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Anomalous radioactivity level and high concentrations of heavy minerals in Lemme area, South-West Estonia

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Abstract As early as in the 1960s, extensive heavy-mineral concentrations containing zircon, monazite, and xenotime were discovered in the Lemme region of south-western Estonia. These concentrations contribute to the elevated radioactivity levels of the enclosing sediments. The near shore sands of the Litorina Sea contain up to 10-cm-thick interlayers with a heavy mineral content of up to 80%. These anomalous layers were formed during the transgressive phase and result from a complicated cross- and alongshore migration of sedimentary material, derived mainly from local Devonian bedrock. Radioactivity level in the study area is higher relative to the majority of the Devonian plateau. The Lemmeoja buried soil has 13 radiocarbon dates in an area of renewed interest for the investigation of the Baltic Sea history.

Keywords *• Radioactivity •Heavy minerals •Transgressions •Nearshore •Aeolian deposits*

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INTRODUCTION

Investigations of the concentrations of uranium and thorium in the bedrock of Estonia began immediately after World War II with studies of the alum shale (Pakerort Stage, Lower Ordovician) and phosphorite. As a result of these investigations, the Sillamäe region in North-East Estonia was deemed as a suitable area for refining uranium and Estonia became one of the largest uranium producers in Europe. Radioactive waste storage nowadays contains at least 1800 tons of uranium and 800 tons of thorium (Kaasik 2006).

During the opencast mining of phosphorite at Maardu area east of Tallinn, the radioactive alum shale (uranium content 80-120 g/t, maximum 300-450 g/t) was deposited in waste dumps (Table 1). At present, the waste hills at Maardu contain 73 million tons of alum shale. This means that even if we consider only the estimated minimum content of uranium (30 g per ton of alum shale), the 2.19 million kg of uranium could have leached into the surface and ground waters (Veski 1995).

The high radon concentrations (up to 12 400 Bq/m^3), on the levels dangerous to human health, have been recorded in dwellings on the outcrops of alum shale (Jüriado *et al.* 2011, 2012; Pahapill *et al.* 2003). The high radioactivity levels have been reported everywhere near the outcrops of alum shale in North Estonia, especially near the North-Estonian Klint (escarpment) and in the slopes of buried valleys (Raukas *et al.* 2007; Vaher *et al.* 2010). Moreover, the clasts and fines of radioactive alum shale occur in variable concentrations in the Quaternary deposits all over Estonia. In addition, the Quaternary deposits contain different proportions of granitoidal material rather rich in U, Th and K, which was transported to the Estonian territory from the outcrop areas of crystalline basement in Finland and the Gulf of Finland by glaciers. The elevated concentrations of uranium and thorium can be found in some varieties of Devonian

Table 1 The concentrations of radioactive elements in alum shale and phosphorite in Harju County, North Estonia (after Petersell *et al.* 2005, 2008).

Element	Regions			
	Western Harju County	Maardu	Kuusalu	Parent rocks of Estonian soil
In alum shale				
Uranium, ppm	86	36	84	2.1
Uranium (prevailing content), ppm	30–170	20–90	30–160	
Thorium, ppm	10	8	12	5.8
Potassium, %	5.9	6.2	5.1	1.86
In phosphorite				
Uranium, ppm		22	16	
Thorium, ppm		7	12	
Potassium, %		<0.2	<0.2	

sand- and siltstones, contributing to the higher radioactivity of Quaternary deposits. One of the areas with higher radioactivity is the Lemme area in SW Estonia, located in the southern border of Pärnu Bay in the eastern coast of Gulf of Riga. During the 1960s, in Lemme area were detected high radioactivity levels, caused by the high concentrations of heavy minerals such as zircon, monazite and xenotime. However, at that time, the radioactivity studies were considered to be classified as secret and top secret information and there were little known about the real situation. Due to the lack of the reliable data we reinvestigated the radioactivity of the Lemme area and this is one of the main novelties of the paper (Fig. 1).

In 1996, the Finnish Centre for Radiation and Nuclear Safety mapped the radioactivity dose rates near Estonian roads. The study found an elevated radioactivity area near the Lemme Brook (Ylätalo *et al.* 1996). Aerogeophysical studies in the early nineties suggested higher radioactivity level also in several other parts of the Devonian plateau. In 2005, Rein Koch (2006) studied the "black sand" on the seashore at Lemme, in which he detected elevated content of U-238 and Th-232. In 2011, Rein Koch and Krista Jüriado investigated the radioactivity and radon levels nearby the Lemme Brook. In order to elucidate the higher radioactivity levels, the mineralogical research team was in 2012 extended by Anto Raukas who has investigated the heavy mineral content of beach and dune sands here already in the 1960s. In 2013, Johanna-Iisebel Järvelill joined to the mineralogical research.

LOCATION, TOPOGRAPHY AND GEOLOGICAL SETTING

Lemmeoja River (Lemme Brook, Orajõgi River or Lemme River) is a rather small river. It flows from the Nigula Bog and drains south of Kabli into the Gulf of Riga. Its length is 23 km and it's the catchment area 57 km^2.

The Eifelian sandstone of the Aruküla Regional Stage of the Middle Devonian, covered with a thin layer of the reddish-brown till of the last glaciation, crops out near the mouth of the river. In the Lemme area, the hilly aeolian topography is about 450 m wide and extends from the sea in the west to the till plain in the east. The dune sands of the Ancylus, Litorina and Limnea stages overlap, forming a narrow meridionally elongated strip (Fig. 2). The dunes of the Limnea age are situated mainly to the west from the Heinaste–Häädemeeste highway, while the older dunes are located on the east of the highway. The clear boundary between the Ancylus and Litorina dunes is absent.

About 350 m from the river mouth (Fig. 1) and within a stretch of 50 m on both banks (Fig 3.), occurs a 20-cm-thick layer of buried soil, formed during the Yoldia regression. The buried Molli- Histic Glaysol at a depth of 342–380 cm has been studied and dated several times (Kessel, Raukas 1967; Haila, Raukas 1992; Reintam *et al.* 2001), including the international project "Geology of the Baltic Sea and the influence of the ice sheets on the structure of the Quaternary cover", which was organized by the Academy of Sciences of the USSR and Academy of Finland during the 1983–1989. Gleysol was formed over the 1500–200 years during the Younger Dryas and Pre-Boreal, with an average accumulation rate of organic carbon of 5.3-2.5 g m^{-2} yr^{-1} (Reintam *et al.* 2001). Based on the ^{14}C dates (Table 2), the Ancylus transgression started some 9500 ^{14}C years ago and culminated in the Lemme area about 9200–9000 ^{14}C years ago. Already in 1981, the Lemme area was proposed (Kessel, Raukas 1981) and later accepted as areal stratotype of the Ancylus Lake and Litorina Sea deposits.

The till below the buried soil and aeolian sediments is rather thin (2–3 m) and has a reddish-brown colour typical for southwestern Estonia, while under the buried soil it is purplish-grey. Sandy loam matrix contains a moderate amount of pebbles (about 9000 in cubic metre), mainly (80–85%) from carbonate rocks (among them about 30–35% dolostones). Igne-

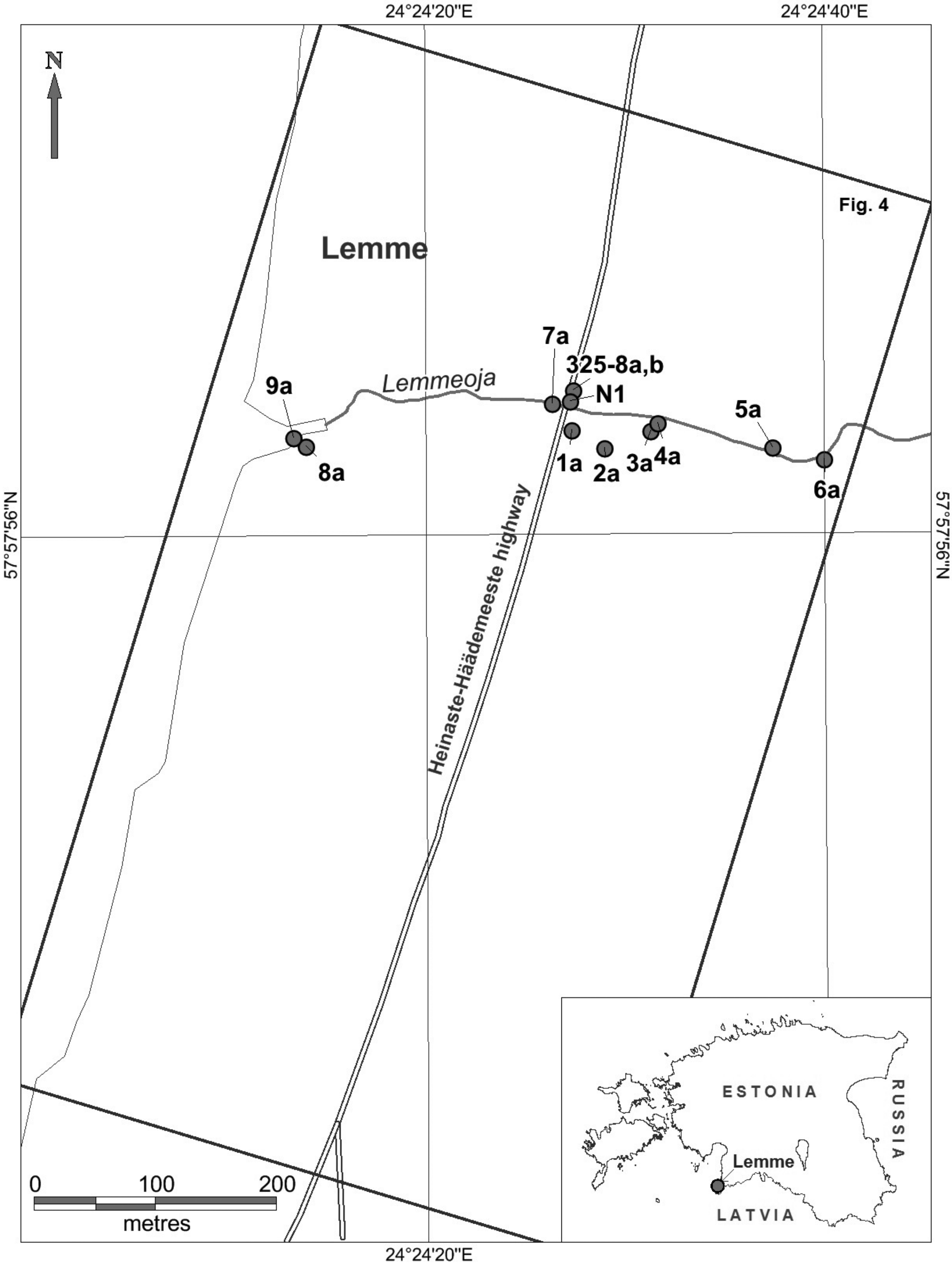

Fig. 1 Location of the Lemme site (325–8a and 8b sample points are from 1965, 1a–9a sample points are from 2011, N1 sample point is from 2012. Point 1a is situated on the top of the wall beside to the road; point 2a is situated somewhere away from the Lemme Brook; points 3a, 5a, 6a are situated on the bank of the Lemme Brook; points 4a and 7a are situated on the bed of the Lemme Brook; points 8a and 9a are situated on the shore).

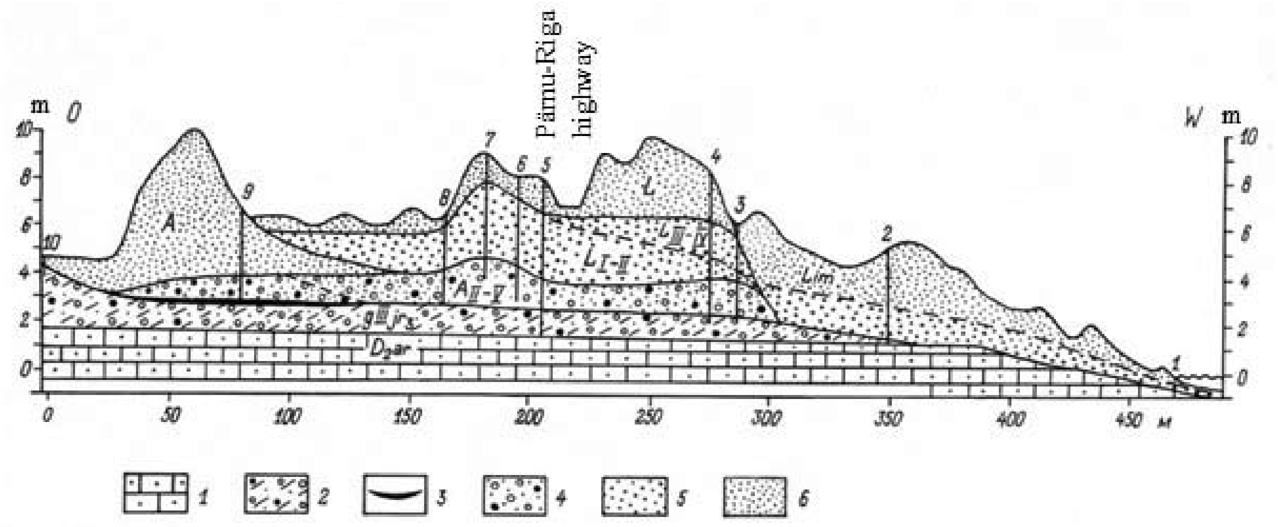

Fig. 2 Cross-section along the Lemme Brook from east to west (after Kessel and Raukas 1967): 1–Devonian sandstones of the Aruküla Regional Stage; 2–till; 3–buried Molli-Histic Gleysol on till beneath sand; 4–gravel; 5–nearshore and beach sand; 6–aeolian sand. Numbers show location of drillings in 1964. Abbreviations: A–Ancylus Lake; Lit–Litorina Sea; Lim–Limnea Sea.

Table 2 Results of radiocarbon dating of the buried soil in Lemmeoja section. Dates were calibrated with using OxCal programme (Bronk Ramsey 2009).

No	Lab. index	^{14}C date	Calibrated age using OxCal (95.4%)
1	TA-123	9100±85	10515-9944
2	TA-122	9240±85	10650-10236
3	Tln-130	9820±130	11751-10775
4	Hel-2208A	9440±100	11105-10415
5	Hel-2208B (by humus)	9430±100	11105-10404
6	Tln-2559	8098±77	9279-8725
7	Tln-2566	8294±75	9470-9034
8	Tln-2561	8773±82	10152-9552
9	Tln-2570	8945±82	10241-9774
10	Tln-2572	9094±61	10480-10179
11	Tln-2564	9162±84	10555-10198
12	Tln-2589	9503±82	11125-10574
13	Tln-2590	9396±75	11068-10306

ous and metamorphic rocks, mainly granites, account for 15–18%, another part consists of Devonian sandstones. The average content of heavy minerals in fine sand fraction (0.1–0.25 mm) of till is 1.5–1.8%.

The buried soil occurs in a large territory, covering at least several hectares. The average thickness of the organic layer is about 20 cm. The organic layer is covered with a gravelly layer of 1–2 m thick transgressive Ancylus Lake (Fig. 2). In some sections this layer is lacking. Compared to till, the gravelly layer contains much more pebbles (1–10 cm) and cobbles (10–100 cm) of igneous and metamorphic rocks (33–59%). This is due to the fact that igneous rocks are much harder than local sedimentary rocks. The distribution of different groups of igneous rocks and indicator boulders in till and beach deposits is similar. Both sediment types contain rapakivi granite from Southwest Finland, which means that sandy-gravelly layer has been formed due to rewashing of the till. The average content of heavy minerals in fine sand fraction of gravelly beach deposits is 1.78%.

It is rather difficult to differentiate nearshore and aeolian sands in the study area. The thickness of aeolian sands is up to 6–7 m. The aeolian sands have been derived from the local source material, while dunes commenced immediately after the source deposits became available on the shore. The process stopped when the dunes became overgrown with vegetation. In the Lemme area, the grain-size composition of different sands is similar. Some sections are characterised by a more or less equal content of fine- (0.1–0.25 mm) and medium-grained (0.25–0.50 mm) sand, but in most cases fine sand clearly prevails (up to 89%). The content of coarse (0.5–1.0 mm) sand is less than

Fig. 3 Molli-Histic Glaysol covered with aeolian sands in 1999. Photo by L. Reintam.

10% and the content of silt fractions is mostly below 3%. The bimineral sands are well-sorted (So 1.4–1.6, Md 0.17–0.31) and consist mainly of quartz (in fine sand 71 - 94%) and feldspars (6–22%). Minerals of heavy subfraction occur in relatively small amounts (0.74–4.4, mainly about 1.5%). The content of weathering-resistant minerals (quartz, garnets, zircone, etc.) in aeolian sands is somewhat higher, while that of lamellate and tabular minerals (especially micas and chlorites) is lower than in the initial beach deposits (Raukas, 1968). The average chemical composition from the seven analyses of aeolian deposits is as follows: SiO_2 89.5%; Al_2O_3 4.41%; TiO_2 0.40%; Fe_2O_3 1.09%; FeO 0.34%; CaO 1.86%; MgO 0.42%; K_2O 1.32%; Na_2O 0.47 %.

