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The geoecological model for small tundra lakes, Spitsbergen

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Introduction

Arctic wetlands are an important geoecosystem in an arid and cold tundra environment of polar oasis on the high-latitude of northern hemisphere (Kostrzewski et al. 2006a), which over the past few years have been subjected to significant environmental changes. Global climate changes have contributed to the significant development of wetlands in areas of glacial retreat and where the deeper summer thawing of permafrost has taken place. However, at the same time the patchy wetlands with a small area tend to disappear as a result of the gradual degradation of the permafrost (Woo & Young 2006, Kostrzewski et al. 2006b). High-arctic lakes are prevalent and highly sensitive types of polar wetlands affected by climate change and variations of geomorphic processes (Yoshikawa, Hinzman, 2003).

The remote location of wetlands in the High Arctic results in the fact that data presenting the current state of the geoecosystems of tundra lakes, supporting an analysis of the stages of evolution and forecasting of their future development is sparse. On the eastern coast of Petuniabukta there is a group of tundra lakes at various stages of geosuccession. Detailed studies of shallow tundra lakes located on raised marine terraces at Ebbadalen valley (Fig. 1, Mazurek et al. in print, Zwoliński et al. in print) discovered the influence of water that feeds into the lakes whose type depends on bedrocks, the intensity of biogenic processes and distance from the sea (Stankowska 1989).

The objective of this paper is to present the conditions and style of functioning of the geoecosystems of tundra lakes. An analysis of their functioning has been based on the diversification and variability of water chemistry and the sedimentological and geochemical properties of lacustrine deposits, which fill the basins of a number of lakes on the eastern coast of Petuniabukta. Hydrographical and lithological mapping covered 16 tundra lakes, and included the research of spatial and temporal variability (in the period 2001–2003 and in 2005–2006) of the chemical composition of water in selected lakes (Fig. 2). This analysis should point to the role of these basins in the paraglacial evolution of mineral matter in a post-glacial valley. In consequence, a model presentation of the development of arctic lake-like wetlands in the dry high-Arctic climate should be obtained.

Study area

The surveyed area is located on the north-eastern tip of Billefjorden, a branch of Isfjorden – the biggest fjord-system in the mid-western coast of Central Spitsbergen (Fig. 3). The eastern coast of Petuniabukta at the mouth of Ebbadalen (Ebba valley) forms a steplike system of raised marine terraces characteristic for the post-Pleistocene shoreline layout of Svalbard (Salvigsen, 1984; Landvik et al., 1987). Geologically, the eastern coast of Petuniabukta is dominated by the Ebbadalen Formation composed of Middle and Upper Carboniferous carbonates, anhydrites, gypsum, sandstone and conglomerates (Dallmann et al., 1994). The lower terraces comprise sandy and gravel sediments originating from local waste material and, to a smaller extent, in cryctallinic Hecla-Hoek rocks. The Ebbadalen tundra lakes occupy shallow depressions un-

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Fig. 1. General view on raised marine terraces on the east coast of Petunibukta (photo Zb. Zwoliński)

derlain by initial soil or thin peat in permafrost terrain (Zwoliński et al., in prep.). According to Gulińska et al. (2003), the soil conditions on raised marine terraces suggest that they belong to the area with loose and poorly developed soils. Rare vegetation of dry deflational lichen-moss tundra ecosystems is comprised mainly of calciophylitic *Dryas octopetala*, *Salix polaris* and various species of *Saxifraga*, all partly interspersed with lichens.

Fig. 2. The closest lake to Skottehytta with water level gauge and measuremets of water temperature (comp. Fig. 4) (photo Zb. Zwoliński)

