m $\mathrm{day}^{-1} \times 10^{-4}$ (in/out) (layers 1 and 2); the 4th-kind condition – extraction of water from the quarry with a constant yield of 158.3 $\mathrm{m}^3\ \mathrm{h}^{-1}$ (in layer 3) (Report… 2007). During the selection of model parameters, the conditions were slightly and intentionally adjusted to avoid over-optimism. A rather high hydraulic conductivity of lower Quaternary loam (~0.001 m day^{-1})

Table 4. Hydrogeological parameters selected for different deposits of the Čedasai model case

Layer	Lithological description	Thickness, m	Hydraulic conductivity, m s^{-1} × 10^{-4}	Recharge, m day^{-1} × 10^{-4}	Storativity
1	Deposits of bog – peat	1–3	0.0006–0.04	0–0.5 (0–0.25)*	0.1
	Glaciofluvial – medium-grained and fine-grained sand		0.9	2.5 (1.25)	
	Glacial – till, sandy loam		0.01	1.2 (0.6)	
	Glacigenic – sandy loam with lenses of gravel-pebble		0.02–0.5	1.5 (0.75)	
	Glaciolacustrine – fine and very fine-grained sand, silt, clay		0.2–1.0	1.3 (0.65)	
	Alluvial – sand and gravel		1.2	3.0 (1.5)	
2	Morainic till of Quaternary deposits (aquitard)	2–13	0.0001	–	0.01
3	Upper layer of dolomite deposits (D_3kp)	2–14	1.1	–	0.002
4	Lower layer of dolomite deposits (D_3ss)	5–19	1.5	–	0.002
5	Clay and clayey-carbonaceous deposits (regional aquitard)	10	0.00001	–	0.001

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* Figures in brackets are the reduced recharge values due to climate change.

and rather high conductivities of other layers were supposed. A more significant contact between the Quaternary and the Upper Devonian aquifer can be caused by the reduction (even up to 2 m) of the thickness of layer 2. This means that the actual depression of groundwater levels caused by the exploitation of the quarry could be slightly smaller.

Modelling with FEFLOW 5.0 was performed in two stages:

1. in the conditions of a steady state flow, before the beginning of the dolomite quarry exploitation;
2. in the conditions of a transient (non-steady) flow, if pumping of water with a maximum extraction of 158.3 m^3 day^{-1} from the Upper Devonian D_3kp aquifer during exploitation of the quarry were to be performed and continued for eight years.

The main result of the proposed modelling is the simulation of the distribution of water levels between the groundwater and the Upper Devonian D_3kp aquifer in both cases mentioned above. In order to represent the groundwater level isolines, a software SURFER-8 was used.

For the variability (sensitivity) analysis, runs of the model were made for four sets of hydraulic conductivity, recharge, storativity and transfer rate. The dependence of water level (after 8-year exploitation of the dolomite quarry) on relative values of these four parameters in the range from 0.1 to 10 is presented in Fig. 5.

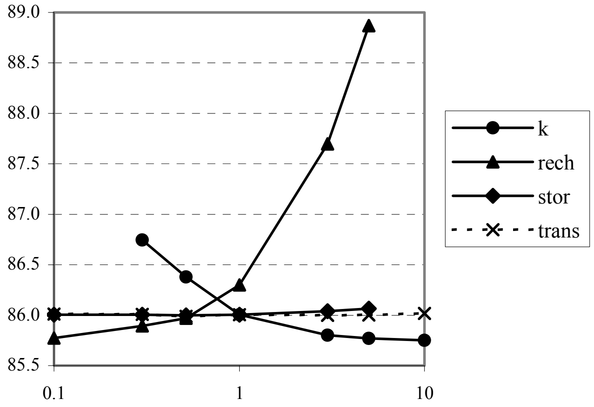

Fig. 5. Variability of water level, m a.s.l. (observation point No. 4 in Figs 4, 8) after eight years of exploitation of the dolomite quarry versus the ratio of parameter value to calibrated value (hydraulic conductivity (*k*), recharge (rech), storativity (stor) and transfer rate (trans)).