REVIEW OF EARLIER STUDIES

In the early 1960s, the high concentrations of heavy (more than 2.89 Mg/m^3) minerals, mainly ilmenite and garnets with admixture of zircone, monazite and xenotime, were detected over a vast area at both sides of the Lemme Brook causing relatively high radioactivity levels (Luntz, Maiore 1960; Luntz 1962; Raukas 1964; Kessel, Raukas 1967). The highest concentrations of heavy minerals were found in the fine- and medium-grained nearshore sands of the Litorina Sea transgressive accumulative terrace. Owing to the moderate uplift of the Earth's crust shoreline (Raukas, Hyvärinen 1992), the study area was rather stable during the transgressions. Therefore the transgressive coastal formations are thicker and the coastal relief forms are characterized by a greater clarity than the regressive ones. Because of the stable shoreline, the material concentrated into a narrow zone. In the course of regressive stages, the shoreline retreated rapidly and beach erosion was less intensive, resulting in the lower production and deposition of the matter.

Also, the deposits of the transgressive phases of the Baltic Sea are more reworked than those of the regressive phases. In the course of the invasion by the sea, the migration of the sediments up to the shore slope caused a more intense mechanical and mineralogical differentiation of their composition. This, in its turn, lead to the accumulation of heavy minerals. The enrichment conditions were particularly favourable in the areas where vertical shift of material was accompanied by a longshore transport (i.e. Lemme area).

The sections contain several, up to tens of centimetres thick layers rich in heavy minerals. The layers at the seaward side of the beach ridges are thicker, more frequent and with higher concentrations of heavy minerals (up to 80%). In some sections of the 1.5–3-m thick sand, the content of heavy minerals is up to 40%. Such anomalous layers, formed during the transgression of the Litorina Sea, represent the result of a complicated cross- and alongshore migration of the sedimentary material, mostly the enriched local Devonian rocks. Based on the 23 analyses from the layers with the heavy mineral content of 5–60% (25.5% in average), Luntz and Maiore (1960) estimated the average monazite content in fine sands as 0.13%. In addition, the spectral analyses indicated following concentrations of heavy metals: Ti 0.2-0.5%, Zr and Y 0.01-0.2%, Yb 0.01-0.05% and Ga 0.001%.

During the field studies in 1964–1966 and 2011–2012, all types of sediments along the river valley from west to east as well as along the Heinaste-Häädemeeste highway from north to south were investigated (Fig. 4).

In 1964-1966, the prevailing fraction 0.25–0.1 mm was investigated using the immersion method (Table 3). The light mineral suite of medium and fine sand consisted mainly of quartz whose content decreased simultaneously with an increase in the content of feldspars in more dispersed fractions. Micas were preserved mostly in very fine sand. Different aggregates and some fragments of phosphatic

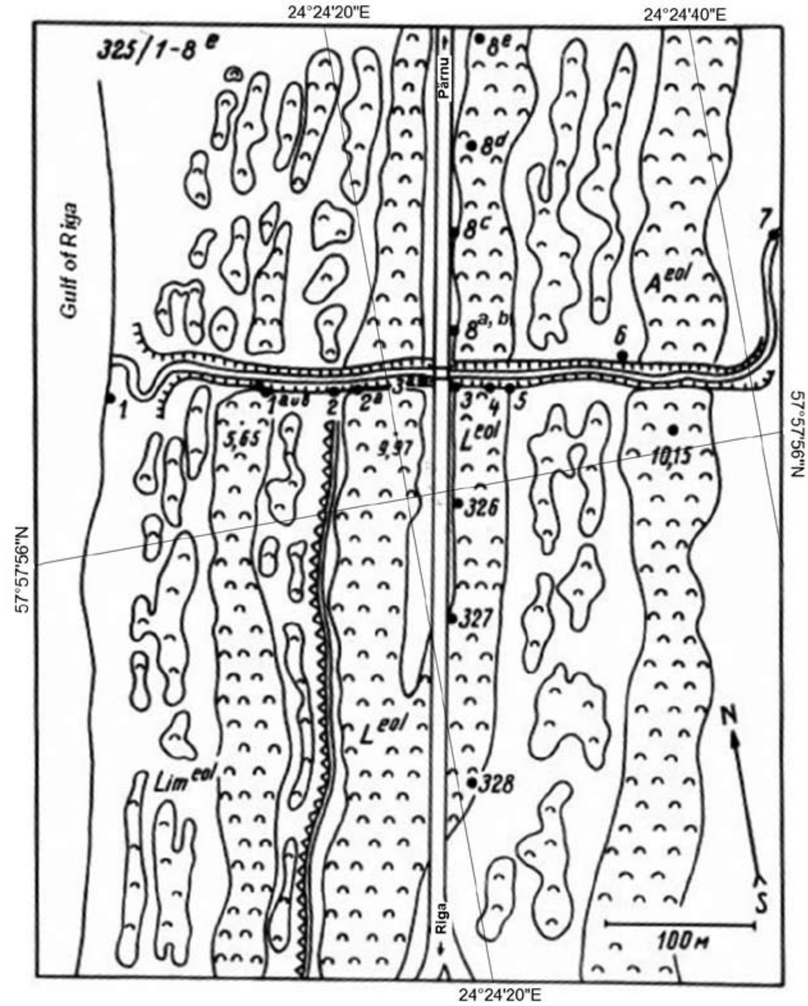

Fig. 4 Location of investigated in 1964–1966 excavations in sand ridges along the Heinaste-Häädemeeste highway.

mollusc shells were also present. Some rare glauconite, chalcedony, and carbonates were occasionally found. Among the feldspars, orthoclase (65-89%) predominated in all mineral suites. Content of placioclases was 10-23%, but microcline content was small.

In the heavy subfraction, over 40 different minerals or mineral groups were detected. The most abundant were garnets (19.9-78.0%). The magnetite-ilmenite and hematite-limonite content was 10-18% and up to 5%, respectively. The content of amphiboles (1.4-49.8%) and pyroxenes (0.3-6.2%) was variable. Zircon and monazite content fluctuated from 0.8 to 2.8%, with higher concentrations in Litorina Sea beach deposits and silt fractions. Tourmaline, epidote, staurolite, andalusite, sillimanite, apatite, titanite, topaz and tsoisite were presented in small amounts (less than 1% of the heavy subfraction).

Initial Devonian rocks of the Aruküla Regional Stage consisted predominantly of quartzose and feldspatic arenite with the quartz content of 60-90%. The heavy subfraction was dominated by ilmenite (30-60%) and transparent allothigenic minerals (15-

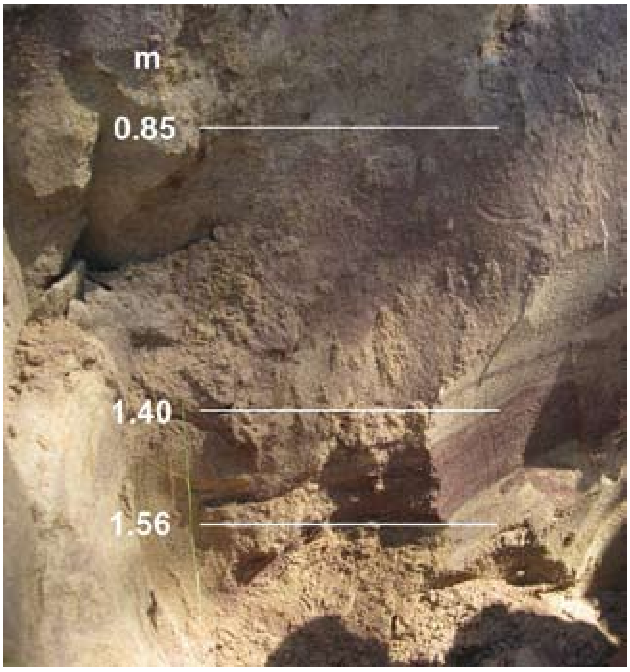

Fig. 5 Reddish interlayer (dark layer) with high content of heavy minerals at a depth 1.40–1.56 m from excavation N1. Photo by K. Jüriado in 2012.

Table 3 Simplified mineral composition of nearsore and aeolian sands (fraction 0.25-0.1 mm) in Lemme area, %. Analysed by A. Raukas, 1964.

No	325-1	325-1a	325-2	325-4	325-6	325-8a	325-8b	325-8c	325-8d	326
Genesis, depth and age	I	II	III	IV	V	VI	VII	VIII	IX	X
Minerals	Light subfraction (density below 2.89 Mg/m^3)									
Quartz	83.2	89.4	93.8	93.4	86.9	88.8	89.3	91.5	91.2	93.5
Feldspars	14.8	10.1	6.2	6.2	11.9	11.2	10.7	8.5	8.8	5.5
Micas	2.0	0.5	-	0.4	1.2	-	-	-	-	1.0
	Heavy subfraction (density above 2.89 Mg/m^3)									
Hematite, limonite	2.4	0.8	4.7	0.6	0,8	0.5	1.2	0.3	1.0	0.9
Magnetite, ilmenite	16.4	17.8	14.7	16.3	14.0	16.0	8.3	14.3	16.5	18.7
Leukoxene	0.9	1.7	0.3	0.2	0.8	0.5	0.3	0.3	0.7	-
Garnets	48.8	39.9	19.9	75,6	55.6	75.9	73.4	78.0	76.8	67.7
Amphiboles	22.7	29.5	49.8	3.0	19.2	2.9	11.3	2.7	1.4	6.1
Pyroxenes	3.3	3.0	3.2	1.8	6.2	0.7	1.8	2.2	0.3	1.8
Zircon, monazite	1.2	1.7	2.8	0.9	1.6	1.0	1.2	0.8	1,4	2.4
Tourmaline	1.2	0.8	0.9	-	0.4	0.2	0.3	-	0.3	0.3
Other minerals	3.1	4.8	3.7	1.6	1.4	2.3	2.2	1.9	2.9	2.1
Md	0.17	0.22	0.28	0.31	0.26	0.20	0.21	0.19	0.21	0.25
So	1.48	1.44	1.50	1.40	1.61	1.55	1.55	1.47	1.61	1.58
Sk	1.39	0.89	0.74	0.83	0.87	1.20	0.91	0.86	0.84	0.78
Heavy subfraction content	1.2	1.4	1.3	37.2	2.0	1.6	7.8	1.4	2.1	1.7

I–Contemporary beach deposits, 0–0.3 m; II–Aeolian sand of the Limnea Sea, 1.4-1.6 m; III–Aeolian sand of the Litorina Sea, 1.0-1.5 m; IV–Interlayer of heavy minerals in nearshore deposits of the Litorina Sea, 1.4-1.6 m; V–Aeolian deposits of the Ancylus Lake, 2,5-2,6 m; VI–Nearshore deposits of the Litorina Sea with low content of heavy minerals, 1.85-1.95 m; VII–Nearshore deposits of the Litorina Sea, 1.2-1.75; VIII–Nearshore deposits of the Litorina Sea, 0.7-0.9 m; IX–Nearshore deposits of the Litorina Sea, 0.5-0.7 m, X–Nearshore deposits of the Litorina Sea, 0.8-1.0 m.

Table 4 Geological description of the section 325-8a.

Depth, m	Layers description
0-0.60	soil
0.60-1.20	pinkish (from the garnet content) fine sand with thin (0,2 – 0, 5 cm) reddish interlayers of heavy minerals
1.20-1.75	the same with abundant interlayers of heavy minerals up to 3 cm in thickness
1.75-1.85	interlayer with high content (61,6%) of heavy minerals
1.85-1.95	yellowish-grey fine sand with low (1,6%) content of heavy minerals
1.95-2.65	pinkish fine sand with abundant interlayers of heavy minerals up to 8 cm in thickness with heavy minerals concentration up to 77%
2.65-3.25	yellowish-grey medium-grain sand with gravel and rare thin (up to 3 cm) interlayers of heavy minerals
3.25-3.40+	gravel

Table 5 Geological description of the section N1.

Depth, m	Layers description
0-0.50	soil
0.50-0.85	pinkish (from the garnet content) fine sand, at the depth 0.72-0.84 reddish interlayer of heavy minerals
0.85-1.40	yellowish-grey, in places pinkish fine sand
1.40-1.56	reddish interlayer of heavy minerals
1.56-1.90	yellowish-grey fine sand
1.90-2.50+	pinkish fine sand with reddish interlayers

40%). Among the latter, garnet and zircon were the most significant, however, also tourmaline and rutile were also found in important quantities. On the lower boundary of the formation, the content of zircon and apatite increased significantly, and staurolite appeared (Kleesment, Mark-Kurik 1997).

The highest concentrations were established in the Litorina terrace close to the river valley located about 50 m to the north (sections 325-8a and b). The elevated concentrations of heavy minerals in the Litorina terrace were detected in north-south direction at the distance at least 1.8 km.

Table 6 Samples from excavation N1.

Sample	Depth, m	Description
Sample 1	2.50	yellowish grey fine sand
Sample 2	0.5-2.5	full section
Sample 3	0.5-1.4	interval
Sample 4	1.4-1.56	reddish interlayer
Sample 5	0.72-0.84	reddish interlayer
Sample 6	0.50-0.85	pinkish fine sand
Sample 7	1.56-1.90	yellowish-grey fine sand

In the excavation 325-8a in 1964 following layers were opened (Table 4).

RESULTS AND STUDY METHODS IN 2011–2012

In 2011 and 2012, the radioactivity levels were in more detail measured in a wide area as well as along the banks of Lemme Brook. In 2011, 13 samples were collected (Table 8, 9) from sampling points (Fig 1, points 1a-9a). Samples were submitted for the laboratory measurements.

Excavation N1 (Fig. 5) near the former (Fig. 1) excavation 325-8a was done in 2012 in order to study mineral composition and radioactivity level below the surface.

In the excavation N1 in 2012, following layers were opened (Table 5).

From excavation N1 seven samples for the laboratory measurements were taken (Table 6).

In 2011 and 2012, the radioactivity was measured from the surface in the whole Lemme area using the microprocessor controlled radiation dose rate and dose meter DGM-1500 (Kata Electronics OY, Finland).

Radon in soil air (kBq/m^3) was measured 2011 using the MARKUS-10 emanometer with RM3-B radon monitor (Studsvik AB, Sweden). The samples for these measurements were collected from several depths in different points of the region.

The samples for the activity concentrations measurements were dried at 105 °C and weighed. From each sample, an aliquot part was closed airtight in ca 55 cm^3 metallic beaker and let stay for at least 28 days to form a secular equilibrium between Rn-222 and its progeny. When dried, the remaining sample material was sieved by Retsch AS200 sieve set into seven fractions: >500μm, >250μm, >150μm, >106μm, >75μm, >38μm and 0-38μm.

Hermetically sealed beakers were analysed by gamma ray spectroscopy. The analysis was performed by the coaxial HPGe (high purity germanium) detector GEM- 35200 (EG&G Ortec). The resulting spectra were analyzed using the IAEA analysis program GANAAS. The spectrometer was calibrated using IAEA standard sources RGU-1, RGTh-1 and RGK-1. The content of Th-232 in the sample was determined using the gamma lines of Th-232 daughter nuclides of Ac-228, Bi-212 and Tl-208. The content of U-238 was determined using gamma lines of Ra-226 daughter nuclides Pb-214 and Bi-214, under the assumption that the U-238 is in secular equilibrium with the daughter nuclide Ra-226, as it was found to be in Lemme area coastal sands (Koch, 2006). The content of K-40 was determined using the 1460.7 keV emission gamma line.

The mineral composition of 7 samples from excavation N1 was investigated from the 0.106-0.15 mm fraction using the immersion liquids and a polarized microscope with the plane-and cross-polarized transmission light (PM). The light and heavy (over 2.89 Mg/m^3) mineral suites were separated. Altogether about 300 mineral grains for the light subfraction and 400 grains for the heavy subfraction were counted in each mineral suite and the results were expressed in the percentages of the respective fraction.

DISCUSSION

Radioactivity

Higher values of dose rate γ= 0.8-1.1 μSv/h were measured at the surface on top of the sand wall located east from the road. The wall consists of surface layer, which was probably piled up during the road construction. The highest value of dose rate, 1.4 μSv/h, was measured from excavation N1 (Photo 2, dark layer). Dose rates from other measurement points ranged between 0.08–0.12 μSv/h. The radon level in soil air, measured on this area at 2011, was low, only 10–11 kBq/m^3.

The results of grain-size analyses (Table 8, 10), except the sample 7a from Table 8, show that the main diameter of sand particles in the sand samples were mainly in the range of >250 μm and >150 μm. The same distribution of sand grain sizes was measured from samples of Lemme area earlier by A. Raukas (1964) as well as in the coastal sand of Lemme area by R. Koch (2006).

In 2011, the activity concentrations of U-238 (Ra-226) (Table 7) are below the mean concentration (26 Bq/kg) of U-238 (Ra-226) in Estonian soils (Realo *et al.* 1995). The exceptions with higher U-238 (Ra-226) values were three samples: the sampling point 1a (115.48 Bq/kg) from depth of 12cm and (154.95 Bq/kg) from depth of 30 cm and sampling point 7a (29.82 Bq/kg).