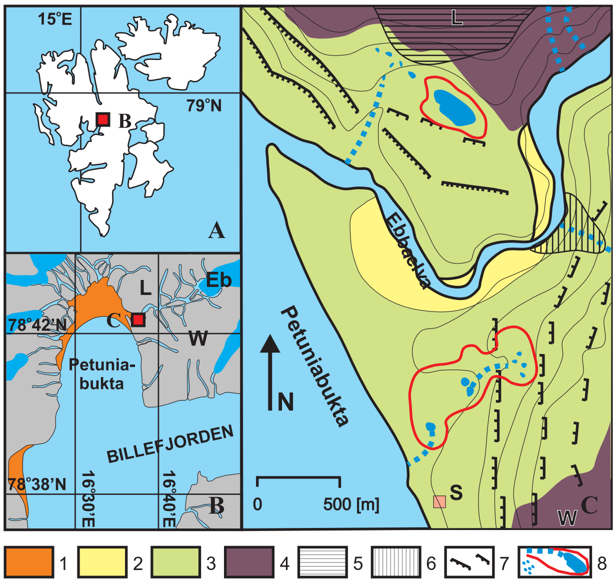

Fig. 3. Location of study area
1 – tidal flats; 2 – areas of glacifluvial accumulation; 3 – raised marine features; 4 – rock walls and slope deposits (undifferentiated); 5 – talus cones; 6 – alluvial fans; 7 – raised terrace level edges; 8 – lakes, episodic streams and borders of catchments under study (red lines); L – Lovehovden; W – Wordiekammen; Eb – Ebbabreen; S – Skottehytta. On the insert C – contour intervals marked with 5 m interval.

The functioning of tundra lake geoecosystem

The hydrological activity of non-glaciated catchments on the sea coast usually appear no longer than for 3–4 months in a year, from June to September (Fig. 4). Short period of functioning of tundra lakes induces that during summer they are one of the most dynamically changing morphogenetic and sedimentary environments, being at that time the highly valuable habitat for flora and fauna (Fig. 5).

During winter, the circulation of water in lake basins ceases, and is replaced by the accumulation of water in snow and permafrost. Shallow lakes and ponds can freeze to the bottom over winter. During warm season, the lakes are supplied initially by meltwater from the lake ice and snow cover melt, and then by the hillslope runoff and saturated overland flow from wetlands and creeks, and/or the seasonal thawing of permafrost. Processes of runoff trigger the inwash of fine particles, resulting in their seasonal decantation. Nevertheless the most efficient supply of sediments to ponds is connected with aeolian activity. Dust and fine-sand particles are delivered by wind either directly to the water, or deposited on the snow surface, mainly during early autumn, when the snow cover is not continuous, and pond depressions are privileged regarding its accumulation.

During the Arctic summer, the spread of tundra ponds changes, some of them disappear periodically or permanently, which results from the increase in air temperature and evaporation, and points among others to the gradual exhaustion of supply from the active layer of the permafrost. The magnitude of evaporation is also definitely influenced by the vegetation occurring on the margins of basins. The lakes usually froze slowly in early or mid-September.

The sources of water inflows reaching tundra lakes are reflected in the chemical composition of water which, in turn, affects the types of ecosystems, the geodiversity of bedrock, waste covers, soils and the biodiversity of the indigenous flora. The high total solute load and hydrochemistry in waters indicate the share of ions coming from weathering processes and supplied by water from the thawing of permafrost and circulation in the active layer (Mazurek et al. in print). Crustally derived ions are released from the permafrost and carried to basins in the active layer by suprapermafrost groundwater. Depending on the geological structure and the diverse weathering processes in the catchment area of lakes, the solutions fed into tundra lakes, with surface and ground water, may have varying contents of crustal components. Hydrochemical mapping showed that sulphates, which are connected with anhydrites and gypsum rocks, are a good geoindicator of terrestrial ions provenance. In quantitative terms, of lower importance for the chemical composition is the marine aerosol (Na^+, Cl^-) and atmospheric (Na^+, Cl^-, SO_4^{2-})