The result of the assessment of the analysed parameters least of all depends on the storativity and transfer rate. So, these parameters are not critical and their variability cannot significantly affect the results of modelling. The largest variability is determined for the recharge (the difference between the upper and lower bounds for the water level in the observation point No. 4 is 3.1 m) and for hydraulic conductivity (difference 1.0 m). Thus, the parameters of recharge and especially hydraulic conductivity are noticeably critical and can affect the results and must be correctly selected during calibration of the model.

RESULTS AND DISCUSSION

Habitats and sub-wetlands

The protected waterfowl habitats are composed of open water, hydrophyte, helophyte, open grass and mire scrub sub-wetlands in the investigated lake and its riparian zone.

Open water covers 41% (19.80 ha) of the lake area. Hydrophytes have colonized 36% and helophytes 23% of it.

Sub-wetlands, situated in the riparian zone (open grass and mire scrub sub-wetlands) cover an area that makes 87% of the lake area. A larger part of this area (59%) is covered with mire scrubs (Fig. 6).

According to some authors (Hickey & Malecki 1997), the most suitable habitats for the Black Tern (*Chlidonias niger*) are those where 50% of the territory is covered with emergent vegetation. The Little Crake (*Porzana parva*) requires similar habitats (Burton & Burton 2002). The open and semi-open habitats (open water and hydrophyte sub-wetlands) cover 30 ha in the investigated lake. The total area of overgrown habitats (helophyte and riparian open grass sub-wetlands are very similar in their morphometrical parameters) is 23.16 ha in the investigated lake and its surroundings.

To conclude, the present proportion of the Lake Čedasas habitats is similar to the proportion of vegetation cover and open water the Black Tern (*Chlidonias niger*) and Little Crake (*Porzana parva*) need for living.

Hydromorphological indicators

Sub-wetlands are best characterized by the lake depth and groundwater level. According to the bathymetrical plan of the lake and hydrogeological map of the riparian zone, isolines best fitting the limits between various sub-wetlands were determined. These lines were taken as the hydromorphological indicators showing the limits of sub-wetlands.

Comparative analysis of the lake's bathymetrical plan and the territory overgrown with macrophytes in the orthophotographical map showed that a larger part of water areas, shallower than 1.05 m, is totally or partially overgrown with water plants. The coincidence of the open water area between these two maps is 99.4%. The coincidence of open water patches dislocation between these two maps is 74.4% (Table 2, Fig. 7).

The percentage of the coincidence of the open water area and its distribution (between the bathymetrical and