The low values of the activity concentrations of U-238 (Ra-226) were detected also in samples from the main coastal sand of Lemme area (Koch, 2006). When compared with other sampling points, the activity concentrations of Th-232 is much higher in the sampling point 1a from depth of 12 cm (493.14 Bq/kg) and (713.87 Bq/kg) from depth of 30 cm and in sampling point 7a (105.59 Bq/kg). The sampling point 1a is situated on top of the wall located east from the road to the east, and represents the point with the high value of dose rate (γ= 0.8 µSv/h). The sampling point 7a is situated on Lemmeoja bed.

Considering the fact that one ppm eU and eTh corresponds to 12.3 Bq/kg and 4.0 Bq/kg, the calculated contents of U-238 and Th-232 in sample for sampling point 1a (30 cm depth) is12.6 ppm for eU and 178.5 ppm for eTh. The activity concentrations of Th-232 from other sampling points remain below the mean Th-232 content (24 Bq/kg) for Estonian soils (Realo *et al*. 1995). The low values of the activity concentrations of Th-232 were measured also in the samples from shore sands of the Lemme area (Koch 2006). The activity concentrations of K-40 remain within the limits that were measured for Estonian coastal sands (Koch 2006) and do not differ much from the activity concentrations of K-40 in various types of sand from different parts of the world (Seddeek 2005).

The depth profile from sampling point 2a indicate that the content of U(Ra) is rather high even along this profile. However, at the same time, the contents of Th-232 and K-40 show different depth trends. The content of Th-232 increases while the content of K-40 decreases with the increasing depth. This may

Table 7 The results of gamma spectrometric analyses of 2011 year samples. The activity concentration of radionuclides is given in Bq/kg. Analysed by R. Koch, 2012.

	Sample 1a, 12cm	Sample 1a, 30cm	Sample 2a, clay	Sample 2a, 25cm	Sample 2a, 60cm	Sample 2a, 1m	Sample 3a, 10cm	Sample 4a	Sample 5a	Sample 6a	Sample 7a	Sample 8a	Sample 9a
Ra-226	115.48	154.95	13.87	15.81	15.36	13.97	16.36	11.54	27.12	18.69	29.82	14.68	14.99
Th-232	493.14	713.87	23.57	35.85	27.84	15.18	21.99	14.18	28.47	25.02	105.59	14.78	10.74
K-40	235.25	74.95	122.81	92.05	116.39	156.46	216.71	229.55	255.23	170.09	147.28	256.76	103.81
Th/U	4.27	4.61	1.70	2.27	1.81	1.09	1.34	1.23	1.05	1.34	3.54	1.01	0.72

Table 8 The percentage of separate grain-size fractions in bulk sample in 2011 analyses. Analysed by R. Koch, 2012.

Grain size	Sample 1a, 12cm	Sample 1a, 30cm	Sample 2a, clay	Sample 2a, 25cm	Sample 2a, 60cm	Sample 2a, 1m	Sample 3a, 10cm	Sample 4a	Sample 5a	Sample 6a	Sample 7a	Sample 8a	Sample 9a
>500 µm	3.793	1.038	6.570	7.377	3.728	21.651	34.163	29.859	36.033	9.214	70.298	1.334	0.104
>250 µm	49.255	59.061	41.243	57.023	55.306	43.914	23.875	29.997	25.234	38.450	18.945	34.382	34.071
>150 µm	42.781	38.504	46.646	30.709	37.815	30.929	25.119	25.088	21.886	42.267	7.638	53.219	64.115
>106 µm	2.483	1.584	3.721	2.494	1.849	2.342	10.547	9.695	7.415	6.482	1.951	8.410	1.452
>75 µm	1.132	0.153	0.613	0.926	0.342	0.361	4.025	3.666	3.852	1.744	0.756	1.925	0.078
>38 µm	0.000	0.109	0.277	0.796	0.442	0.564	1.434	1.243	3.528	1.152	0.302	0.520	0.009
0.38 µm	0.000	0.000	0.515	0.382	0.397	0.000	0.354	0.245	1.476	0.378	0.041	0.134	0.000

Table 9 The content of radionuclides (Bq/kg) in bulk samples which is obtained by the gamma spectrometric analyses of 2012 year excavation N1 samples. Analysed by R. Koch, 2013.

	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Ra-226	55.48	60.15	83.08	154.09	128.10	110.43	25,61
Th-232	135.22	173.23	246.91	533.86	402.78	360.28	55,74
K-40	194.43	193.36	159.18	108.56	126.75	13763	236,05
Th/U	2.44	2.88	2.97	3.46	3.14	3.26	2,18

Table 10 The percentage of separate grain-size fraction in bulk sample for 2012 year excavation N1 samples. Analysed by R. Koch, 2013.

Grain size	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
>1500 µm		2.178					
>500 µm	15.908	4.787	1.745	4.188	1.023	0.947	3.670
>250 µm	68.719	68.449	62.179	61.941	63.883	50.663	65.079
>150 µm	15.918	22.692	34.385	31.831	33.920	47.631	29.469
>106 µm	1.308	0.581	1.422	1.849	0.941	1.069	1.454
>75 µm	0.064	0.129	0.108	0.054	0.083	0.078	0.114
>38 µm	0.044	0.114	0.037	0.011	0.025	0.038	0.030
0...38 µm	0.037	0.065	0.027	0.011	0.020	0.028	0.026

Table 11 The simplified mineral composition in the section N1, fraction 0.150-0.106 mm, %. Analysed by J.-I. Järvelill, 2014.

Minerals	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Light minerals							
Quartz	88.2	79.9	82.3	84.8	85.8	78.6	72.8
Feldspars	11.8	19.8	17.4	15.2	14.2	21.4	27.2
Aggregates		0.3					
Glauconite			0.3				
Heavy minerals							
Garnets	77.3	67.0	74.2	76.7	74.6	77.3	52.6
Amphiboles	4.2	9.9	7.9	5.0	4.4	4.9	34.3
Pyroxenes	2.1	4.0	1.9	0.5	1.3	0.2	4.5
Zircon, monazite	3.8	2.4	1.6	1.5	2.4	2.0	0.8
Green biotite	1.7	1.4	1.2	0.2	0.2	1.6	0.3
Tourmaline	2.1	1.8	0.9	0.5	0.2	0.2	1.5
Carbonate aggregates			0.2			0.2	
Ore minerals	5.9	11.7	10.9	13.1	15.0	13.0	4.3
Rutile	0.4	0.6			0.2	0.2	0.3
Titanite	0.4	0.2	0.2		0.4		
Epidote		0.4		0.2	0.7		
Leucoxene	0.8	0.6	0.7	0.5	0.2	0.4	
Muscovite	0.4	0.2		1.0	0.2		1.5
Brown biotite	0.8		0.2	0.2			
Glauconite				0.5			

be explained by the fact that solubility of U-bearing minerals in water is higher than for the Th-bearing minerals. Therefore, the decreasing trend in the K-40 content may be influenced by plant vegetation.

The activity concentrations data from 2012 year excavation N1 (Table 9) show elevated contents of Th-232 and U-238(Ra-226), except sample 7. At the same time the rather high activity concentration of K-40 in sample 7, imply probably on the higher content of amphiboles in sample (Konzett *et al.* 1997) or of organic substances in this layer.

The grain size distribution from Table 10, except for the sample 6, implies to beach sand at Lemme seashore. The grain size distribution of sample 6 implies to seabed sand (Koch, 2006).

The ratio Th/U in all measured samples (Tables 7 and 9), except for the sample 9a (Table 7), is higher than one. All values of ratio Th/U fall within the range 0.72-4.61. According to Adams and Weaver (1958), the thorium-to-uranium ratios in sedimentary rocks range between 0.02-21.

Heavy mineral content

Thanks to the characteristic lithologies in the catchments, the heavy-mineral analysis enables a reliable differentiation of the sediment provenance from different sources along the coastline (Prizomwalat *et al.* 2013).

Since the finer fractions contain the higher concentrations of zircon and monazite, the new analyses in 2014 were conducted on the 0.150–0.106 mm fraction. According to the previous results from the finer fractions, the average content of heavy minerals and light minerals in the samples was 60.8% and 39.2%, respectively (Table 11). Also, the highest concentrations of heavy minerals were detected in samples 3-6. The light mineral assemblage consists mainly of quartz (81.8%) and orthoclase (15.8%), while content of plagioclases was only 1.5%. The content of other light minerals was below 1%.

In heavy subfraction, garnets represent the most abundant mineral (71.4%). The content of amphiboles and pyroxenes was 10.1% and 2.1%, respectively. Zircon and monazite were detected in relatively high concentration averagely 2.1%. In addition, also, ore minerals were abundant, reaching 10.6%. The investigation of finer fractions with no doubts is more promising.

CONCLUSIONS

In the Litorina Sea accumulative terrace in the Lemme area in, the high concentrations of heavy minerals were detected. . The radioactivity level in area is higher than in most other areas of the Devonian plateau. The Lemmeoja buried soil has 13 ^{14}C dates and the area is well investigated using a series of pedological, palaeobotanical and lithological-mineralogical methods. It serves as the key section for the investigation of the Baltic Sea history. The deposits of the transgressive phases of the Baltic Sea are more reworked than those of the regressive phases. In the course of the invasion by the sea, the migration of the sediments up to the shore slope caused more intensive mechanical and mineralogical differentiation in their composition. This, in turn, resulted in the accumulation of heavy minerals, causing the high radioactivity level in the study area. The heavy minerals in the area may have practical importance.

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Sediment deposition in the Puck Lagoon (Southern Baltic Sea, Poland)

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Abstract The article describes present-day processes related to sediment flux and deposition in the Puck Lagoon, southern Baltic Sea). In situ sediment traps were used for determining the sediment properties in the lagoon and its tributaries. Both sediment sources and the volume of incoming sediment were taken into account and a distinct zone of sediment deposition was discovered in the central part of the Puck Lagoon. The rate of sediment deposition in the Rzucewo Deep exceeded 8.0 mm y^{-1}, whereas in other parts of the Puck Lagoon it ranged from 1.9-3.9 mm y^{-1}. These findings provide the basis for predicting future sedimentation conditions in the Puck Lagoon.

Keywords *• sediment deposition rate • sediment flux • sediment traps*

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INTRODUCTION

In the marine environment, the processes related to the presence and movements of particles on the seabed are described by the terms deposition, accumulation and sedimentation. According to Reineck (1960) and McKee *et al.* (1983), sediment deposition refers to the temporary placement of particles on the seabed. In shallow and dynamic marine environment, the particles in surficial sediments undergo many episodes of displacement and removal from the seabed. The sum of the episodes of sediment deposition and removal over a longer time scale is defined as accumulation. Sedimentation is the overall process of particle transport to emplacement on, removal from and preservation in the seabed.

A number of studies on sedimentation processes in the Baltic Sea, focusing either on a short or long time scale, were published (Winterhalter *et al.* 1981; Blaszczyszyn 1982; Pempkowiak 1991; Walkusz *et al.* 1992; Pustelnikov 1992, 1994; Szczepańska, Uścinowicz 1994; Christiansen *et al.* 2002; Emeis *et al.* 2002; Hille *et al.* 2006; Mattila *et al.* 2006; Suplińska, Pietrzak-Flis 2008).

Lagoons, being a transit zone for suspended matter on its way from land to the open sea, play a role of sedimentation basins for sedimentary material, which originates from a variety of sources and consists of inorganic (mineral) and organic particles. The sediment inflow and its distribution in the Puck Lagoon are not well known yet. Despite the convenient location and physical features of the Puck Lagoon, so far no research has been done on sediment deposition in this water body.

The aim of this study was to determinate the vertical sediment flux, i.e. the amount of suspended sediment that is settling towards the seabed per unit area and per unit time (Lund-Hansen, Christiansen 1998), and the rate of sediment deposition [mm $year^{-1}$]. The object of the study is the particle fractions that are the main component of suspended matter and bottom sediments. In order to estimate the sediment input from various sources, we used the results of our study concerning the size of river load into the Puck Lagoon as well as the data about the abrasion material supplied to the lagoon and aeolian transport processes.

STUDY AREA

The Puck Lagoon is the most peripheral, western area of the Gulf of Gdańsk (Fig. 1). It covers 103 km^2, its average depth is 3.13 m (approximately 30% of the

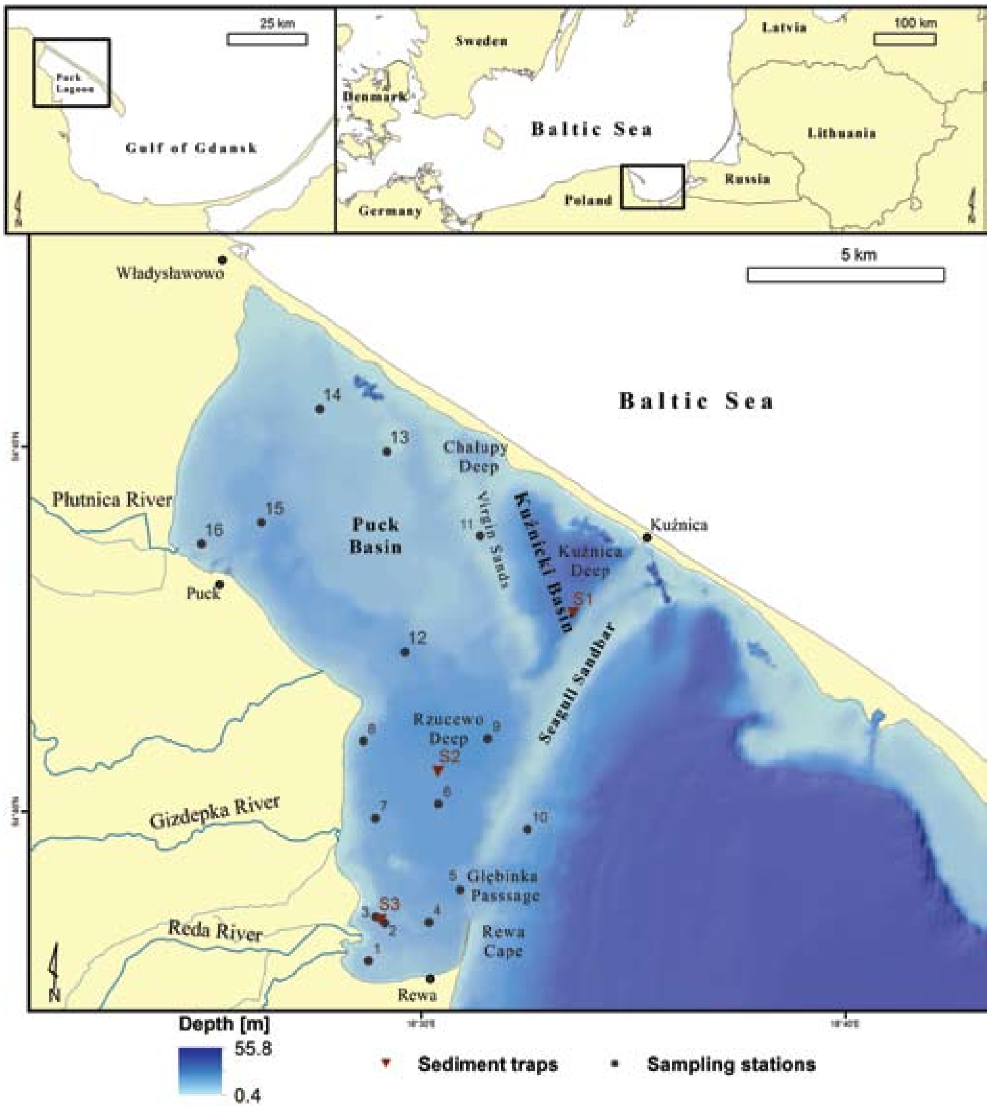

Fig. 1 Location of sampling stations (Nos. 1–16) in the Puck Lagoon

area is situated at 0 to 2 m depth) and the water capacity is 0.32 km^3. To the north-east it boarders with the accumulative Hel Spit, while to the south-east with temporarily emerging sand ridge of the Seagull Sandbar and the Rewa Cape. It joins the Gulf of Gdańsk along the 1.8 km wide Głębinka Passage which is an artificially deepened waterway of 3−4 m depth. Another isthmus, 1.3 km wide, is located near Kuźnica. To the west, the Puck Lagoon is surrounded by Pleistocene moraine upland with ice-marginal valleys and erosion river valleys cutting deeply into it.

The characteristic feature of the Puck Lagoon is the varied seabed formation that allows for defining two basins. The Puck Basin runs along the western coast in a form of gully delineated by 3- and 4-m isobaths, whose deepest site is the Rzucewo Deep (max. depth 5.7 m). The Kuźnica Basin runs along the Hel Spit and covers the Kuźnica and Chałupy Deeps (max. depth 9.7 m and 4.0 m, respectively). The exchange of water between the basins is hampered by the shallows of the Virgin Sands reaching from the Hel Spit in the north-west to the Seagull Sandbar in the south-east. The bottom of the lagoon is in the immediate vicinity of the mouth of ice-marginal valleys with rivers flowing in and the moraine hills forming cliffs on the seashore.