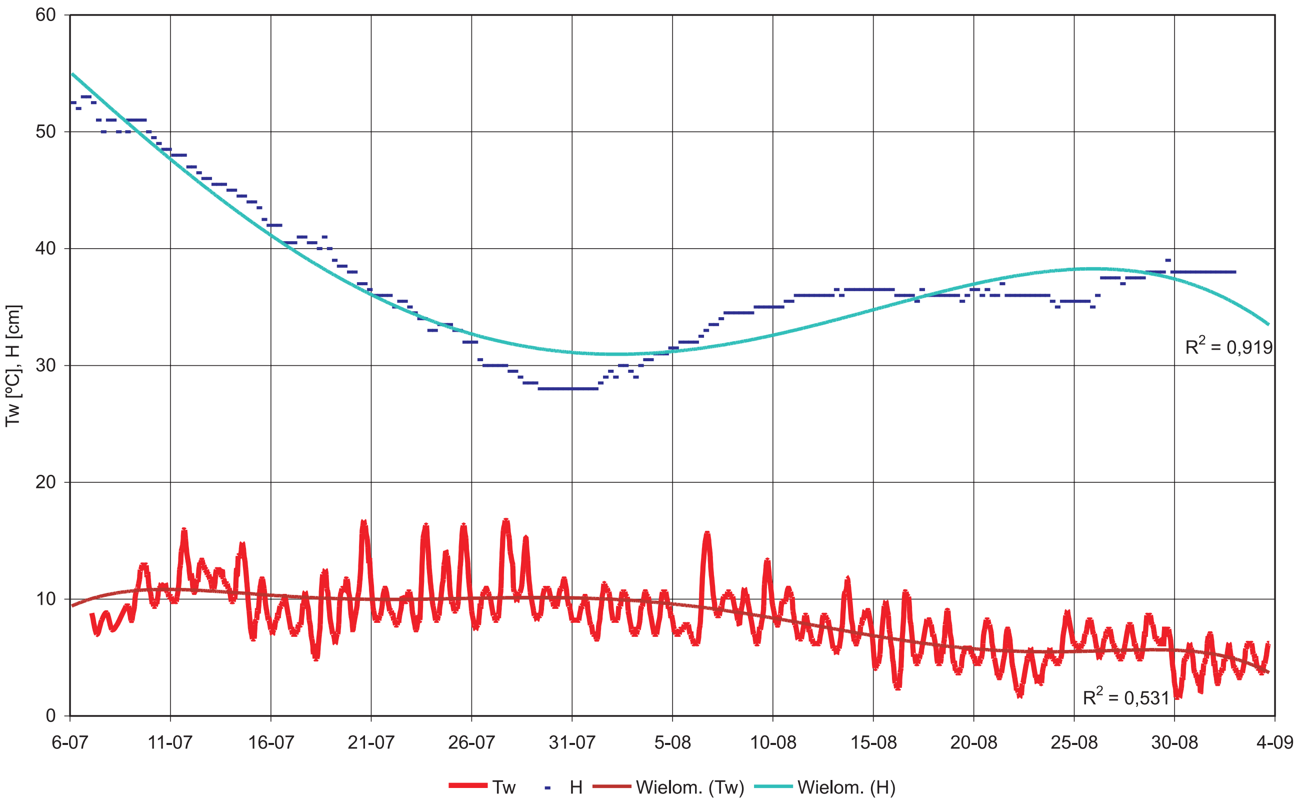

Fig. 4. Course of water level (H, four times per day) and water temperature (Tw, hourly intervals) in lake near Skottehytta during summer season 2006 (comp. Fig. 2)