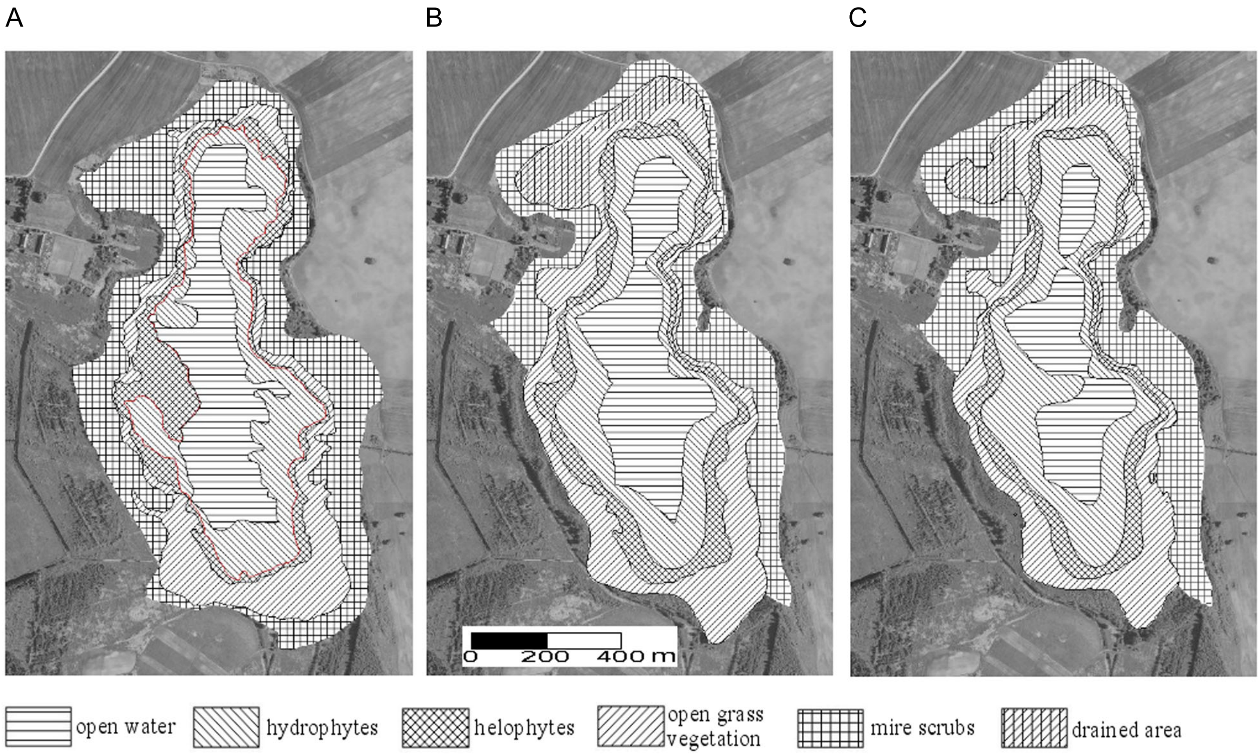

Fig. 6. Sub-wetlands in the Čedasas aquatic ecosystem: **A**, areas according to orthophotograph and satellite image; **B**, areas according to isolines in the bathymetrical plan (natural conditions); **C**, simulated areas (according to isolines) after the 10 cm decline of the water level.

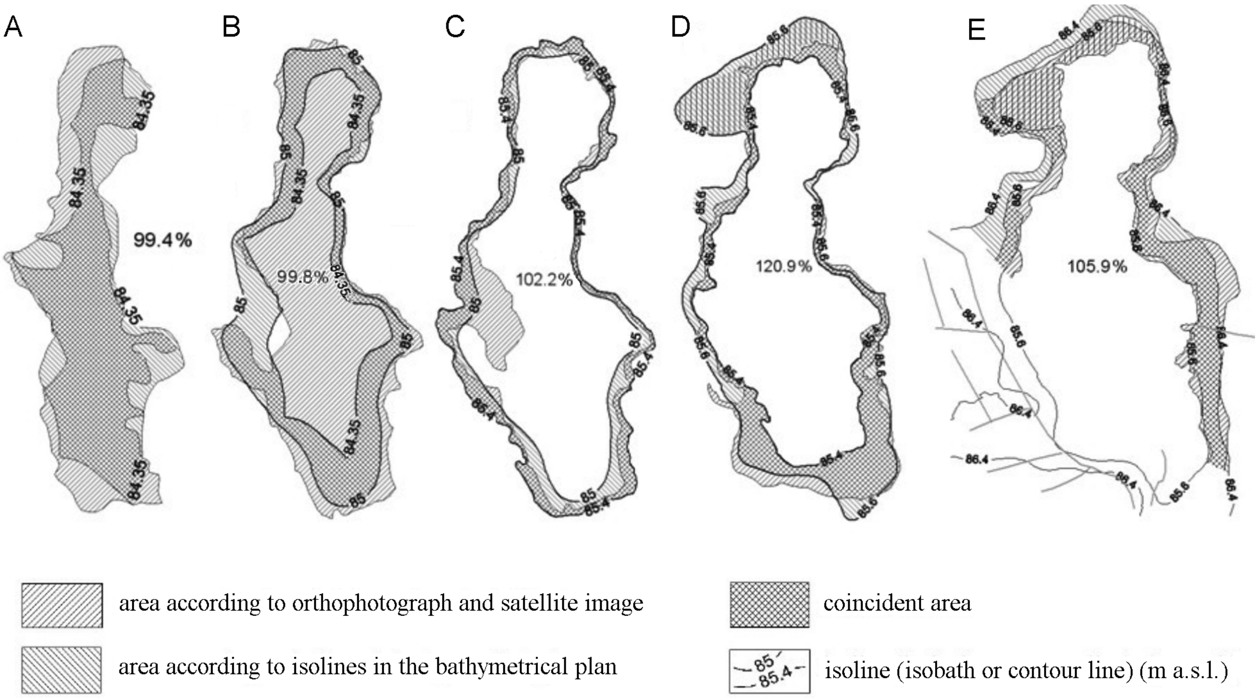

Fig. 7. Coincidence of the sub-wetland area and location in Lake Čedasas: **A**, open water; **B**, hydrophytes; **C**, helophytes; **D**, open grass vegetation; **E**, mire scrubs.

