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Water retention of arctic zone soils (Spitsbergen)

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A b s t r a c t. The water retention characteristics of the arctic zone soils ((TurbicCryosol (Skeletic), TurbicCryosols (Siltic, Skeletic) and BrunicTurbicCryosol (Arenic)) derived in different micro-relief forms were determined. Water retention curves were similar in their course for the mud boils, cell forms, and sorted circles *ie* for TurbicCryosols. For these forms, the mud boils showed the highest water retention ability, whereas the sorted circles – the lowest one. Water retention curves for the tundra polygons (Brunic TurbicCryosol, Arenic) were substantially different from these mentioned above. The tundra polygons were characterized by the lowest bulk density of 1.26 g cm^{-3}, whereas the sorted circles (TurbicCryosol, Skeletic) – the highest: 1.88 g cm^{-3}. Total porosity was the highest for the tundra polygons (52.4 and 55.5%) and the lowest – for the sorted circles (28.8 and 26.2%). Pore size distribution of the investigated soils showed that independently of depths, the highest content of large and medium pores was noticed for the tundra polygons *ie* 21.2-24.2 and 19.9-18.7%, respectively. The lowest content of large pores was observed for the cell forms (6.4-5.9%) whereas the mud boils exhibited the lowest amount of medium sized pores (12.2-10.4%) (both TurbicCryosols Siltic, Skeletic). The highest content of small pores was detected in the mud boils – 20.4 and 19.0%.

K e y w o r d s: soils, arctic zone, water retention, pore size distribution

INTRODUCTION

The hydrophysical properties of soils *ie* water retention and hydraulic conductivity in both saturated and unsaturated zones, shape the soil water balance. Humidity conditions in the soils exert a decisive influence on their thermal and mechanical properties that shape the temperature in the soil profile (Czudnowski, 1967; Kutilek and Nielsen, 1994; Lal and Shukla, 2004; Shein and Gonczarov, 2007; Walczak, 1977). Knowledge of the hydrophysical properties is necessary for interpretation and forecasting of practically all physical, chemical, and biological processes that occur in the soils, since modelling of these processes requires representative data on the soil hydrophysical characteristics (Olejnik and Kędziora, 1991; Raut *et al.,* 2012; Witkowska-Walczak *et al.,* 2004, 2012; Zawadzki, 1999).

The recent climate change started about the middle of 19th century. Currently the estimation of the initial period is a matter of general agreement and it is not strictly equal to local or regional observations. The observed warming has been greater over land than that over oceans. Since continents occupy larger areas on the northern hemisphere, there was a tendency for a higher temperature rise in the northern than in the southern hemisphere. Values of the average temperature rise also differ in accordance with differences in the climate of various regions. The rise is very small in the equatorial regions and it increases with latitude, both north and south. For example, in Central Europe, the average temperature increased between 1.1-1.3°C, whereas within the Arctic Circle at latitudes between 70 and 90°, the average rise was 2.1°C during 1880-2004 (Kirkham, 2011; Kutilek and Nielsen, 2010; Paltineau *et al*., 2012; Trenberth *et al*., 2007).

The rise of average temperature, especially in the arctic zone and specific periglacial conditions, initiated many scientific investigations in this terrain (Klimowicz *et al*., 2013; Świtoniak *et al*., 2013; Zagórski *et al*., 2012). One of such places is Svalbard Archipelago and its largest island – Spitsbergen. The island is characterized by a gentle climate, and the recent rise of air temperature is the cause of glacier thawing (Fisher and Skiba, 1993; Klimowicz *et al.,* 2008, 2009).

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The main processes in the arctic zone are cryogenic *ie* frozen segregation processes, swelling, shrinking and cracking, cryostatic stresses, frozen and gravitational slope movements (Angiel, 1994; Washburn, 1980). Consequently, there is a diversity of micro-relief surface forms as the result of the above-mentioned processes and the varied grain size distribution and water properties. The good conditions for biosphere development triggered soil-forming processes, especially on flat surfaces with low inclination (Bockheim, 1980; Klimowicz *et al*., 2008; Klimowicz and Uziak, 1996; Melke *et al.,* 1990; Tedrow, 1977).