Two genetic types of bottom sediments are present in the Puck Lagoon, i.e. lagoon clastic formations and Late Glacial and Early Holocene freshwater marsh-limnic sediments exposed in rather small seabed areas. Next to the abraded cliff edges, coarse gravels and coarse sands with boulders occur (Fig. 2). Medium-grained sands can be found in the shoreline area, up to the 1 m isobath; they make up shallow water shoals such as the Virgin Sands and the Seagull Sandbar. The dominant type of sediment, which appears in the vast area of the seabed, is fine-grained sand. It can be found in the western and south-western area of the lagoon, in the mouth of the Reda River and on the eastern edge of the Kuźnica Deep. Coarse silty clays are to be found in the deepest areas of the Kuźnica, Chałupy and Rzucewo Deeps. The outcrops of marsh-limnic sediments (peats and lime gyttja) occur in the area of the seabed where the ice-marginal valleys of Reda River and Płutnica River are extended (Jankowska 1993). Present-day terrestrial sediments forming on the bottom of the Puck Lagoon originate from river inflow, coastal abrasion and aeolian transport.

The movement of sedimentary material within the Puck Lagoon waters depends on the bathymetry and morphology of the seabed and water circulation. The variability of currents and the resulting exchange of water between the Puck Lagoon and the Gulf of Gdańsk is determined by the wind and wind-induced changes in the sea level, seiche and small (a couple of centimetres high) tides. It must also be noted that the rivers flowing into the Puck Lagoon induce currents in the river mouth areas, which are formed according to the river runoff. The circulation is not stable though because it depends on the wind direction. The main axis of flow and water exchange in the Puck Lagoon is a gully stretching from Głębinka to Puck. Another system is connected with the Kuźnica Basin where the dominant currents move clockwise (Fig. 3).

Salinity (mean 7.3 PSU) is an important factor influencing the sedimentation of suspended particles. Salinity is influenced by seawater masses flowing from the outside of the Puck Bay (0.5 km^3) and freshwater inflow (0.2 km^3). The impact of freshwater is limited only to the river mouth area where the salinity ranges from 0.5 to 5.32 PSU. The variability of salinity in the river mouth areas is extremely important because it determines the process of flocculation. During the year, the mean salinity in the Puck Lagoon varies slightly from 7.2 to 7.5 PSU. The lowest salinity is observed in spring and autumn, which is caused by an increased inflow of freshwater. The highest salinity values occur in winter. Salinity shows no signs of stratification because the lagoon is relatively shallow and high-energy, i.e. the water mixes intensively. The annual outflow of water from the Puck Lagoon into the Gulf of Gdańsk equals ca. 0.8 km^3 (Nowacki 1993). The coefficient of annual water exchange in the lagoon is high (2.5).

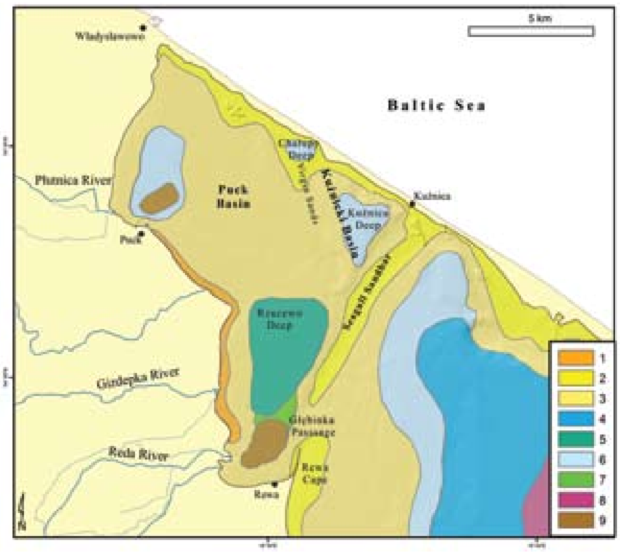

Fig. 2 Sketch of bottom sediments in the Puck Lagoon area (according to H. Jankowska 1993). 1 – pebble gravel, 2 – medium sand, 3 – fine sand, 4 – coarse sand, 5 – coarse silt on calcareous gyttja, 6 – coarse silty clay, 7 – calcareous gyttja, 8 – peat

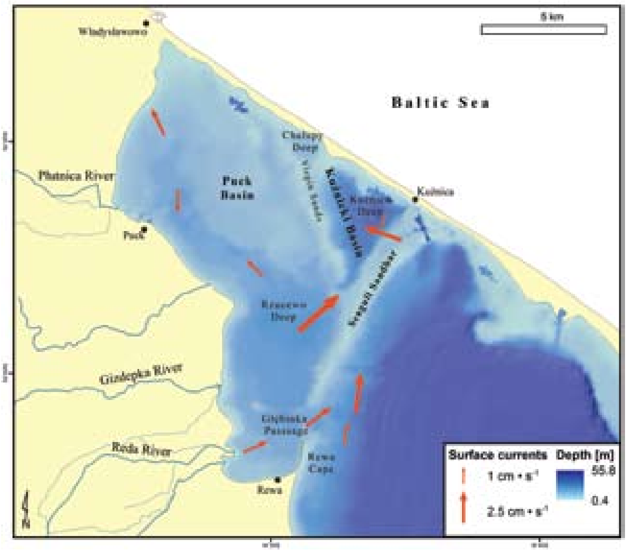

Fig. 3 Average of current surface velocities in the Puck Lagoon (according to J. Nowacki 1993)

MATERIAL AND METHODS

Quantitative analysis of sediment influx

The primary objective of this study was to evaluate the importance of sediment transport into the Puck Lagoon by river runoff, wind and abrasive processes. Rivers are the main source of terrestrial sediment supplied to the Puck Lagoon, transporting about 12 000 tons of sediment annually (Szymczak, Piekarek-Jankowska 2009). Approximately 3 000 tons of this load consists of suspended sediment which becomes suspended matter in the water column. The riverbed load accumulates exclusively next to the river mouth (Szymczak, Piekarek-Jankowska 2007).

The abrasion processes occur on the western cliffed coast of the Puck Lagoon whose length is approximately 7 900 m. The active sections constitute one third of that distance. The abrasion rate has been estimated at 0.11 m yr^{-1} (Zawadzka-Kahlau 1999). The coast of moraine upland is formed by till and fluvioglacial sand and gravel, whereas the coast of ice marginal valleys is built by peat and fluvial silts and sands. Because of abrasion, each year 10 900 tons of sediment reaches the Puck Lagoon which includes 2 300 tons of fine-clastic material (calculations after Bogacka, Rudowski 2001).

The amount of matter transported by wind into the Puck Lagoon is 6.7 tons km^{-2} per month, which amounts to 8 300 tons per year. The weight share of organic matter is about 40%. The other 60% (almost 5 000 tons) consists of various inorganic substances among which the grains of dune sands and atmospheric dust are most common (Pęcherzewski 1994).

The amount of material eroded from the sea bottom is unknown. A total of 31 200 tons of sediment from the aforementioned sources reaches the Puck Lagoon each year, and that includes 45% of fine-grained clastic material being a part of suspended matter.

Fieldwork

The data discussed in this article were collected during fieldwork undertaken in the Puck Lagoon in 2002−2009. During the 2002−2003 season, bottom sediments and water samples from 16 stations were examined (see Fig. 1). At each sampling site, water samples were collected twice (in autumn and spring) from the surface layer, halfway the maximum depth and 0.5 m above the bottom by using bathometer. Surface sediments were collected in spring by using the van Veen grab sampler. During the season 2008−2009, only the samples of near-bottom water were taken with a bathometer before the installation of sediment traps and immediately after their removal.

The sediment trap experiments were conducted in two periods, i.e. from June 2003 to May 2004, and from September 2008 to April 2009. The traps were installed at three stations (Fig. 1) which clearly differed with regard to bathymetry and bottom sediments, and whose characteristics are presented in Table 1. The first experiment was planned in two stages. Two traps were installed at each station in June 2003. In order to analyze seasonal variation in sediment flux, one trap was deployed for 12 months, while the second one was planned to be recovered after six months and replaced with the new one for the next six months. After six months, only trap S1/03 was taken out, while traps at stations S2 and S3 were found to have been destroyed, probably by fishermen or diving tourists. At the second stage of experiment in November, traps were installed at the same locations. After six months, in May, traps S2/04 and S3/04 were taken out, while trap S1was found destroyed. The third experiment employing sediment traps started in September 2008. The traps were deployed at the Kuźnica Deep (S1/09) and the Rzucewo Deep (S2/09) for seven months, i.e. until April 2009.

Taking into account the results of studies on the efficiency of sediment traps conducted by other researchers (Gardner 1980; Butman 1986; Butman *et al.* 1986), a decision was made to use cylindrical traps made of polyvinyl chloride, whose inner diameter was 95 mm, height 500 mm and capacity 3.5 l. Such traps ensure the realistic measurement of sediment flux in the environment characterized by high water mobility (Hargrave, Burns 1979; Blomqvist, Kofoed 1981) because the trapped sediment cannot be redeposited. Each trap was vertically mounted on a stand with its outlet 0.7 m above the seabed. Sediment traps before mounting had been filled with seawater from the depth at which they were located. The samples of bottom sediment and water from the depth of trap deployment were collected at each site. Traps were emptied after six or seven months of exposure. The outlet was covered and the trap was carefully brought up to the surface.

Laboratory analysis

In order to estimate the concentration of suspended matter, seawater samples were filtered through reweighted Whatman GF/F fiberglass filters (0.7 µm). Due to the very low concentration of suspended matter, the filters were rinsed with distilled water to re-

Table 1 The sediment trap locations in the Puck Lagoon and the results of measurements

Station name	Station coordinates/Position	Water depth [m]	Exposure time	Suspended sediment		Sediment in traps		
				Concentration [g·m^{-3}]	Share of organic matter [%]	Dry mass [g]	Mean sediment flux [g m^{-2} day^{-1}]	Share of organic matter [%]
S1/03 Kuźnica Deep	18°33.254’ E 54°42.995’ N	7,0	VI–XI 2003	3,7	25	31,8	21,25	15
S1/09 Kuźnica Deep			IX 2008–IV 2009	3,4	5	18,4	12,4	16
S2/04 Rzucewo Deep	18°329.316’ E 54°42.372’ N	5,0	XI 2003–V 2004	12,3	75	70,2	46,94	25
S2/09 Rzucewo Deep			IX 2008–IV 2009	7,8	5	35,9	24,15	18
S3/04 Reda River mouth	18º28.851’ E 54º38.730’ N	2,8	XI 2003–V 2004	6,8	21	29,4	19,67	11

cover the filtrate for the particle size determination. The grain size of suspended matter was measured by means of a Fritsch laser particle sizer *Analysette 22* (1-2000 µm). The organic matter content in suspension was determined as a loss of weight on ignition (LOI) at 550ºC.

Material from sediment traps was filtered immediately after transport to the laboratory and later dried out at 105ºC. Both surface sediments and the material from the traps were fractionated by means of sieve analysis with 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm mesh size sieves. The fraction less than 0.063 mm was analyzed by pipetting (Łęczyński, Szymczak 2010) to distinguish the fractions of particles with a diameter 0.063–0.032, 0.032–0.004, and < 0.004 mm. The content of organic matter in bottom sediments and the material deposited in sediment traps was determined by using 30% hydrogen peroxide (Mikutta *et al.* 2001).

RESULTS

Concentration of suspended matter

The concentration of suspended matter, measured at 16 sampling stations (Table 2) in the Puck Lagoon, showed high seasonal variability (2.1−19.8 g m^{-3}) which is most likely connected to the seasonality of hydrodynamic phenomena in this area. In the autumn season, the suspended matter concentration in the surface water layer varied from approximately 3.5 to almost 19 g m^{-3} (Fig. 4a). The highest values were observed in the Puck Basin, nearby Puck cliff and to the

Table 2 Sampling stations location and the results of suspended sediment measurements

Station name	Station coordinates/ Position	Suspended sediment concentration [g·m^{-3}] autumn 2002	Suspended sediment concentration [g·m^{-3}] spring 2003	Grain size composition of suspension [%] <0,004 mm	0,004–0,008 mm	0,008–0,016 mm	0,016–0,032 mm	0,032–0,063 mm	0,063–0,125 mm	>0,125 mm
		surface water layer / above the seabed								
1	18°28.72’ E	9.84	7.85	1.8	6.3	10.1	13.2	59.9	6.4	2.3
	54°38.124’ N	9.27	7.5							
2	18°29.0736’ E	4.02	6.67	0.5	11.1	8.6	15.4	58.7	3.9	1.8
	54°38.6472’ N	3.39	6.79							
3	18°28.851’ E	11.46	8.33	0.7	8.2	9.6	12	61.2	5.2	3.1
	54°38.73’ N	13.27	8.33							
4	18°30.11’ E	3.98	7.12	1.3	11.5	13.8	20.3	49.6	2.6	0.9
	54°38.678’ N	18.16	7.1							
5	18°30.822’ E	4.06	5.6	2.6	9.3	13.7	12.5	57.3	3.4	1.2
	54°39.14’ N	8.97	6.97							
6	18°30.24’ E	6.69	7.84	3.7	8.8	10.2	11.7	62.1	2.8	0.7
	54°40.308’ N	12.41	7.75							
7	18°28.758’ E	17.3	6.88	2.5	7.6	11.9	13	58.6	4.3	2.1
	54°40.08’ N	6.7	7.02							
8	18°28.41’ E	3.65	7.37	3.8	8.9	9.2	9.7	60	5.1	3.3
	54°41.133’ N	3.58	8.48							
9	18°31.35’ E	6.06	3.51	2.6	9.7	14.9	20.6	48.7	2.6	0.9
	54°41.226’ N	6.8	6.63							
10	18°32.365’ E	4.22	2.13	5.2	9.3	9.8	17.3	52.2	4.5	1.7
	54°40’ N	6.19	5.54							
11	18°31’ E	9.12	5.12	2.3	4.8	15.8	18.7	49.9	5.2	3.3
	54°44’ N	7.65	7.45							
12	18°29.316’ E	7.68	6.44	4.1	8.9	10.9	12	58.4	3.4	2.3
	54°42.372’ N	6.21	7.81							
13	18°28.72’ E	14.26	6.23	1.7	6.8	11.2	17.9	56.7	4.1	1.6
	54°45.11’ N	10.46	7.66							
14	18°27.1’ E	16.32	6.98	2.6	8.5	10.1	27.6	47.3	2.6	1.3
	54°45.66’ N	12.08	7.69							
15	18°25.818’ E	19.85	7.37	3.3	5.6	11.7	17.8	59.2	1.8	0.6
	54°44.076’ N	15.61	7.98							
16	18°24.414’ E	6.33	7.47	1.6	7.3	12.6	26.6	48.4	2.7	0.8
	54°43.752’ N	5.5	7.01							

south of the Gizdepka River mouth. Such distribution of suspended matter may be the result of supplying the waters of the lagoon in sediment material from two sources, i.e. from Gizdepka River, a river with the richest river load, and from abrasion of the cliff section. The lowest concentration of suspended matter was observed between the active cliff areas and nearby the Rewa Cape and the Głębinka isthmus.

The concentration of suspended matter in the near-bottom water layer was slightly higher than in the surface water layer, and it fluctuated from 3.7 to 15.8 g m^{-3} (Fig. 4b). The lowest values occurred alongside the western coast of the lagoon in the river mouth area. The highest concentrations of suspended matter in the near-bottom layer were observed to the north off Puck cliff and in the Głębinka area, where suspended matter is delivered via Reda River and due to the water exchange between the Puck Lagoon and the Gulf of Gdańsk.

In the spring season, the concentrations of suspended matter in the surface water layer in the Puck Lagoon were lower compared to those in autumn, ranging from 2.1 to almost 8.5 g m^{-3} (Fig. 5a). The highest values of suspended matter were reported along the western edge of the Puck Lagoon and the Reda River mouth area. The isograms of suspended sediment concentration were parallel to the coastline, which proves that the concentration of suspended matter decreases with increasing distance from the source of matter.

The differences in the suspended matter contents in the near-bottom water layer were insignificant; the concentration values ranged from 6.6 to 8.4 g m^{-3} (Fig. 5b). The highest values occurred along the lagoon coast in the area bordering with Puck cliff and the Reda River mouth. A higher share of suspended matter in the near-bottom water layer may have resulted from the resuspension of bottom sediment that often occurs in the shallow areas of this water body.