orthophotographical maps) is smaller than mentioned above, if another indicated depth is taken (Table 2). Therefore, >1.05 m depth is essential for preservation of open water areas in the investigated lake and it was considered as the hydromorphological indicator of these sub-wetlands.

The hydromorphological indicator of helophyte areas corresponds to the main helophyte distribution between the shoreline of the lake and the 0.4 m isobath: the area coincidence is 102.2%, location coincidence 68.7% (Table 2, Fig. 7). Misalignment of the sub-wetland area and dislocation of these sub-wetland patches between the two maps are mostly caused by the bathymetrical map scale that gives insufficient information at small depths. For example, there are on average less than two measured points in 1 ha of 0–0.4 m depth.

Comparative analysis of the riparian zone of the lake (overgrown with scrubs and grassy vegetation) and the groundwater level in this zone showed that grassy vegetation with predominance of terrestrial helophytes occurred mainly on the territories where groundwater depth varied from the lake shoreline to 0.2 m. Therefore, it was supposed that the hydromorphological indicator of open grass sub-wetlands corresponded to the groundwater level not shallower than 0.2 m.

The last hydromorphological indicator was determined for mire scrub sub-wetland. Comparative analysis of the dislocation of scrubs and the groundwater level parameters showed that mire scrubs form in the areas where the groundwater level varies between 0.2 and 1 m (Table 2, Fig. 7).

To sum up, the best coincidence in the investigated lake was observed between the open water area discerned from the orthophotograph and the area within 1.04 m depth isobath limits; between the area covered by hydrophytes and the area within 0.4–1.05 m depth isobath limits; between the area covered by helophytes and the area within 0.4 m depth isobath limits. The best coincidence between open grass sub-wetlands and the area within 0.2 m groundwater depth limits as well as between the mire scrub area and the area within 0.2–1.0 m groundwater depth limits was observed in the riparian zone of Lake Čedasas.

There are two most important hydromorphological indicators for the protected waterfowl in the investigated lake:

1. The boundary between hydrophyte and helophyte sub-wetlands, where the best coincidence with 0.4 m isobath was determined (Table 2). This limit indicates the total area of open and semi-open habitats (open water and hydrophyte sub-wetlands) that serve as nourishment areas for the Black Tern (*Chlidonias niger*) and Little Crake (*Porzana parva*).
2. The part of the riparian zone, where groundwater depth is greater than 0.2 m, indicating the limits for the overgrown habitats (helophyte and open

grass sub-wetlands) suitable for the Black Tern (*Chlidonias niger*) and Little Crake (*Porzana parva*) as breeding areas.

Finally, the mire scrub sub-wetland predominates in the riparian zone where the groundwater level declines more than 0.2 m during the dry season, which lasts for the most part of the period of vegetation growth. This hardly penetrable scrub belt surrounding the lake is also very important for the Black Tern (*Chlidonias niger*) and Little Crake (*Porzana parva*) as a protective zone, determining the safety of the whole habitat in Lake Čedasas. It guarantees a limited use of the lake for the recreational purposes and a quiet ambiance for the breeding birds.

Change in the area and location of sub-wetlands

Simulation of groundwater level changes showed a decrease in the groundwater level in the area of the dolomite quarry. After some time, the groundwater level will become stable and will be maintained thus during the whole of the quarry exploitation period. The 3D model results revealed a well-defined depression of the groundwater level, reaching even 6.5 m (very close to the results of calculations (6.8 m) performed during environmental impact assessment; see Environmental… 2008) – below the natural groundwater level that formerly surrounded the quarry (Figs 8, 9). However, its real influence is observed only within 600–700 m and reaches only the Minava Stream (decrease in the groundwater level close to the Minava Stream is only 0.2–0.3 m), flowing from Lake Čedasas to the Vyžuona River (Fig. 1). So, the decrease in the groundwater level reaches 10 cm in the surroundings of the investigated lake (Figs 8, 9). Nevertheless, the Lake Čedasas water level will decline by about 10 cm, because the precipitation will decrease and evapotranspiration will increase (Table 1).