The aim of this paper was to determine the water retention characteristics of the arctic soils derived in different micro-relief forms.

MATERIAL AND METHODS

The area of research covers the NW part of Wedel Jarlsberg Land (77°26' – 77°35'N and 13°55' – 14°54'E) (Klimowicz *et al*., 2008) (Fig. 1). The whole area is divided by lines of mountain ridges, between which there are valleys widening towards the sea, in its proximity creating vast plains in the form of marine terraces. Water retention was determined for the soils formed on four characteristic micro-relief surface forms (Tedrow, 1977; Washburn, 1980):

– Mud boils are circular and inconsiderable raised forms with a diameter between 50 and 70 cm. Very poor vegetation and their light grey colour, which can be seen from a long distance, make an impression of 'spots'. Therefore, larger surfaces of mud boils are often called the 'spotted' tundra or 'spotted' soils.
– Cell forms are flat 4-6-sided polygons with a diameter between 50 and 100 cm. They are neighbours of mud boils and sorted circles, but not so popularly. Fine rock material can be observed in the cracks around these forms. It is usually submerged in the detritus-soil material under the terrain surface. The shallow ground water level and anaerobic conditions promote gleyic processes.
– Sorted circles are very expressive forms in the landscape, especially these above the terrain surface. They are circular or elongated ramparts with a diameter between 100 and 300 cm. Their heights are different; some of them are flat, and the others can be located below the terrain surface.
– Tundra polygons are large surface forms. Their diameters are usually between several to dozen meters. They are shown by lines of ice wedges (or soil wedges) in which mineral and organic material is located. They are common forms in some surfaces of lower sea terraces.

The experimental fields were located within the micro-relief forms, described above. Soil pits were made, and profiles were described according to the WRB classification system (Jahn *et al.,* 2006). The soil profiles represented the following groups according to the WRB (IUSS Working Group WRB, 2007):

– TurbicCryosols (Skeletic) in sorted circles,
– TurbicCryosols (Siltic, Skeletic) in mud boils,
– TurbicCryosols (Siltic, Skeletic) in cell forms,
– Brunic[x]TurbicCryosols (Arenic) in tundra polygons ([x]Prefix "brunic" in the last case is not listed as a possible qualifier for Cryosols. However, it was used because soils meet the referring criteria).

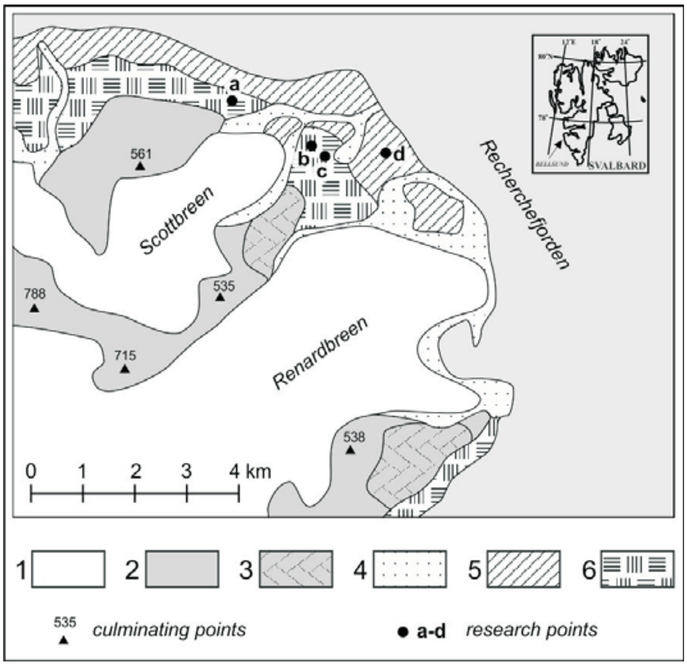

Fig. 1. Soil map of the investigated region (scheme), 1 – glaciers, 2 – formations without soil cover – massive rocks, rock debris, 3 – rendzinas – RendzicLeptosols (Gelic), 4 – formations without soil cover, mainly glacial and fluvioglacial deposits, locally initial and weakly developed soils, 5 – brown soils – BrunicCryosols (Arenic), 6 – gley soils – TurbicCryosols (Siltic, Skeletic).