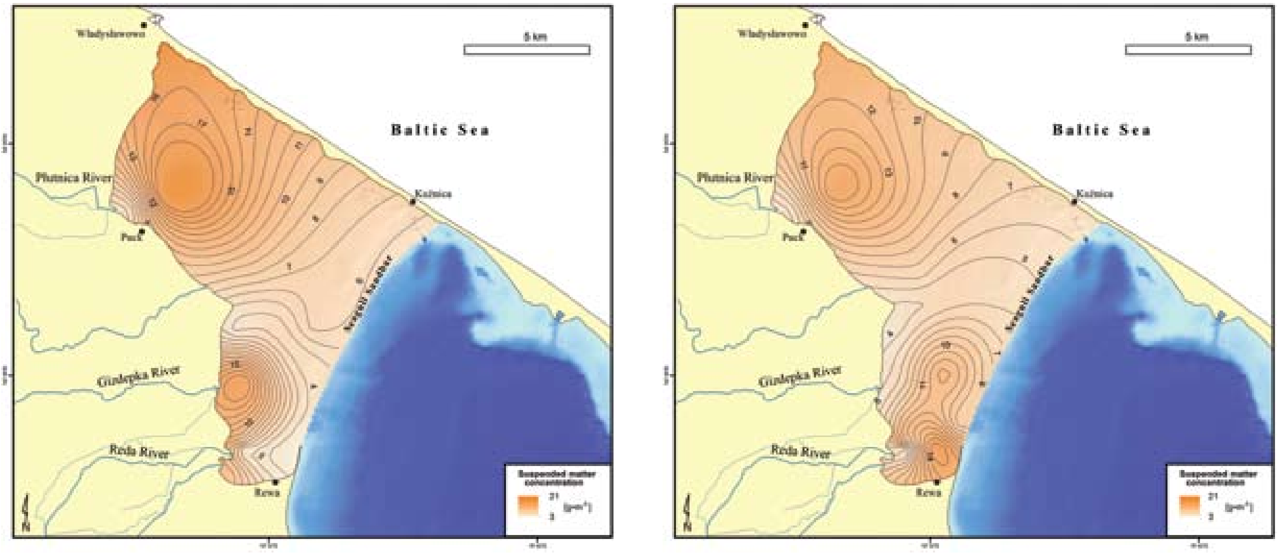

Fig. 4 Average concentration of suspended matter (g m^{-3}) in surface water layer **(a)** and above the seabed **(b)** in autumn 2002

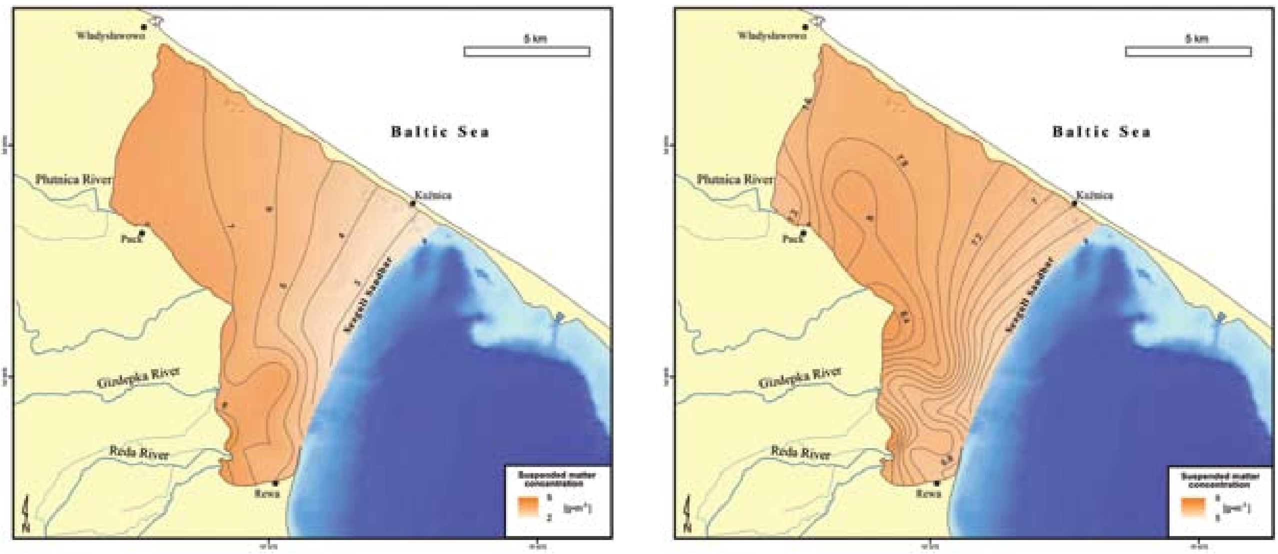

Fig.5 Average concentration of suspended matter (g m^{-3}) in surface water layer **(a)** and above the seabed **(b)** in spring 2003

Composition of suspended matter

The composition of suspended matter differs greatly between the two seasons. In autumn, the dominant part is inorganic, reaching 70%. In contrast, during spring and summer, the organic matter content in the suspension rises to 45% due to phytoplankton blooms (Pliński 1993; Renk 1993). The phytoplankton growth can increase the suspended matter concentration in the surface water layer by even 3 g m^{-3}.

Increased contents of mineral fraction were observed in the suspended matter samples collected in October and April from the near-bottom water layer; the contents were on average 3% higher compared to those measured in surface water samples. Such variability indicates the occurrence of resuspension processes resulting in the enrichment of suspended matter in mineral fractions at the sea bottom. It also points to the fact that the primary production decreases with increasing depth.

Based on the grain size composition of inorganic suspension in the lagoon waters (see Table 2), grains with the diameter ranging from 0.001 to 0.125 mm were found. Coarse silt (0.063–0.031 mm) and medium silt fractions (0.031–0,016 mm) constituted more than 80% of suspension. The share of sandy fraction was slightly over 8%.

Vertical sediment flux

The significant differences in the suspended sediment concentration in the near-bottom water layer were observed in various areas of the basin immediately before anchoring the sediment traps. In November 2003, the suspension concentration in the Rzucewo Deep (S2/04) was 12.3 g m^{-3}, which is almost half as high as in the Reda River (S3/04) mouth area. In September 2008, the suspension concentration approximately a sediment trap in the Rzucewo Deep was 7.8 g m^{-3}. In June 2003, the lowest value (3.7 g m^{-3}) was measured in the waters of the Kuźnica Deep (S1/03), which is most peripheral to the potential area of sediment origin. The same situation was observed in 2008, when the suspension concentration equalled 3.4 g m^{-3}. This finding is supported by the fact that the suspension concentration depends on the distance from the potential sources of sedimentary material.

The sediments collected inside the traps differed with respect to their quantity and quality. The mean sediment mass collected in the traps within the 6- and 7-month periods varied from 18 to over 70 g (see Table 1).

The values of diurnal vertical flux of sediment per surface area were calculated based on the dry mass of sediment deposited inside the traps in a given exposure time. The highest sediment flux (46.94 g m^{-2} day^{-1}) was typically measured at station S2/04 in the central part of the basin. The sediment flux observed in the Kuźnica Deep (S1/03; 21.25 g m^{-2} day^{-1}) was more than two times lower; this specific site is the deepest and furthest removed from the potential sediment sources among all stations. The Reda River mouth station, which is the shallowest and the closest to the shore site, was characterized by the lowest sediment load per unit surface area. In 2008 and 2009, the sediment flux per unit surface area was definitely lower, and equalled 12.4 and 24.15 g m^{-2} day^{-1} at stations S1/09 and S2/09, respectively.

Composition of deposited sediments

The material accumulated in sediment traps included 11–25% of organic matter (see Table 1). Material that is more organic was found in the traps located at lower depths further away from the shoreline. The organic matter content in recent lagoon deposits in these parts of the Puck Lagoon was lower and accounted, on average, for 1–10%. The highest values of organic matter concentration in bottom sediments were observed in the immediate vicinity of the Płutnica River mouth as well as at the extension of the estuary of Gizdepka River in the western part of the Rzucewo Deep.

The results of granulometric tests were described by applying Shepard classification (1954) with the sand, silt and clay-size based on a Wentworth grade scale (1922). The material deposited in sediment traps was classified as clayey silt and silt. Sediments from the traps deployed in the Kuznica and Rzucewo Deeps were characterized by increased share of sand (Fig. 6 a, b). On the other hand, sediments from the Reda River mouth displayed the highest share of silt, the lowest share of organic matter (11%) and were rich in clay fractions.

DISCUSSION

The obtained results indicate that the contents of suspended matter in water samples from the Puck Lagoon are comparable with those reported for the entire Gulf of Gdańsk (0.36–35.0 g m^{-3} Burska, Graca 2011), the southern part of the Baltic Sea (0.6–12.4 g m^{-3}) (Emelyanov, Pustelnikov 1982; Emelyanov, Stryuk 2002) and the Pomeranian Bight (1.55–12.02 g m^{-3}) (Jähmilch *et al.* 2002). In comparison, the mean concentration values of suspended particulate matter in the Vistula Lagoon (Chubarenko *et al.* 1998) and the Curonian Lagoon (Pustelnikov 1998) range from 20 to 85 g m^{-3} and from 10 to 85 g m^{-3}, respectively.

The percentage share of inorganic matter in the Puck Lagoon is generally larger than in the Baltic Sea, where it accounts for about 46% (Emelyanov, Pustelnikov 1982). Based on the grain size analysis of

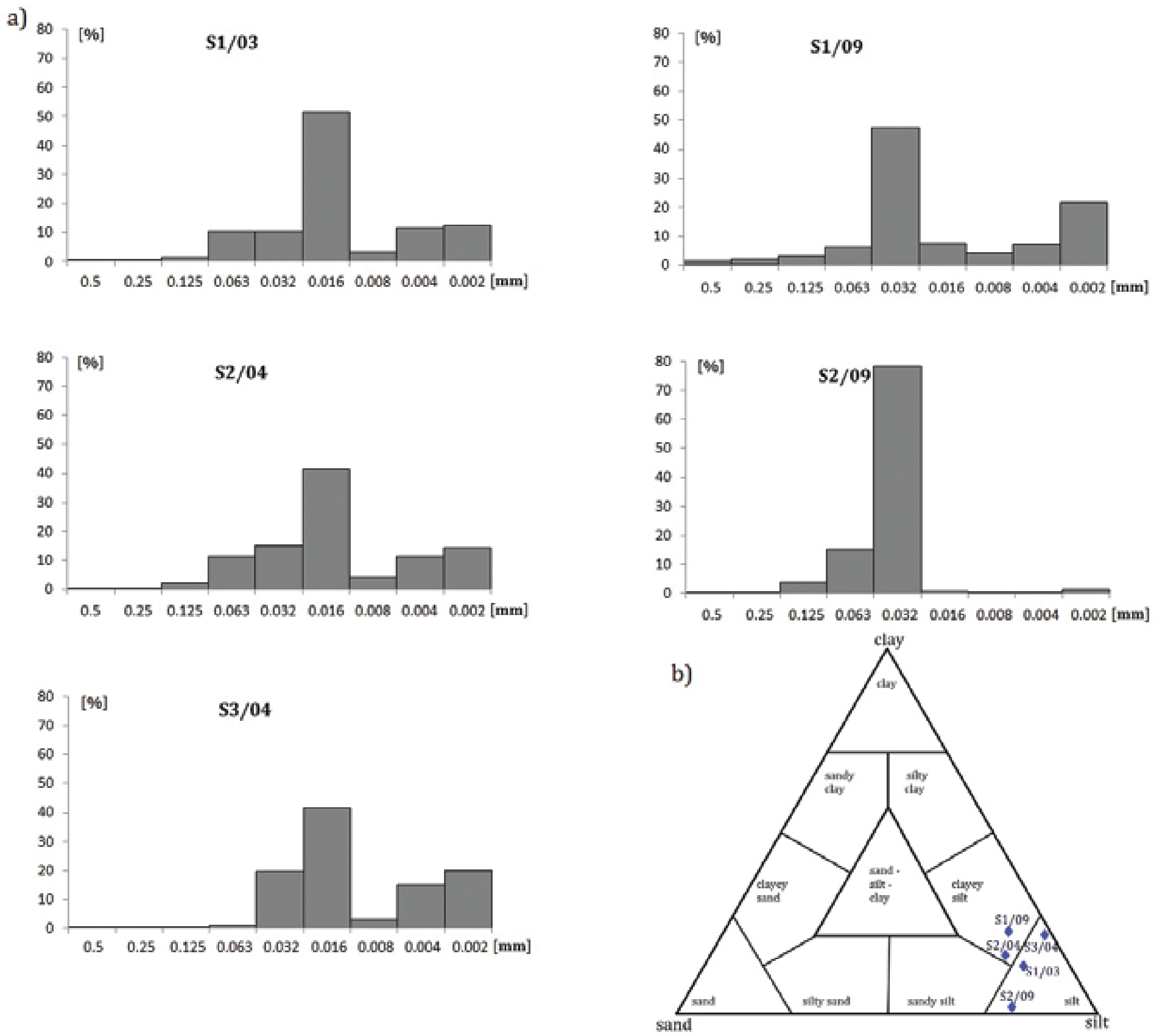

Fig. 6 Histograms of grain size distribution **(a)** and Shepard's (1954) classification triangle of sandy-clayey sediments **(b)**

suspension from the Puck Lagoon, it was determined that the silt fraction dominates. In the open seawaters, it accounts for 72% (Emelyanov, Pustelnikov 1982), while in the other lagoon waters for over 60% of total suspension.

The mean value of sediment flux per unit area in the Puck Lagoon was estimated at 24.88 g m^{-2} day^{-1}. A similar value, namely 28.61 g m^{-2} day^{-1}, was calculated for this area by Żytkowicz (1994). Similar studies were also conducted in other parts of the Baltic Sea. The sediment flux in the Pomeranian Bight, as measured with 50- and 40 cm high traps installed at the depth of 16 m and exposed for 45 days during the summer season, was 75 and 87 g m^{-2} day^{-1}, respectively (Jähmlich *et al.* 2002). Hille *et al.* (2006) reported the vertical flux of sediment of 0.35 ± 0.30 g m^{-2} day^{-1} at a depth of 150 m in the Eastern Gotland Basin.

The sediment transported to the Puck Lagoon from different sources as well as the suspension present in its saline waters is dominated by inorganic fraction with the grain diameters between 0.063 mm and 0.008 mm, which constitutes 80% of the composition. Considering this, it might be expected that the seabed deposit will contain a large amount of silt fraction. However, the grain size analysis conducted by the authors showed that the share of silt and clay fractions (< 0.063 mm) in bottom sediments of the Puck Lagoon accounts for a few percent only, rarely for more than 20% (Fig. 7).

This inconsistency can be explained by the mixing of water masses, accompanied by resuspension of fine sediment fractions that keeps them suspended in the water column where they are subjected to advection towards the final deposition area (Christiensen *et al.* 1997) as well as by the export of suspended matter with the waters out flowing into the open areas of the Gulf of Gdańsk. The suspended matter is transported from the Puck Lagoon by the currents, most probably

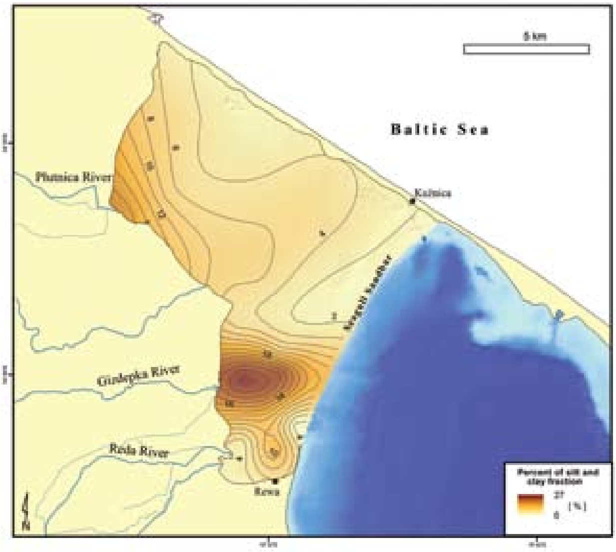

Fig. 7 Share (%) of silt and clay fraction in the surface layer of bottom sediments

in the surface water layer, and moved away according to the direction of circulation, along the shore towards the north, or via the Reda River waters into the area of the Głębinka isthmus. In the river mouth area the process of flocculation may occur, which speeds up the settling of matter.

Due to the existing wind regime, the wave-induced resuspension is a very frequent process in the area of investigation. In shallow waters, resuspension is possible 25% of the total number of days per year, while in the deeper parts of the Puck Lagoon, resuspension is still possible but its frequency is lower. For an average wind speed of 5 m s-1, the current velocities of 1 cm s^{-1} were sufficient to resuspend grains <0.1 mm in diameter. At the current speed higher than 0.4 m s^{-1}, which occurs during storms (wind speed of 10−15 m s^{-1}), the sediment transport including the sandy fraction takes place, and the current velocities are sufficient to erode grains 0.063–2.0 mm in diameter from the seafloor.

The systematic measurements of wind-induced wave action were not conducted in the inner Puck Lagoon therefore it is not possible to analyze seasonal variability of this phenomenon for this particular water body. On the other hand, working under the assumption that wave action in a given basin is proportional to wind speed and by using the data in Table 2 (Łomniewski *et al.* 1975; Miętus, Sztobryn, 2011), it can be stated that the period covering autumn, winter and early spring (from September through April) was characterized by much higher occurrence of storms than the spring-summer period. The mean number of days with a wind speed greater than 15 m s^{-1} increases in September (1.8 days) to reach the maximum value between December and January (4.6 days). The spring-summer period (from May through August) can be characterized as calm and lacking significant storms (0.8 day). This means that the observed seasonal variability of suspension concentration can be correlated to the overall seasonal variability of hydrodynamic phenomena in the Puck Lagoon.

Suspended matter in the water column as well as the sediment undergoing deposition is much richer in organic matter than bottom sediments. The percentage share of organic and inorganic matter present in suspension was estimated in each collected sample. The highest share of organic matter was observed in the waters surrounding traps in both seasons, particularly at the Rzucewo Deep.