Based on the simulation results of groundwater changes in the riparian zone of Lake Čedasas, it is assumed that the water budget will change as a consequence of climate change and extraction of groundwater in the dolomite quarry. The obtained results showed that according to the hydromorphological indicators, the open water territory will be divided into two separate areas and will diminish by about 25%, assuming the impact of dolomite quarry exploitation and climate change. The area covered by hydrophytes will increase by about 15% and the area covered by helophytes will diminish by about 17% because of the water level decline in the lake. Thus, the total area of Lake Čedasas will decrease by about 8%.

However, the area of the open grass sub-wetland will decline by about 5%, whereas the area of the mire scrub sub-wetland will increase by as much as 28% (Table 2, Fig. 7).

In order to evaluate more precisely the water balance and water level changes of the lake as well as the resulting habitat changes, the FEFLOW 5.0 model (more suitable for the simulation of groundwater flows) should be combined with other surface outflow models (FEFLOW 6.0, GSLOW versions).

To conclude, the FEFLOW 5.0 simulation results of our study indicate that exploitation of the dolomite quarry and further climate change will only slightly influence the groundwater levels in the riparian zone of Lake Čedasas. The climate and groundwater changes in the riparian zone will change the water level of the lake. The most negative influence on the protected waterfowl will be the reduction of the open water area (nourishment zone) as well as of the helophyte and open grass sub-wetlands (breeding zone), assuming that the lake level and the groundwater level of the riparian zone will decrease by 10 cm. The increase in the area overgrown with scrubs could, as we have indicated earlier, have some positive protective value.

CONCLUSIONS

1. The FEFLOW 5.0 model was used for the simulation of groundwater inflow and outflow. If these water budget elements can determine water level changes in lakes, positive results of the application of this model are observed (as in our case). However, if water level changes in lakes are mainly affected by surface water inflow and outflow, the application of the FEFLOW 5.0 model is insufficient. In this case, other models (FEFLOW 6.0, GSLOW versions) must be used in order to simulate the water level changes in lakes.
2. The groundwater level change in the riparian zone of Lake Čedasas was simulated by FEFLOW 5.0. The decrease in lake water level was predicted on the basis of the change in water balance due to climate change. A similar change in the water level of Lake Čedasas may be expected assuming that the water level in the lake varies similar to the groundwater level in the riparian zone.
3. The existing proportion of open, semi-open and overgrown habitats in Lake Čedasas and its surroundings is similar to the proportion of vegetation cover and open water needed by the Black Tern (*Chlidonias niger*) and Little Crake (*Porzana parva*) inhabiting the study area.
4. According to the analysis of the most important hydromorphological indicators (0.4 m depth in Lake

Fig. 8. Simulated groundwater level (m a.s.l) of the Čedasai area: **A**, according to the natural groundwater regime prior to the beginning of exploitation of the dolomite quarry; **B**, according to the affected groundwater regime, after eight years of exploitation of the dolomite quarry; **C**, simulated drawdown of groundwater level (m) in the area of Lake Čedasas (marked with A in part B of the figure). 1–5, observation points.