T a b l e 1. Grain size distribution, bulk density and porosity of the investigated arctic soils

Micro-relief forms	Grain size distribution (%)										Bulk density (g cm^{-3})	Total porosity (%)
	Fraction (mm)											
	<0.002	0.002-0.005	0.005-0.02	0.02-0.05	0.05-0.1	0.1-0.25	0.25-0.5	0.5-1	1.0-2.0	>2.0		
	0-5 cm											
Mud boils	10	18	34	11	4	2	3	10	8	32	1.52	42.4
Cell forms	5	10	34	16	8	7	6	9	5	26	1.68	36.4
Sorted circles	4	7	19	8	5	9	15	22	11	29	1.88	28.8
Tundra polygons	0	1	4	8	8	8	13	34	24	18	1.26	52.4
	10-15 cm											
Mud boils	10	20	40	13	4	2	3	5	3	21	1.57	40.7
Cell forms	5	10	31	14	7	6	6	12	9	30	1.76	33.6
Sorted circles	4	7	21	9	5	8	16	20	10	22	1.94	26.2
Tundra polygons	0	1	8	12	10	9	14	27	19	18	1.18	55.5

The soil water static properties were measured on samples collected from the experimental fields in a disturbed and undisturbed state (in soil cores, h = 5 cm, dia = 5 cm) in 5 replications from two depths *ie* 0-5 and 10-15 cm. The soil samples were taken during four successive sunny days in June.

The grain size distribution was determined using the laser diffraction method (Ryżak and Bieganowski, 2013), bulk density – by the standard gravimetric method (drying in 105°C) (Table 1), specific density – by the standard method in a pycnometer, whereas total porosity was calculated on the basis of bulk and specific densities. The skeleton parts of arctic soils (gravel and stones) are additionally shown in Table 1.

The water retention curves *ie* the relationship between soil water potential and water content, were determined in a standard pressure chamber (SoilMoisture Comp., Santa Barbara, CA, USA) during the drying process at eight pressure values: 1 – 1 hPa, 2 – 10 hPa, 3 – 31 hPa, 4 – 100 hPa, 5 – 160 hPa, 6 – 500 hPa, 7 – 1 000 hPa, and 8 – 15 000 hPa, corresponding to the soil water potentials: -0.1, -1, -3.1, -7, -16, -50, -100 and -1 500 kJm^{-3}, respectively. All values of the water content are shown in volume units (% cm^3 cm^{-3}, % vol.).

The following groups of pores are distinguished on the basis of water retention curves and total porosity (Kutilek, 2011):

– large pores – dia > 50 μm (total porosity minus water content at -7 kJ m^{-3}),
– medium pores -50 μm > dia > 0.2 μm (water content at -7 kJ m^{-3} minus water content at -1 500 kJ m^{-3}),
– small pores – dia < 0.2 μm (water content at -1 500 kJ m^{-3}).

All statistical calculations were made by the STATISTICA program (SAS, 1989). The tables and figures show mean values.

RESULTS AND DISCUSSION

The static hydrophysical characteristics *ie* water retention curves or the relationship between soil water potential and water content, for the soils formed on the micro-relief forms are presented in Fig. 2. The data of water content are mean values; the standard deviations were not higher than ±1.4 % vol. for soil water potential higher than -7 kJ m^{-3} and ±0.6% vol. for the lower values of water potential.