The shallow water areas are often subjected to wave-induced resuspension and contain relatively coarse sediments with only small amount of organic matter. The finest particles with high contents of organic matter are resuspended in shallow water and finally deposited in deeper water, with very infrequent resuspension events. In the Puck Lagoon, just as in other shallow reservoirs, a lower share of organic fraction in the bottom material in comparison to suspension could be caused by the consumption of organic matter by bacteria and benthic fauna (Kranck 1984; Eisma, Kalf 1987).

Rate of sediment deposition

Based on the sediment mass increase in sediment traps and the share of organic and inorganic substance in the deposited material, the mean rate of sediment deposition was calculated at 3.98 mm y^{-1}. The study showed that the rate of sediment deposition varied in different parts of the Puck Lagoon, ranging from 1.97 mm y^{-1} (S1/09) in the deepest part to 8.02 mm y^{-1} (S2/04) in the central part of the area of investigation. In 2003–2004, the mean rate of sediment deposition was higher and reached the value of 4.69 mm y^{-1}. In 2008–2009, the mean rate equalled 2.93 mm y^{-1}.

A general approach to the process of sediment deposition is to consider the local basin as a geomorphic system. Such a system consists of several compartments, each with its own distinct spatial and temporal scale. For each compartment, a sediment system can be identified which contains interacting elements such as, water motion, sediment transport, sediment deposition and morphology at corresponding scales. The water motion results from energy input of wind, waves and currents, while ice phenomena are the driving force behind the sediment transport and sedimentation processes (Dean, Dalrymple 1991; Pruszak *et al.* 2008).

As previously mentioned, the Puck Lagoon is a relatively shallow marine area. It is a well-known fact that when the waves occur in shallow water, the sea bottom is reached by the unsteady fluid motion

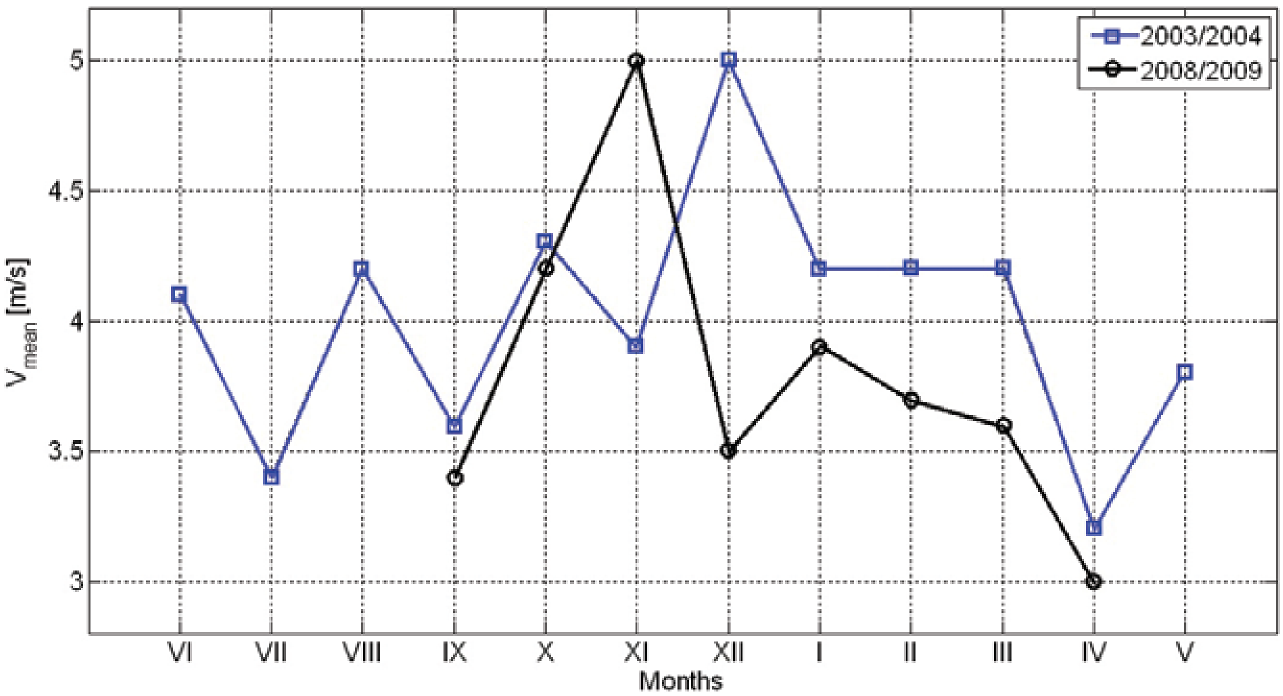

Fig. 8 Series of wind speed recorded in the Puck Lagoon in 2003–2004 and 2008–2009

caused by the wave action (Ostrowski 2004). For low depths, the magnitude of particle displacement and velocity is significant. This unsteady fluid motion at the sea bottom produces hydrodynamic forces that act on the sediment particles and therefore contribute to sedimentation processes. Theoretically, a mathematical model may help to explain the influence of hydrodynamic forces on the deposition rate (Massel 1996; WAMDI Group 1988). However, the Puck Lagoon is a very dynamic region in which the determination of wave and current fields is extremely difficult from the available theoretical models (Robakiewicz 2012). It is mainly because physical processes in this area, apart from their natural randomness, are highly nonlinear and unstable and thus difficult for exact mathematical description (Komar 1998). Bearing in mind that waves and currents in the Puck Lagoon are a result of the wind blowing over a stretch of water surface, a simple analysis of the wind conditions has been carried out. The mean values of wind speed for the periods 2003–2004 and 2008–2009 are presented (Fig 8).

It is noticeable that the mean wind speed during the two separate field surveys depended on the time of measurement. The average wind speed in 2008–2009 was over 5% lower than that in 2003–2004 (Table 3). It should be noted that all mean monthly values of wind speed in 2008 and 2009, excluding November, are lower than the corresponding values in 2003–2004. Therefore, it can be stated that the wind and wave conditions in the Puck Lagoon were calmer during the entire 2008–2009 season. Bearing in mind that the wave height calculated from the Krylov's model (Krylov *et al.* 1976) is proportional to the square of the wind speed, and that the wave force is proportional to the square of the wave height, we can roughly estimate that the sedimentation processes in this shallow basin are proportional to the fourth power of wind speed. This could provide basis for the conclusion that in 2008–2009 a change in the wind speed by 5% led to the ca. 20% increase in the energy state of the wave field. This is one of the possible explanations of a rather large difference between the deposition rates determined in the Puck Basin in 2003–2004 and 2008–2009.

The ice cover in the basin is another factor, which significantly affects the deposition of sediment. On average, in the years 1986-2005, the number of days with ice observed in the Polish coastal zone changed approximately from 10 days in Świnoujscie to two days in Krynica Morska (for all winters, and approx. 20 days and 9 days only in winters when sea ice appeared in a given region) (Miętus, Sztobryn 2011). In the Puck Bay, the highest average number of days with ice was 74. During extremely severe winters, when ice cover in the lagoons is present for more than 128 days, the thickness of ice cover can reach up to 70 cm (Łomniewski *et al.* 1975; Miętus, Sztobryn 2011). Based on the comparison of the 2003–2004 and 2008–2009 ice seasons (Table 4), it can be concluded that the 2008–2009 ice season was calmer and longer, while the 2003–2004 ice season lasted only 26 days, with the ice cover thickness of 50 cm.

To summarize, the differences in the deposition rates result from the impact of two factors. Firstly, poorer anemometric and hydrodynamic conditions

Table 3 Number of days with wind speed exceeding 10 and 15 m s^{-1} in the period 1951–1975 in Poland

Month / Wind speed	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	Number of days											
10 m s^{-1}	7.6	7.4	7.0	4.5	4.2	3.5	3.6	5.0	4.8	4.7	6.4	4.8
15 m s^{-1}	3.1	2.8	3.1	1.6	0.8	0.8	1.0	1.0	1.8	1.8	2.2	4.6

Table 4 The ice seasons in the Puck Lagoon in the periods 2003–2004 and 2008–2009

Date		The maximum thickness of the ice (cm)	Days with ice cover
The term of the first ice	The term decay of the last ice		
09 I 2004	04 II 2004	50	26
26 XII 2008	27 II 2009	10	47

Table 5 The sedimentation rates obtained in various basins of the Baltic Sea

Basin, location	[mm y^{-1}]	Method	References
Arkona Basin	0.30	LSR / ^{210}Pb	Schneider, Leipe 2007
Bornholm Basin	0.31		
Landsort Basin	0.31		
Gdańsk Basin	0.21		
Gotland Basin	0.18		
Eastern Gotland Basin	0.17–3.0	LSR / ^{210}Pb	Hille *et al.* 2006
Southern Baltic	0.4–2.3	SR / ^{210}Pb, ^{137}Cs	Pempkowiak 1991
	0.15–2.25		Walkusz *et al.* 1992
Gulf of Finland	0.63–1.12	SR	Pustelnikov 1992
Curonian Lagoon	2.5–3.6		Pustelnikov 1994
	5.0–15.0		Emelyanov *et al.* 1998
Gulf of Gdańsk	7	LAR / ^{210}Pb	Damrat *et al.* 2013
	1.4	SR	Emelyanov, Wypych 1987 (*according to Pustelnikov 2008*)
Vistula Lagoon	5.3–7.5		
Puck Bay	1,61	LAR / ^{210}Pb	Szmytkiewicz, Zalewska 2014

LSR – linear sedimentation rate, LAR – linear accumulation rate, SR – sedimentation rate.

in 2008–2009 resulted in the lower content of suspended sediment in the water column therefore less particles had been deposited in sediment traps compared to 2003–2004. On the other hand, the winter of 2003–2004 was more dynamic, with a 50-cm-thick ice cover and the ice season in the Puck Bay lasting continuously 26 days. In 2008–2009, the ice cover was frequently disappearing for periods, and the ice season lasted two times longer than in 2003–2004. These findings indirectly prove that the duration of ice season influences the deposition rate in the Puck Bay. The deposition rate increases with decreasing period of ice cover. Two times longer period of ice cover and only 5% lower mean monthly values of wind speed in 2008–2009 resulted in two times lower deposition rate compared to that in 2003–2004.

The values of sediment accumulation rate for the southern area of the Baltic Sea are presented in Table 3. The calculated values of sediment deposition rate in the Puck Lagoon are similar to the values reported by Pustelnikov (1994) and Emelyanov, Wypych (1987) for other lagoons in the southern part of the Baltic Sea. It must be mentioned however, that sediment deposition rate in the Puck Lagoon refers to fresh, not yet compacted sediments temporary placement on the seabed, while the values listed in Table 5 refer to the measurements performed on the cores of partially compacted bottom material.

Under the assumption that the whole sediment (from all sources) spreads evenly, a 0.11 mm thick layer would have been deposited on the sea bottom in the investigated area within a year. Most of the coarse-grained sand and gravel material from the riverbed load and cliff erosion accumulates in the nearshore zones. Fine clastic material would have formed a 0.05 mm thick layer. However, we need to bear in mind that the predicted values do not take into account the inflow of water and suspended sediment from the Gulf of Gdańsk.

In the years 1951–1990, the sea level in the Gulf of Gdańsk was rising 4.02 mm per year. At present, the calculated rate of sea level rise is estimated to be about 1.7 mm per year in the south-eastern Baltic Sea (Helcom 2007). The analysis of inflowing sediment volumes, corresponding deposition rates and the observed sea level changes indicates that the Puck Lagoon is filling at the lower rate than the sea level rise.

CONCLUSIONS

The study showed that the mean sediment flux, calculated from *in situ* experimental data, was variable; it ranged from 19.67 to 46.94 g m^{-2} day^{-1} and strongly depended on hydrodynamic conditions. Those conditions during the study duration (2002–2003 and 2008–2009) differed hence the seasonal and spatial variability of sediment deposition rate ranged from 1.89 to 8.02 mm y^{-1}.

Material undergoing sedimentation was dominated by silt and clay fractions however bottom sediments in the Puck Lagoon contained very little of these two fractions. This indicates that the sedimentation phenomena in the Puck Lagoon are dominated by resuspension and resedimentation processes. The central part of the Puck Lagoon is characterized by enhanced sediment deposition. The deposition is centred in the Rzucewo Deep as indicated by the highest level of sedimentary material in the water column and the high share of organic matter and silt fraction in both the collected material and bottom sediments.

The rapid exchange of water masses between the Puck Lagoon and the Gulf of Gdańsk, caused by currents and wind-generated wave action and countered by the observed intensive deposition of fresh sediments, results in the transport of vast amounts of sediment outside the Puck Lagoon and its deposition at greater depths. The Kuznica Deep is an exception, being a closed basin delineated by 6-m high hillsides with a steep slope in the east. This particular area is supplied in sedimentary material during storms therefore the sediment thickness ranges there from four to five metres.

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Weather conditions during a transatlantic flight of *Lituanica* on July 15–17, 1933

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Abstract This article focuses on the 1933 transatlantic flight of the airplane *Lituanica* and weather conditions en-route. Using reanalysis methods and comparative analysis of historiographical data, the authors aimed to restore the weather conditions and to evaluate pilots' decision-making process in rapidly changing situation during a flight from New York to Kaunas. In this study, the apparent flight path of *Lituanica* (actual flight path remains undocumented) was divided into three stages, with weather conditions investigated for each segment. The findings suggest that weather-based decision making was essential throughout most of the flight and could have played a vital role in the final stage. Over the European mainland, deteriorated weather conditions became unfavourable to maintaining the heading to Lithuania. The adverse weather had forced pilots to abandon their flight plan and consequently led to an attempted forced landing and the fatal crash in Germany.

Keywords • *Steponas Darius • Stasys Girėnas • Lituanica flight • meteorological reanalysis*

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INTRODUCTION

The flight of the Lithuanian–American pilots Steponas Darius and Stasys Girėnas over the Atlantic Ocean is considered to be one of the greatest national narratives of the 20th century and the iconic symbol of the Lithuanian identity (Bumblauskas *et al.* 2012). Both pilots were born in Lithuania, emigrated to the United States of America in their teen years, served in American Army during World War and became naturalised citizens of the USA. After the war, S. Darius (1896–1933) achieved his Captain rank in the Lithuanian air force, and conceived an idea to "hop" over Atlantics. He became even more determined when, on his way from Kaunas back to Chicago in 1927, he had witnessed a triumph of Charles Lindbergh in Paris – the first man to make a solo flight over Atlantics. In 1932, he teamed up with his countryman S. Girėnas (1893–1933), a Chicagoan businessperson and stunt pilot. They bought a serial plane *Bellanca CH–300* and rose further funding without any support from commercial companies or governments. The flight was symbolically dedicated to "Young Lithuania" and was sponsored by donations from pilots' families and major Lithuanian colonies on the Eastern coast. The remodelled plane was named *Lituanica*. The primary goal was to fly from New York to Kaunas, take rest, and hop back. Technically, the flight was hardly set for a world record, yet was considered as an extremely daring effort. Ideologically, the flight was unique: the pilots sought to break into the "elite of the elite" of modern aviators and thus to win fame, respect, and inspiration for their Motherland and Lithuanians around the world. This aim had cost them lives, and won an enduring glory of the modern Lithuanian national heroes.

Paradoxically, multiple researches into this famous story were limited regionally and thematically, and were based on (or strongly influenced by) subjective memoirs rather than on primary sources and objective analysis (e.g., Jurgėla 1935). Only once in more than 80 years a fragmentary, incomplete set of documents was published (Dariūtė *et al.* 1991). Academic publications like this one are a new trend in long–

time efforts to disclose the apparent factual complexity behind a notorious "tragic victory" of Darius and Girėnas. A reason to that is the first on–going international research (launched in 2011 in Lithuania, Germany and the USA), which reveals a new spectrum of the archival sources (Sviderskytė, 2013) and sets new tasks for today's scientists.

The documentation of two official investigations into the crash of *Lituanica* is essential for the complete analysis of this historic flight, crash and sustained aftermaths. Yet a precise study revealed that the German Report (LCVA, 1933/1) had been hastily completed in just seven days and clearly lacked thorough argumentation. The subsequent Lithuanian Act (LCVA, 1933/2) was quite analogous, though the time of investigation extended to five weeks. There are reasons to assume that both official findings did not fully unclose the primary material used by investigators, but unfortunately, most of it became sparse by being classified, lost or deliberately destructed. The package of appendix documentation, found in a Private Archive in 2012 (Sviderskytė 2012) contained "filtered" data that was directly used for and mentioned in both findings – the Report and Act. Thus, the "missing gap" in documentation of the official investigations ought to be filled by application of trans–disciplinary methods – e.g., constantly improving computer modelling and 3–D reconstructions (Štulas 1996; Sviderskytė, Silva 2013) or modern reanalysis. The latter is to be used for two reasons: to specify disputable, fragmentary described weather conditions during the flight and crash of *Lituanica*, and to form solid grounds for estimating an actual flight path of *Lituanica* from New York to crash site near Soldin, Germany (now Myślibórz, Poland).