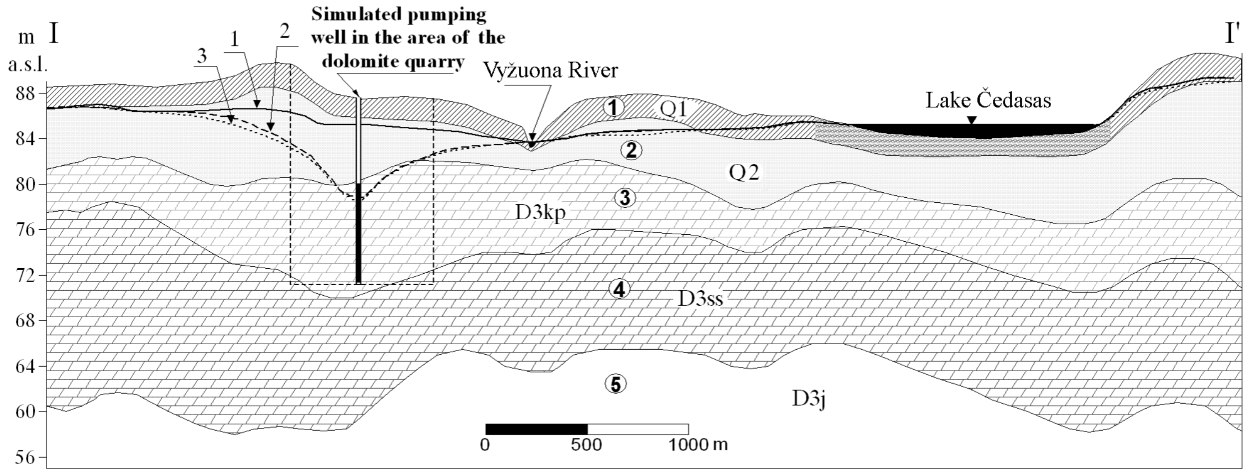

Fig. 9. Geological–lithological cross section along line I–I′ (Fig. 2) and simulated groundwater level: 1, according to natural groundwater regime prior to the beginning of exploitation of the dolomite quarry; 2, according to the affected groundwater regime, after eight years of exploitation of the dolomite quarry (the 4th-kind boundary condition – extraction of water from the quarry with a constant yield of 158.3 $m^3 h^{-1}$); 3, after eight years of exploitation of the dolomite quarry in case of reduced groundwater recharge due to climate change. Numbers in circles (1–5) – layers according to Table 4.

Čedasas and 0.2 m groundwater depth in the riparian zone), the most suitable habitat structure for protected waterfowl is composed of three zones: nourishment (open water and hydrophytes), breeding (helophytes and riparian grass vegetation) and protective (hardly penetrable scrub belt surrounding the lake).

5. Normally, after water extraction in the dolomite quarry, the lake water and riparian zone groundwater levels will remain unchanged. The assumption that precipitation and temperature will be changing in the future, like now, and water will be extracted from the dolomite quarry, suggests a change in the water budget. In this case, the Lake Čedasas water level will decrease by 10 cm and the proportion of these zones will change from 41 : 32 : 27 to 38 : 28 : 34. A negative influence will be felt in the nourishment and breeding areas of protected waterfowl, which tend to decrease slightly.

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Märgala keskkonna muutumise prognoos põhjavee dünaamika modelleerimise alusel: uuringu tulemused Kirde-Leedust

Julius Taminskas, Rimantas Petrošius, Rasa Šimanauskienė, Jonas Satkūnas ja Rita Linkevičienė

Artikli peamine ülesanne on hinnata võimalikke muutusi ühel Kirde-Leedu kaitsealusel märgalal, mis asub kavandatava dolokivikarjääri mõjualas. Mõju ulatust hinnatakse veelindude elupaikade pindala muutuste järgi. Čedasase järve ja selle kaldavööndi märgalal eraldatakse taimestiku struktuuri alusel järgmisi alamalasid: avaveeala, vee-, soo- ja rohttaimede alad ning soine võsastik. Modelleerimine näitas, et põhjaveetaseme langus karjääris 6–7 m ei põhjusta veetaseme langust järves ja selle kaldavööndis, kuid koos ennustatava kliimamuutuse mõjuga põhjustab veetaseme languse 10 cm nii järves kui ka selle ümbruses. Isegi see väike langus kutsub ökosüsteemis esile hulga muutusi: avaveeala kahaneb 25%, kuid hüdrofüütide ala kasvab 15%, samas kui helofüütide ja rohttaimede alad vähenevad vastavalt 17 ning 5%, aga võsastikud hõlmavad isegi kuni 28% suurema ala. Tulemused veenavad, et rakendatud matemaatiline mudel on edukalt kasutatav märgalade hüdrogeoloogia ja keskkonnatingimuste seoste uurimisel.