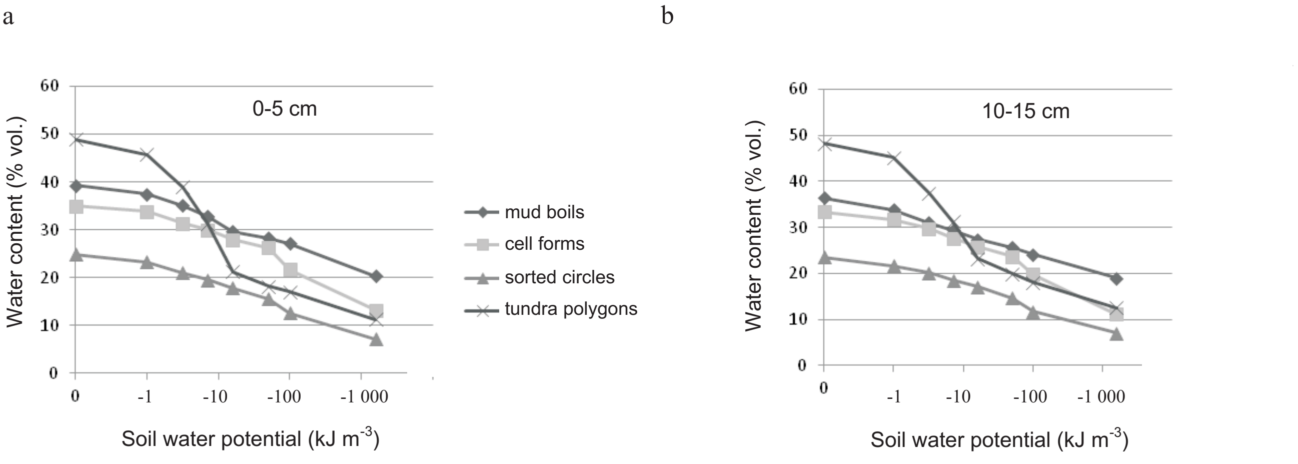

Fig. 2. Relationship between soil water potential and water content (% vol.) at: a – 0-5 and b – 10-15 cm for soils formed on different micro-relief forms.

The greatest ability to retain water at the 0-5 cm depth for the highest values of water potentials (-0.1 – -7 kJ m^{-3}) (Fig. 2) is shown by the tundra polygons (48.9-31.2% vol.), next by the mud boils (39.3-32.8% vol.) and cell forms (35.0-30.0% vol.), whereas the smallest ability is exhibited by the sorted circles (24.9-19.6% vol.). For the lower water potentials (-7 kJ m^{-3} – -1 500 kJ m^{-3}), the differences in water content for the forms vary from 30.0 to 13.2% vol. for the cell forms, 32.8-20.4% vol. for the mud boils, 31.2-11.3% vol. for the tundra polygons, and 19.6-7.2% vol. for the sorted circles, respectively.

At the 10-15 cm depth (Fig. 2), for the higher values of water potentials (-0.1 – -7 kJ m^{-3}), the shape of water retention curves is nearly the same for the upper soil layer, but the water content is lower. It varies between 48.2-31.3% vol. for the tundra polygons, 36.4-29.4% vol. for the mud boils, 33.4-27.7% vol. for the cell forms, and 23.6-18.5% vol. for the sorted circles. For the lower water potentials (-7 kJ m^{-3} – -1 500 kJ m^{-3}), the differences in water content vary from 48.2 to 31.1% vol. for the tundra polygons, 29.4 to 19.0% vol. for the mud boils, 27.7 to 11.2% vol. for the cell forms, and 23.6 to 18.5% vol. for the sorted circles, respectively.

The total porosity and content of differently sized pores are presented in Table 1 and Fig. 3. The analysis of the data in Table 1 indicates that the highest total porosity at both soil depths is exhibited by the tundra polygons, 52.4 and 55.5% respectively, whereas the lowest ones by the sorted circles – 28.8 and 26.2%. At 0-5 cm, the total porosity is higher for the mud boils (1.7%), cell forms (2.8%) and sorted circles (2.6%) than at 10-15 cm, and only for tundra polygons this relation is reverse *ie* the total porosity is higher at 10-15 cm (3.1%).