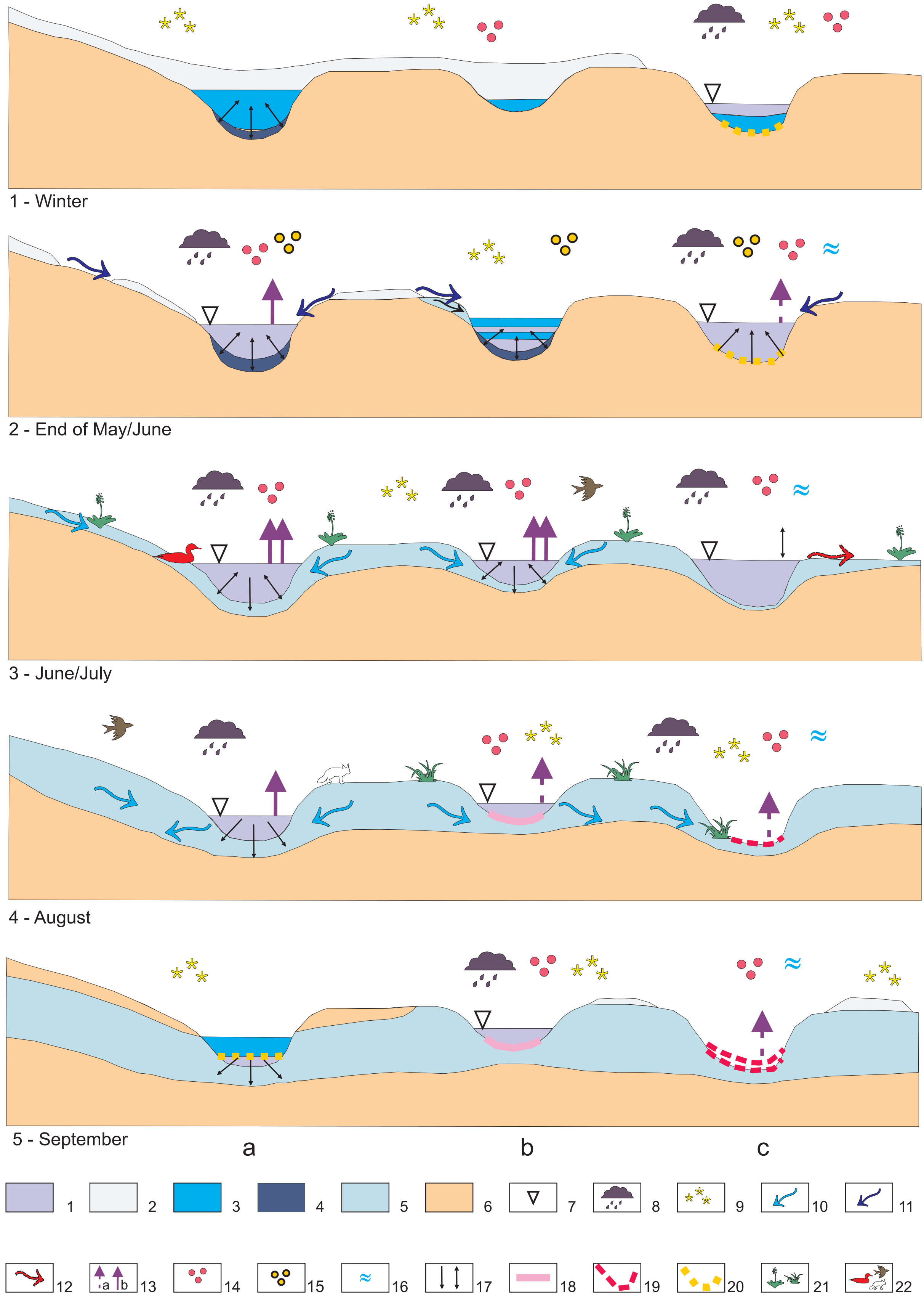

Fig. 5. Conceptualisation (1–5) and possible options (a-c) of input, transformation and output in context of matter flux within geoecosystems of tundra lake-like wetlands on raised marine terraces on Spitsbergen

1 – water, 2 – snow cover, 3 – ice, 4 – talik, 5 – active layer, 6 – frozen ground, 7 – water mark, 8 – rainfall, 9 – snowfall, 10 – subsurface runoff, 11 – surface runoff, 12 – episodic outflow, 13 – evaporation: a – low, b – high, 14 – wet and dry deposition, 15 – aeolian fallout, 16 – marine aerosol, 17 – matter exchange, 18 – mineral and organic sediments, 19 – precipitation of $CaCO_3$ and/or $CaSO_4$, 20 – cryochemical precipitation, 21 – tundra vegetation, 22 – animals.

supply, however these sources may modify the chemistry of waters in shallow terrace basins.

Saturated areas around lakes are often zones of richer tundra vegetation made up of various species of lichens, liverworts, moss, grass and herbs which are a source of components of biogenic origin. a factor that contributes to the eutrophication of soil and the resulting accelerated plant growth is the presence of birds around the surveyed lakes. Despite its slow rate, the decomposition of organic matter in the tundra ecosystem releases biogenic compounds, including sulphates, potassium and nitrates from waters feeding into lakes, in particular at the end of the polar summer.