The aircraft in flight is influenced by many different factors. Yet when it comes to *Lituanica,* the critical thinking is often being put aside, and weather conditions are blamed as a prime (if not the only) culprit of the catastrophe. This attitude was formed up in about two weeks after the crash, and it was embedded for decades, when the Act was published on October 9th, 1933: purportedly, Darius and Girėnas would gloriously reach their destination in Kaunas and certainly would not dye, *if* a stormy weather would not stop them somewhere over the Polish Corridor. Alas, it is not quite correct, because 1) earlier mishaps encountered en–route, e. g. an increased fuel consumption, could lead to fatality as well; 2) the "critical situation" mentioned (left unclarified) in both official investigations supposedly appeared *after* the pilots turned off the course, and their flight time till attempted forced landing was minimum 1.5 hours; 3) the airplane crashed near the town of Soldin, where was no storm at all; 4) in midsummer of 1933, tense political situation detained investigators from explicit, scrutinized examinations; it is obvious from numerous ambiguities and loose interpretations of the final flight leg and even weather conditions in official findings. Interestingly, the German investigators underlined human errors (fatigue, disorientation, lack of fuel) and mentioned deteriorated weather as a secondary cause (poor visibility near Soldin and more adverse weather towards the East). Meantime, the Lithuanians added possible engine disturbances caused by unclean fuel filter and especially stressed "difficult atmospheric conditions" (severe turbulence, stormy weather with rain showers near Danzig (now Gdańsk), "very bad" weather near Soldin: drizzle, low cloudiness, scattered fog and darkness). What makes these different interpretations even more remarkable is that they are based on a quite similar data (enclosed in the appendix of the official investigations; Sviderskytė 2012), provided by German, Lithuanian and American meteorologists Dr. Soultetus (first name not indicated), S. Olšauskas and J. H. Kimball, and also by the Lithuanian Aero Club representative Major V. Morkus (the latter reported: "As to weather conditions, all questioned locals said it was very dark, low clouds, and foggy. Some drizzle, but no storm. To the East, that is, near Danzig, severe lightning could be seen and perhaps thereat was a storm"). If these inadequacies would be clarified by comparing historiographical and reanalysis data, perhaps then we could move towards the trickiest puzzle: how these pilots found themselves so close to the Polish Corridor, in a knowingly dangerous region of non–flying zones and other extreme difficulties for navigation at night, and why they allegedly attempted forced landing in such a remote vicinity?

As to the actual flight path of *Lituanica,* the findings of the German and Lithuanian investigators were almost identical: purportedly, the pilots made their records on the maps during only 1/3 of the flight; their logbook allegedly disappeared; thus the flight path could be tracked down from New York to Newfoundland only; the aircraft flew to Europe unnoticed; firstly and lastly it was seen flouncing about at a risky altitude over north eastern Germany (all this was confirmed by the pilots' message dropped in Grand Falls, Newfoundland, their markings in 22 maps and other documents). However, the presented versions of the whole flight trajectory lacked solid argumentation. E.g., Lithuanian officials stated that the pilots were determined to use an alternate northern route through Scotland, yet at the beginning they flew towards London "to check their calculations" (LCVA, 1933/2). The Germans simply asserted that the pilots did not fly over London and England at all, and they certainly did not intend to reach Berlin, as "this was unnecessary" (LCVA 1933/1). In both official findings and appendix documentation (Private Archive 1933) there was not a word about the primary intended path, which was most carefully studied by Captain S. Darius and which extended through London and Berlin; no hint that the region of crash was almost directly on the intended flight trajectory, marked on at least one map. Was this unremarked by coincidence? The alternate planned path planned by S. Darius crossed Scotland and continued over the Baltics, at northern coast of Germany. So what was his final option – intended or alternate flight path? Did pilots change their minds en–route? Did they manage to adjust masterfully to deteriorated weather conditions? On the other hand, were they "totally disoriented", as the German investigators presupposed (LCVA 1933/1)?

On the eve of the crash, it was notified that a "thunderstorm" had started to form up over the Atlantic, and weather conditions near Iceland had become severe (Jurgėla 1935; Kalvaitis 1983; Dariūtė 1990). Meteorologist J. H. Kimball of U. S. Weather Bureau in New York (he was "telling flyers when to Hop" since Ch. Lindbergh solo flight in 1927; Kimball, 1928) sent S. Darius the map indicating probable favourable weather. However, the next day, after *Lituanica* took off, he postponed the later starts due to low clouds and rainy zones over the ocean. So what was the real situation during *Lituanica* flight? How it affected human and fuel resources en–route? Did *Lituanica* fly unnoticed over Europe because of weather? Was it inevitable to fly at dangerous low altitude over Germany? To answer it, we need reanalysis of weather conditions over the Atlantic, also at the approaches of Europe and in northeastern region of Germany on July 15–17, 1933.

DATA AND METHODS

In this study, the apparent flight path of *Lituanica* was divided into three stages (Fig. 1). To avoid complexity of the time zones crossed, only Greenwich Time (UTC) was used in this text.

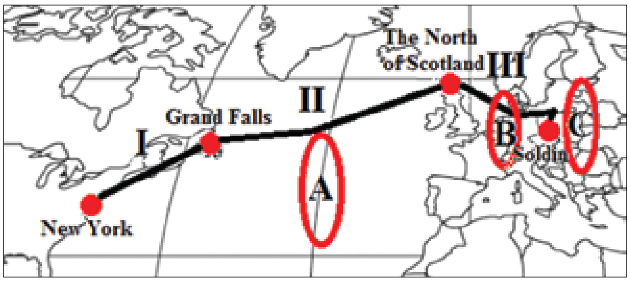

Fig. 1 The stages (I, II and III) of the *Lituanica* flight on 15–17 July, 1933. Letters indicate areas, which could affect the flight: **A** – precipitation and possible thunderstorm area in low-pressure vortex (1933 07 16, 00–12 UTC); **B** – area of low clouds and rain in the occluded front (1933 07 16 12–18 UTC); **C** – the zone of rain and thunderstorms in the atmospheric wave-front (1933 07 16, 21 UTC). More precise location of pressure systems are presented in pictures below.

The first stage was a path flown in about 9 hours on July 15; it mostly extended at the Eastern coast of the USA and ranged from Floyd Bennett Field in New York to northeastern edge of the island of Newfoundland. It was fairly recorded, marked on the maps by S. Darius in flight and descripted in both official findings.

The second stage extended over the ocean and was less documented. A remarkable distance was flown at nighttime. Actual trajectory was not marked on extant maps. No records indicated when and where the island of Great Britain was reached on July 16th. As this study showed, the pilots probably flied about 1400 km towards London; then they encountered deteriorated weather and turned north. The Lithuanian official investigators proposed the following "most reliable" version: Darius and Girėnas flew 2500 km towards London, then turned north and "overflew northern Scotland towards Kiel" (LCVA 1933/2). However, where exactly they crossed Great Britain? In this study, a northern edge of Scotland was picked (strictly conditional location, as possible as any other). Thus, the second stage ranges from Grand Falls, Newfoundland to northern edge of Scotland.

The third stage extended up to the crash site in Germany. From the point of historiography, this part of the flight path is extremely difficult to describe because of insufficient documentation and prevailing controversies. E.g., purportedly overflown locations in Germany were named by unidentified sources; both official investigations only cite same two witnesses; logbook with flight records was said to be found at the crash site and "gone". It is notable that S. Darius was warned in advance and for at least three times to avoid the northeastern region of Germany during the flight, and he was well informed that the only airports' line en–route would not operate that night (BLKM 1933). Nevertheless, the final stage of flight ended there. The Lithuanian official findings indicate four locations (LCVA 19333/2). Firstly, the aircraft was allegedly noticed (heard only) over Stargard (now Stargard Szczeciński, Poland) at 10 PM on July 16. Later at about 11.15–20 PM it was spotted circling at altitude of few hundred feet, which is dangerously low, over Berlinchen (now Barlinek, Poland). Then it was heard again at Kuhdamm (now Pszczelnik, Poland). Finally, at 11.36 PM (00.36 AM, July 17 local time) the plane crashed in a forest near Soldin (now Myślibórz, Poland). Similarly to the Lithuanian official findings, in this study it was generally presumed that *Lituanica* flew over northern edge of Scotland, then continued over the North Sea, heading to southeast towards Kiel, then turned east and flew along the southern coast of the Baltic Sea, but due to worsened weather changed to southwest (hypothetically, towards Berlin) and reached the vicinity of Soldin.

The German and Lithuanian investigators grounded their findings on at least three sources, which contained meteorological data. In 2012, these documents were found packed in one file (Private Archive 1933; a study revealed that the packed documents were appendixes, mentioned in official findings and mysteriously "disappeared" from the archives of state institutions; Sviderskytė, 2012). They had been written by three experts from Germany, Lithuania and the United States:

- Undated (not later than July 24) reference by German meteorologist Dr. Soultetus "Weather conditions over Atlantic Ocean, England and Germany on July 15–17 this year" (duplicate translated to Lithuanian);
- Undated (no later than August 30) reference signed by chief of the Lithuanian Meteorological Bureau S. Olšauskas "Weather conditions in vicinity of Berlin–Soldin at night from 7 PM July 16 to 8 AM July 17, 1933", with three synoptic charts attached;
- A letter of August 9, sent to Lithuanian consul general in New York P. Žadeikis by the U. S. Weather Bureau in New York meteorologist J. H. Kimball; also, there were extant charts signed by J. H. Kimball, which he sent to S. Darius just a few hours prior to take–off.

As aforementioned above, the German and Lithuanian official investigators underlined different meteorological factors (air pressure, precipitation, cloudiness) and drew contradicting conclusions. To our best knowledge, no further analysis was ever made after 1933. Fortunately, modern science enabled us to bring some more light into this matter.

An analysis of weather conditions requires comprehensive 3–D meteorological fields along the track of the airplane. Therefore authors decided to use the Twentieth Century Reanalysis (20CR further in the text) V2 (version 2) as the main dataset. Data here are available on sub–daily timescale from 1871. Additionally, one alternative dataset was included to the analysis – Daily Northern Hemisphere Sea Level Pressure Grids (NHSLPG). NHSLPG sea level pressure data available since 1899 and data resolution is coarser than 20CR – only 5° x 5° longitude / latitude grid. NHSLPG was used only for analysis of synoptic situation across Northern Atlantic as well as over Europe. Data access is available through Research Data Archive of the Computational and Information Systems Laboratory at the National Center for Atmospheric Research in Boulder, Colorado website – http://rda.ucar.edu/. 20CR analyses are generated by assimilating only surface pressure data and using prescribed monthly sea surface temperatures and sea ice distributions as boundary conditions within up–to date general circulation model (GCM). The GCM produces global analysis every six hours as the most likely state of the atmosphere, and an uncertainty estimate of that analysis using 56 ensemble members forecast. The model has a spatial resolution of about 200 km on an irregular Gaussian grid with 28 vertical levels and the model top is at 0.2hPa and a complete suite of physical parameterizations. 20CR also includes the radiative effects of historical time–varying CO_2 concentrations, volcanic aerosol and solar variations using the long wave and shortwave radiation models (Compo *et al.* 2011).

20CR archive suggests two types of data: ensemble mean and ensemble spread, however in current study we used ensemble mean only. 20CR data archive is an open access database, available through the NOAA Earth Systems Research Laboratory (ESRL) website http://www.esrl.noaa.gov/psd/data/20thC_Rean or through the National Energy Research Scientific Centre (NERSC) portal http://portal.nersc.gov/pydap/.

20CR troposphere data are reliable according other reanalysis datasets: NCEP/NCAR1, NCEP/DOE, ERA–40, ERA–Interim, JRA–25, MERRA etc. The largest uncertainties associated with this database identified in Polar Regions as well as in the stratospheric layers. In general 20CR data has lower level of accuracy for the period until 1940s (Brönnimann *et al.* 2012; Paek, Huang 2012).

It should be noted that reanalysis provides more information about weather conditions of the past than it was available in 1933. The meteorologists of the thirties relied on measurements of relatively rare surface meteorological stations network and not always reliable ship information (Kimball, 1928; besides, *Lituanica* flew well north from intense shipping lanes). Nowadays particularly important vertical atmospheric radio sounding then was carried out irregularly, and only in a few places in the world (the first radiosonde was launched in 1930). Modern reanalysis, based on measurements throughout more than 60 years, allowed us to restore weather conditions with sufficient precision – both over the ocean and the land surface, as well as the higher layers of the atmosphere.

RESULTS

The first stage: New York – Grand Falls (Newfoundland)

Airplane *Lituanica* piloted by S. Darius and S. Girėnas took off from New York Metropolitan Airport *Floyd Bennett Field* at 10:24 AM (UTC) July 15, 1933 heading toward the island of Newfoundland. Overflying Grand Falls the pilots threw down a message with the coordinates and UTC time 19:10 PM. While there is about 1710 km between the two points, it can be stated that in case of flying in a straight line average speed was about 195 km/h (almost the same as mentioned in the official findings of German official investigators – 190 km/h).

It is likely that the pilots flew along the North American East coast, being able to navigate visually. 20CR humidity fields show (Fig. 2) that cloudiness in the lower troposphere (up to 2500 meters) during the first stage of flight was quite low (up to 20 %). Mostly clear and maybe in some places partly cloudy weather conditions ought to allow, by today's terms, their VFR (Visual Flight Rules) flight to be relatively easy.

The fact that the weather was mostly clear was confirmed by J. H. Kimball (Private Archive 1933). He indicates that "*the flight from New York through Southern New England was under low clouds and in a head wind. Through Northern New England and on to the Newfoundland Coast the winds were helping, and the sky, mostly clear*".

Table 1 provides a short description of apparent flight route and weather conditions (based on 20CR data) during the first stage of flight. The meteorological flight conditions were good, surface pressure gradually increased; there were light wind conditions and no dominant wind direction at a height of 2–2.5 km. At the beginning, the wind blew mostly from southeast and southwest. The main zones of clouds and precipitation laid to southwest and north from flight path.

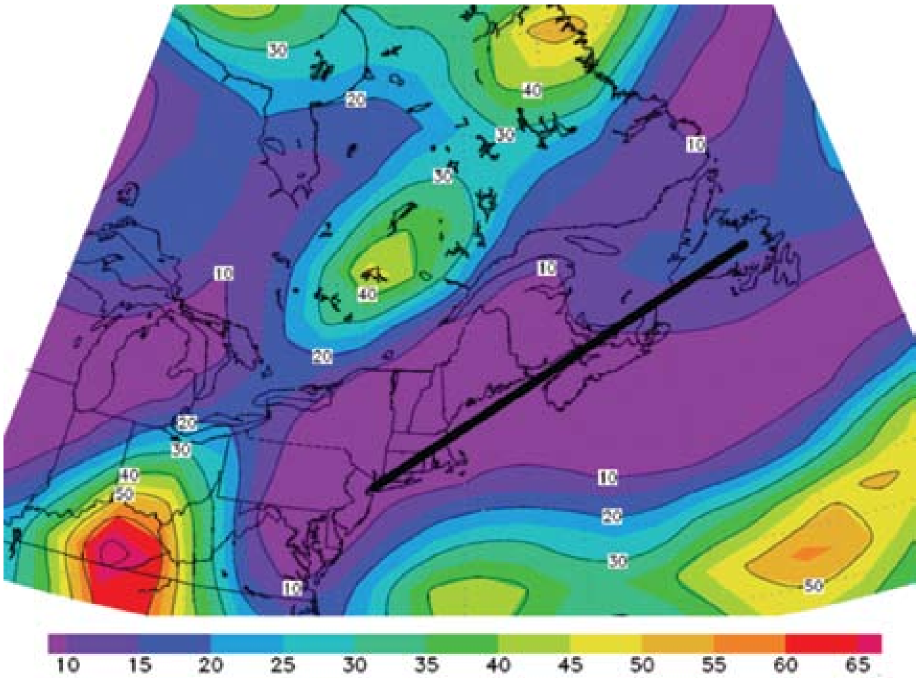

Fig. 2 The mean total cloud cover (%) in the lower troposphere (0–2500 m) at 12–18 UTC (15 July, 1933). Black line indicates the expected flight path.

Table 1 The apparent route of *Lituanica* during the first stage of flight and short description of weather conditions.

UTC time	Possible location of plane; Solar elevation angle	Weather conditions
10:24	Floyd Bennet Field airport, New York, NY 40°35' N 73°53' W; 7°	Fair weather, light wind
11:00	41°15' N 72°48' W; 14°	Fair weather, light wind
12:00	42°20' N 70°57' W; 27°	Fair weather, light south–eastern wind
13:00	43°22' N 69°01' W; 40°	Fair weather, light south–eastern wind
14:00	44°22' N 67°02' W; 51°	Fair weather, light south–eastern wind
15:00	45°21' N 64°58' W; 61°	Fair weather, light wind
16:00	46°17' N 62°51' W; 65°	Fair weather, light south–eastern wind
17:00	47°10' N 60°40' W; 63°	Fair weather, light wind of changing direction
18:00	48°01' N 58°23' W; 54°	Fair weather, moderate south and south–western wind
19:10	Grand Falls (Newfoundland) 48°57' N 55°39' W; 43	Fair weather, moderate south–western wind

The second stage: Grand Falls (Newfoundland) – The northern part of Great Britain

During the second stage, *Lituanica* crossed the Atlantic Ocean. This study assumes that the flight speed remained 195 km/h. It is likely, that initially the pilots were heading towards London. However, it is almost certain that their actual route was stretched more to north. The reason to that could be the zone of precipitation formed up in the middle of the Atlantic Ocean (Fig. 3).