The pore size distribution shows that the highest amount of large pores (dia > 50 μm) was observed at both depths for the tundra polygons, 21.2% at 0-5 cm and 24.2% at 10-15 cm,

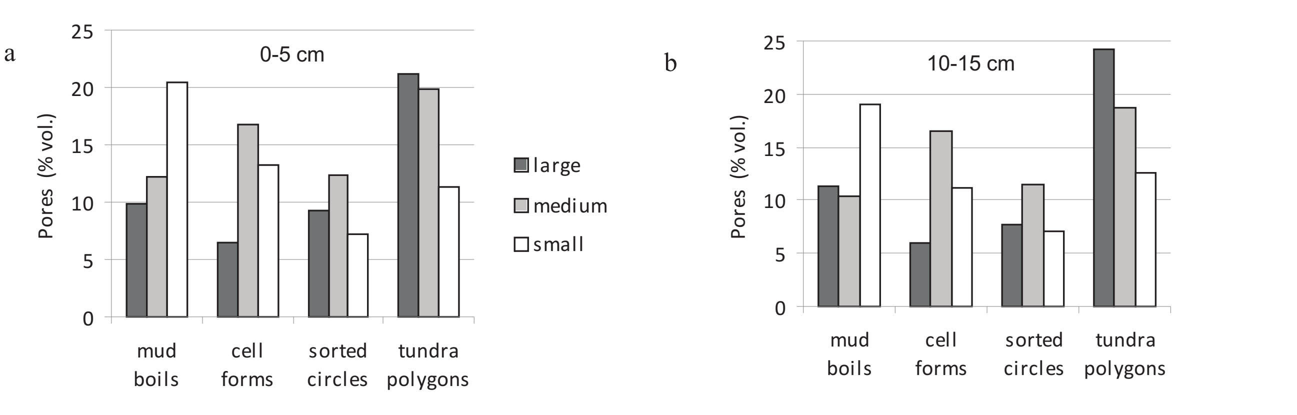

Fig. 3. Content of pores (% vol.) of different size at: a – 0-5 and b– 10-15 cm in the investigated micro-relief forms; large pores – dia > 50 μm, medium pores – 50 μm > dia > 0.2 μm, small pores – dia < 0.2 μm.

whereas the lowest ones for the cell forms – 6.4 and 5.9%. The mud boils and sorted circles had a medium content of large pores *ie* 9.8 and 11.3% at 0-5 cm and at 9.2 and 7.7%, 10-15 cm, respectively. This shows that the differences in the large pore content of the investigated micro-relief forms are significant, for example, their content in the tundra polygons and cell forms reached 14.8% at 0-5 cm and 18.3% at 10-15 cm, respectively.

The content of medium pores (50 μm > dia > 0.2 μm) is more homogeneous than that of the large pores. The highest values were found at both depths for the tundra polygons – 19.9 and 18.7%, and the lowest for mud boils, 12.2 and 10.4%, respectively. So the differences are less, at 0-5 cm -7.7 % between tundra polygons and mud boils whereas at 10-15 cm – 8.3%, respectively.

The content of small pores (dia < 0.2 μm) is relatively high in all the investigated micro-relief forms and exceeds 10%, except the sorted circles. The highest values at both depths are observed for the mud boils (20.4 and 19.0%), next for the cell forms (13.2 and 11.2%) and tundra polygons (11.3 and 12.6%), whereas the lowest ones – for the sorted circles – 7.2 and 7.1%, respectively. In this case, the differences in the amount of pores between the mud boils and sorted circles are much higher *ie* 13.2 % at 0-5 cm and 11.9% at 10-15 cm, respectively.

The analysis of the shapes of soil water retention curves for both depths (Fig. 2) shows that these are nearly the same. The retention curves for the mud boils, cell forms and sorted circles are nearly parallel in all cases, and the mud boils exhibit the highest, the cell forms medium, whereas the sorted circles the lowest moisture. The water retention curves of the tundra polygons have the highest moisture content at the highest water potentials whereas their moisture contents at potentials lower than -7 and -16 kJ m^{-3} decreases rapidly and they are placed between those for the cell forms and sorted circles.