The concentrations of most chemical components in the waters of the surveyed lakes display a slow increase from the beginning of the polar summer to the peak of the summer season. As the temperature rise, the water evaporates and the water table in the lakes is lowering, contributing to a gradual saturation of components. The soluble cations sequestered in near-surface permafrost comprise an important pool of solutes that may be released into the active layer during periods of deeper thaw (Kokelj, Burn 2003; Kokelj et al. 2005). As the permafrost table continues to degrade, the specific conductivity of lake water increases during the polar summer as did the share of calcium, magnesium, bicarbonate ions and sulphates. The highest specific conductivity values in water were observed at the time of decreases in air temperature and in the formation of the ice cover. The total loss of water in the basin results in a situation where the surface of lake deposits contains a large quantity of easily dissoluble constituents. During the precipitation period, these compounds may be washed inside deposits or may enrich waters in the succeeding phase of functioning of ponds.

The increase of air temperature leads to the melting of the first autumn ice cover and the relapse to the lower conductivity of water comparable with values preceding the formation of the ice cover. If the temperature falls below 0°C causing the lake freezing, the concentration of salt in the remaining bottom water strata increases due to cryochemical processes (Pulina 1990; Healy et al. 2006; Zwoliński 2007). The cryochemical processes lead to precipitation of calcite and gypsum crystals.

The sedimentation of autochthonous and allochthonous deposits, as well as the partial crystallisation of salts in lake basins is of particular significance for the creation of a present-day climax relief, aimed at levelling the topographical surface. The formation of such surface changes the hydrogeological conditions and reorganises the water runoff system from raised marine terraces. That occurs in spite of the fact that lakes are characterised by a relatively low dynamic and persistent morphogenetic and sedimentary systems.

Final remarks

Wetland geoecosystems on raised marine terraces operate only from June to August and occasionally to September each year. Factors such as the hydrological regime and water chemistry determine the development of Arctic wetlands on Petunia Bay coast in the dry climate zone of the High Arctic. Tundra pond levels usually fluctuate diurnally, seasonally and annually due to evaporation, groundwater recharge or seepage losses. They may evoke water level drawdowns which will result in partial drying and exposing the sediments. They may remain dry for several consecutive years, and consequently assume some characteristics of terrestrial geoecosystems until water levels are restored by above-average precipitation and runoff.

The gradual disappearance of lakes is pointed out by the morphological and sedimentological traces of their earlier extent. The bottoms of lakes, which are exposed to subaerial conditions, start to undergo other weathering processes and, with the participation of advancing tundra vegetation, develop under the influence of gradual pedogenic processes.

The chemistry of lake water on raised marine terraces of the eastern coast of Petuniabukta is influenced by the size of the surface catchment area, the type of substrate sediments (which include carbonate rocks and sediments) and the intensity of hydro-bio-geo-chemical processes occurring in the topsoil. Differences in the mineralisation and chemical composition of tundra lake water in catchments, with the significant thickness of permafrost active layer during the polar summer, result mainly from the supply of meltwater, from its degradation and from the thawing of snowcover. Due to low total of summer rainfall, the liquid precipitation in Arctic wetlands plays only a limited role.

The coastal wetlands of the Central Spitsbergen include, among others tundra lakes located in the zone of isostatically elevated coasts. a highly distinctive feature of the lakes is that they occur exclusively on the raised marine terraces. Due to their transitory location, the lakes are affected by the litoral and paraglacial geoecosystem and, on occasion, by the proglacial and glacial geoecosystem. Zwoliński (2002; 2007) classifies longer and shorter-term residence of minerals in the lakes as a part of the redeposition cascade found in the matter circulation system of the polar oasis. During its cycle, mineral matter undergoes various hydro-bio-geo-chemical transformations in solutions and diagenesis of muddy bottom sediments. The seasonal nature and the related hydrochemical dynamics of tundra lake water provide evidence of their role in the paraglacial evolution of mineral matter. Should be noted that in ecological terms, lake-like wetlands are the most lively systems from amongst geoecosystems distinguished by Kostrzewski et al. (2006a) in Ebbadalen.

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