Such courses of water retention curves for the soils derived on four micro-relief forms result in big differences in the water content, *ie* at 0-5 cm for -0.1 kJ m^{-3} – 24.0% vol., for -7 kJ m^{-3} and -1 500 kJ m^{-3} – 13.2% vol., whereas at 10-15 cm – 24.6, 12.8, and 11.9 % vol., respectively. This is undoubtedly caused by the grain size distribution and bulk densities of the soils (Table 1).

The most coarse parent material was found in the tundra polygons. It was coarse sand at the soil surface and slightly heavier coarse loamy sand below the surface. The amount of particles bigger than 2 mm in diameter was less than 18% mass, which significantly distinguished them from the other forms. In the sorted circles, a coarse sandy loam texture was found, which indicated in this case a significantly higher amount of gravel and stones. It should be taken into account that the test material was collected in this case 'inside' the circle, while the coarsest particles are deposited during periglacial processes in the outer ring of the mould. In both the structural grounds, as well as in the mud boils, the texture of silt loams was observed, the latter being characterized by a much higher proportion of the smallest parts. The share of the gravels and stones in both forms was high, reaching more than 30% mass.

The tundra polygons are characterized by the bulk density of 1.26 g cm^{-3} and the sorted circles 1.88 g cm^{-3}. The mud boils and cell forms have the mean values of bulk density – 1.52 and 1.68 g cm^{-3}. For the lower soil water potentials (lower than -7 kJ m^{-3}), the impact of bulk density is not so clear for soil water binding and the differences are lower (differences - 11.9% vol. at -16 kJ m^{-3} and 13.2% vol. at -1 500 kJ m^{-3}). In the 10-15 cm layers of the investigated soils, the amount of water retained at potentials lower than -7 kJ m^{-3} is the highest for the tundra polygons and the lowest for the sorted circles (differences: 24.6% vol. at -0.1 kJ m^{-3} and 12.8% vol. at -7 kJ m^{-3}). The tundra polygons are characterized by bulk density of 1.18 g cm^{-3}, whereas the sorted circles -1.94 g cm^{-3}. The mud boils and cell forms have bulk density of 1.57 and 1.76 g cm^{-3}, respectively, and the water content differences are 10.3% vol. at -16 kJ m^{-3} and 11.9% vol. at -1 500 kJ m^{-3}.

CONCLUSIONS

1. Water retention curves were similar in their course for the mud boils, cell forms and sorted circles *ie* for Turbic Cryosols. For these forms, the mud boils showed the highest water retention ability whereas the sorted circles – the lowest one.

2. Water retention curves for the tundra polygons (BrunicTurbicCryosol, Arenic) were strongly different from these mentioned above. For the high soil water potentials (higher than -7 kJ m^{-3}), they retained a considerably larger amount of water whereas for the potential lower than -7 – -16 kJ m^{-3}, their ability for water retention rapidly decreased and it was lower than that for the cell forms.

3. The tundra polygons (BrunicTurbicCryosol, Arenic) were characterized by the lowest bulk density of 1.26 g cm^{-3}, whereas the sorted circles (TurbicCryosol, Skeletic) – the highest 1.88 g cm^{-3}.

4. Total porosity was the highest for the tundra polygons (BrunicTurbicCryosol, Arenic) (52.4 and 55.5%) and the lowest for the sorted circles (TurbicCryosol, Skeletic) (28.8 and 26.2%).

5. Pore size distribution of the investigated soils showed that irrespective of depths, the highest content of large and medium pores was noticed for the tundra polygons (Brunic TurbicCryosol, Arenic): 21.2-24.2% and 19.9-18.7%, respectively. The lowest content of large pores was observed for the cell forms (6.4-5.9%) and the amount of medium pores – for the mud boils (12.2-10.4%) (both Siltic, Skeletic TurbicCryosols). The highest content of small pores was in the mud boils (Siltic, Skeletic TurbicCryosols) – 20.4 and 19.0%.

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