Synoptic analysis of the process (based on NHSLPG data) showed that the low–pressure centre was located near coordinates 50 N–30 E and the low-pressure area deepened and gradually retreated to the north. The precipitation rate, according to 20CR data, in the low-pressure area could exceed 10 mm per 12 hours. Such amount of precipitation depends to continuous or intermittent moderate rain or shower category that could be produced by *Nimbostratus* or *Cumulonimbus* clouds systems. These types of clouds usually penetrate through lower and middle troposphere, i. e. their tops could exceed 5–6 km height. It is assumed that the pilots turned north, presumably to a much thinner cloudiness: the overloaded *Lituanica* was unable to fly over higher formations, so it had to be diverted away from the frontal cloud system; besides, this precipitation zone had to be avoided even more as it was approached in darkness. There is no reliable data about thunderstorm probability in this area. However, the analysis of the development of the precipitation field (according 20CR data) suggests that the low pressure system above North Atlantic developed on the frontal wave of the main polar front, which separates different air masses: tropical air circulating in the northern periphery of Azores High from the polar one that stretched over sub–polar and middle latitudes in the North Atlantic. It means that low-pressure system was at its earliest development phase when the heaviest rains and thunderstorms available near the peak of the frontal wave.

These and further assumptions enabled to specify more clearly the foggy statements about a *"storm of the medium strength over Atlantic"* (Kalvaitis 1983) and a legendary story of a famous American flyer W. Post, who took off from the same airport just one hour prior to S. Darius and S. Girėnas and landed safely in Germany on July 16th. It was said that *"in the evening of July 16 a severe thunderstorm extremely complicated his flight. Only the radio compass helped him out, so he was not forced to abandon his planned route"* (Dariūtė 1990). It is notable that W. Post had landed in Berlin only to refuel and attempted to continue to fly eastwards, heading to Novosibirsk. Yet in a few hours, he was forced to land in Konigsberg (now Kaliningrad, Russia) because of unfavourable weather and the next morning only he was able to continue his flight safely.

The strongest westerly and southwesterly winds were likely in the Central Northern Atlantic and over Biscayan Gulf and western France, approximately between 44 and 48 N. However, in general the mean wind speed in the lower and middle troposphere along the flight path was equal or less than 10 m/s. Moreover, the predominant wind speed during major part of the flight could be attributed to the gentle breeze category with variable wind direction and only few

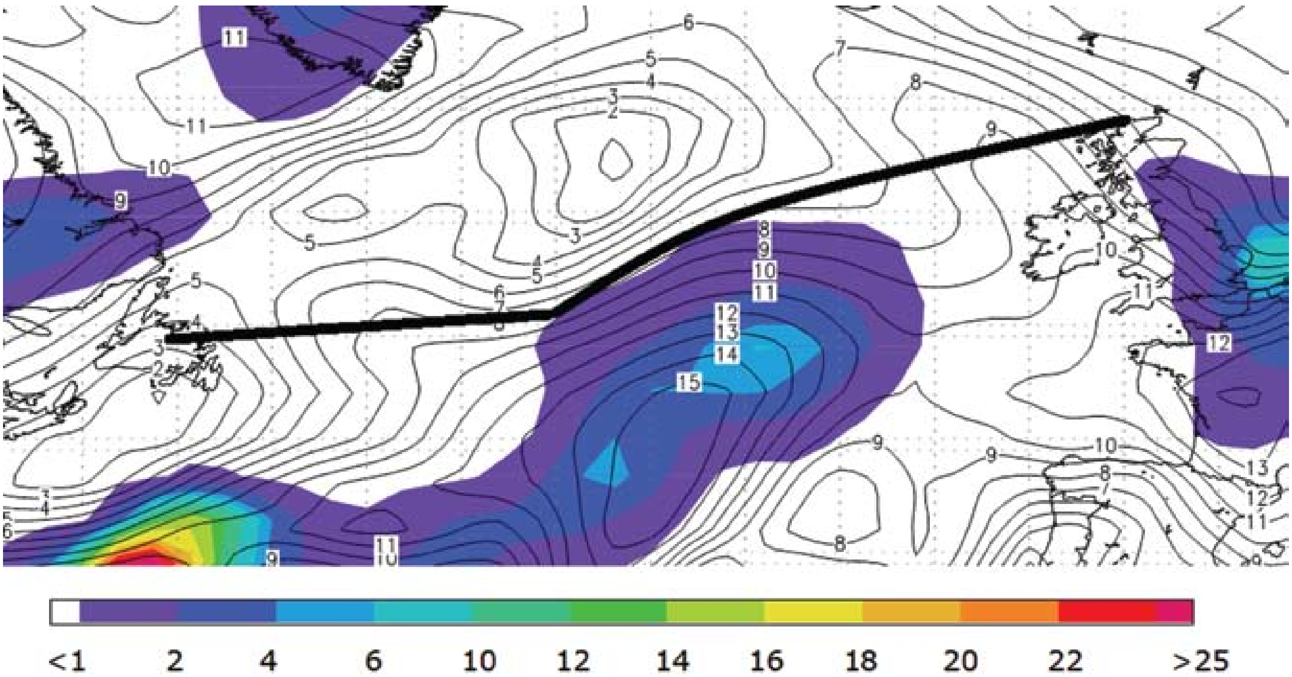

Fig. 3 The mean precipitation amount (mm/12 hours) (colours) and mean wind speed at 750 hPa level (contours) at 00–12 UTC (16 July, 1933). Black line indicates the apparent flight path.

areas show mean westerly wind speed higher than 5 m/s. A while later, approaching British Isles, the wind speed likely has increased to 10 m/s.

It is assumed that the pilots S. Darius and S. Girėnas, when flying in southwest – northeast direction, took into account the risk of getting inside the frontal clouds seen to the right of their flight route: high possibility of an increased wind speed, strong wind shear, higher fuel consumption and turbulence impact on the aircraft. Contradicting to meteorologist J. H. Kimball's statements, it could be concluded that possible low-pressure centre was located to the south and southeast from the flight route, but not to north as was emphasized in abovementioned letter (Kimball 1933). Furthermore, the developing cyclone was moving slowly to the north, so possibly the pilots gradually had directed the aircraft north-bound in order to avoid precipitation, turbulence and strong winds zones and so remaining in more favourable conditions with weaker winds and thinner clouds (Table 2). Continuing to oppose Mr. Kimball further statements that moderate to fresh winds blow from northwest during first part of the ocean and later from west and southwest, it could be demonstrated that, according 20CR data, moderate wind speed conditions were possible during short time of the flight only, and that light to gentle breezes dominated during rest of the time.

The third stage: The northern part of Great Britain – Soldin (Germany, present Poland)

This study assumes that during the third stage of flight the average speed of the plane could reduce to 170 km/h (same was concluded by German official investigators; very probably, they counted an average speed by simply evenly dividing an apparent flight path). The pilots have crossed the North Sea in south–east direction, reached Kiel and turned eastwards, and then flew towards Lithuania along the southern coast of the Baltic Sea (same assumption was made by Lithuanian official investigators). The worsening weather conditions and the storm clouds in surroundings of Kolberg (present Kołobrzeg, Poland) forced the pilots to turn southwest. This turning point is very likely, taking into an account the location of the atmospheric front (Fig. 4). According to official version coined by Lithuanian investigators, S. Darius and S. Girėnas were heading to Berlin, knowing there had to be several airports lit at night; but while on their way they encountered ”critical situation” and searched for area suitable to make a forced landing. In German findings disorientation and lack of fuel were indicated as the main causes of fatal “crisis”; Lithuanians pointed out possible engine problems and adverse weather. Whatever a true cause was, the

Table 2 The apparent route of *Lituanica* during the second stage of flight and short description of weather conditions.

UTC time	Possible location of plane; Solar elevation angle	Weather conditions
19:10	Grand Falls (Newfoundland) 48°57' N 55°39' W; 43	Fair weather, light western wind
20:00	49°35' N 53°32' W; 33	Fair weather, light western wind
21:00	50°16' N 51°06' W; 21	Fair weather, light western wind
22:00	50°53' N 48°35' W; 11	Fair weather, light north–western wind
23:00	51°27' N 46°01' W; 1	Fair weather, light western wind
00:00	51°58' N 43°23' W; –7	Fair weather, moderate western and north–western wind
01:00	52°25' N 40°42' W; –13	Fair weather, light south–western wind
02:00	52°49' N 37°57' W; –15	Good, cloudy, light south–western wind
02:25	52°58' N 36°47' W; –16 Turns bit more to the north–east	The high rain clouds on the east (maybe even illuminated with lightning)
03:00	53°28' N 35°22' W; –15	Mostly cloudy, light south–western wind
04:00	54°16' N 32°48' W; –12	Mostly cloudy, light south–western wind
05:00	55°01' N 30°08' W; –5	Mostly cloudy, light south and south–western wind
06:00	55°43' N 27°23' W; 3	Mostly cloudy, light southern wind
07:00	56°20' N 24°32' W; 12	Mostly cloudy, light southern wind
08:00	56°54' N 21°36' W; 21	Mostly cloudy, possible light rain, light south–western wind
09:00	57°23' N 18°36' W; 31	Overcast, light western wind
10:00	57°48' N 15°30' W; 40	Overcast, light north–western wind
11:00	58°08' N 12°20' W; 48	Overcast, light north–western wind
12:00	58°23' N 9°08 W; 52	Overcast, moderate west and north–western wind
13:00	58°34' N 5°53' W; 53 About 13:15 reached the north coast of Scotland	Mostly cloudy, moderate north–western wind
13:50	58°33' N 3 °04' W; 49 Flew over the east coast of Scotland (in the north)	Mostly cloudy, moderate north–western wind

location of attempted landing fits well with reanalysis data on the cloudiness and precipitation: the zone between Stargard and Soldin was less cloudy.

The synoptic analysis of July 16, 1933 showed that there were two areas of active low pressure in the European domain: cyclone above South Scandinavia (old centre) and the trough over Eastern Alps and Pannonia lowland. The latter has been developing within perturbed cold front (frontal wave), which was quasi–stationary and separates two very different air masses: one warm and moist situating over Eastern Europe, and the other one, colder and drier, over

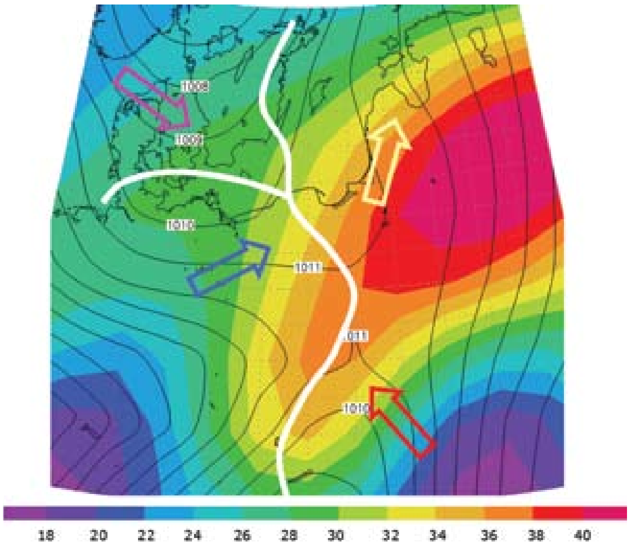

Fig. 4 The integrated water vapour content in a vertical atmospheric column (mm) (colours) and mean sea level pressure (hPa) (contours) at 6 PM UTC (16 July, 1933). White wavy line represents possible position of the main front (from south to north) and occluded fronts (from west to east) position. Coloured arrows show the prevailing air mass advection near surface: blue – cool and dry, purple – cold and wet, red – warm and dry, yellow – warm and wet.

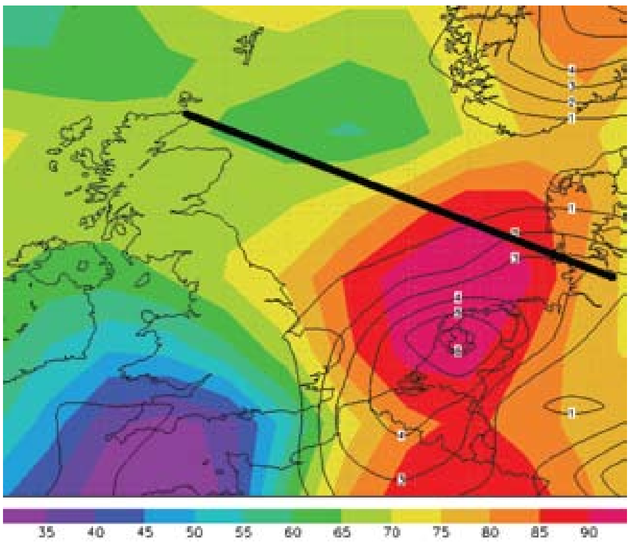

Fig. 5 The mean precipitation amount (mm/6 hours) (contours) and total cloud cover (%) (colours) at 12–18 UTC (16 July, 1933). Black line indicates the apparent flight path.

Western and Northern Europe (Fig. 4). This trough slowly advanced to northeast, producing heavy rainfall, thunderstorms and squalls, until finally decayed on July 17 and retreated further to the Russia.

At the first part of this stage, cloudiness over the North Sea gradually increased (Fig. 5). Approaching the German coast an occluded front with precipitation of moderate intensity (up to 2–4 mm in six hours) was crossed. At the coastal area, the cloudiness decreased, and it is likely that the pilots could see contours of coastline in the dusks, and thus they turned eastward along the coast.

After crossing one frontal area and seeing another, more powerful cloud zone being approached (the flashes of thunderstorm could be seen in night sky at 9–10 PM, UTC), the pilots probably turned southwest (Fig. 6A). Cloudiness decreased in vicinty of Stargard and Soldin (Table 3). It is likely that the low level clouds did not constitute a continuous layer, and the pilots managed to navigate visually by surface lights. In terms of weather conditions, it is not actually clear – why they did not attempt to reach Berlin (as the Lithuanian official investigators supposed)? Instead, they decided to attempt a forced landing in a remote area near Soldin (Fig. 6B). If at that point a "crisis" encountered earlier got even worse, it surely was *not* for the weather. In the area of an alleged forced landing there was no rain, and even some patches of clear sky could be seen. It was extremely difficult task to land *Lituanica* at night, as it had no lights. The pilots could hardly separate wooded area from plain terrain, thus they made their last turn as low as possible. The manouver was risky, and yet it could be complicated even more due to gusty western wind.

According to a survived data of meteorological stations located at this time in West Prussia and being in operational regime – Stettin (now Szczecin), Horst (now Niechorze) and Rederitz (now Nadarzyce, Poland) overcast weather with intermittent light rain and drizzle prevailed in West Prussia in midday and 6 PM on July 16, 1933. Also, south–south–westerly wind turned to the west–southwest and wind speed ranged from light to fresh breeze; ceiling from 250 m to 500 m; however, it exceeded 2500 m over the Baltic Sea coastline (Horst Meteorological Station). In the morning of July 17, low cloud cover with ceiling of about 200–300 m in all above mentioned weather stations as well as dominated westerly and south-westerly winds was recorded. Therefore, such conditions fit well with the statements made by S. Olšauskas (Personal Archive, 1933). The report of Dr. Soultetus also contained information about low cloudiness with ceiling 100–200 m which prevailed over Northern Germany. However, he made no reference to weather stations or exact location. Additionally, this report contained information about the wind in the evening of July 16:

Table 3 The apparent route of *Lituanica* during the third stage of flight and short description of weather conditions.

UTC time	Possible location of plane; Solar elevation angle	Weather conditions
13:50	58°33’ N 3 °04’ W; 51 Flew over the east coast of Scotland (in the north)	Mostly cloudy, moderate north–western wind
15:00	57°52’ N 0°10’ W; 42	Mostly cloudy, moderate north–western wind
16:00	57°08’ N 2°19’ E; 34	Mostly cloudy, moderate north–western wind
17:00	56°22’ N 4°45’ E; 24	Mostly cloudy, moderate north–western wind
18:00	55°33’ N 7°02’ E; 15	Mostly cloudy, moderate north–western wind
19:00	54°41’ N 9°14’ E; 5	Mostly cloudy, possible light rain, light north–western wind
19:25	54°19’ N 10°07’ E; 1 Reached Kiel, turned eastward and flew along the coastline	Mostly cloudy, possible light rain, moderate north–western wind
20:00	54°18’ N 11°40’ E; –4	Mostly cloudy, light rain or drizzle, light western wind
21:00	54°14’ N 14°17’ E; –10	Mostly cloudy, light rain or drizzle, moderate south–western wind
21:30	54°10’ N 15°36’ E; –12 Reached surroundings of Kolberg and turned south–westward	Rain, thunderstorm flashes in high and thick cumulonimbus clouds can be seen in the East, moderate south–western wind
21:30 – 23:36	Approached Stargard 53°20’ N 15°02’ E; –14. Looked for a place to land between Stargard and Soldin. Crashed near Soldin 52°52’ N 14 °50’ E; –14	Partly cloudy, light rain or drizzle, moderate probably gusty western wind.

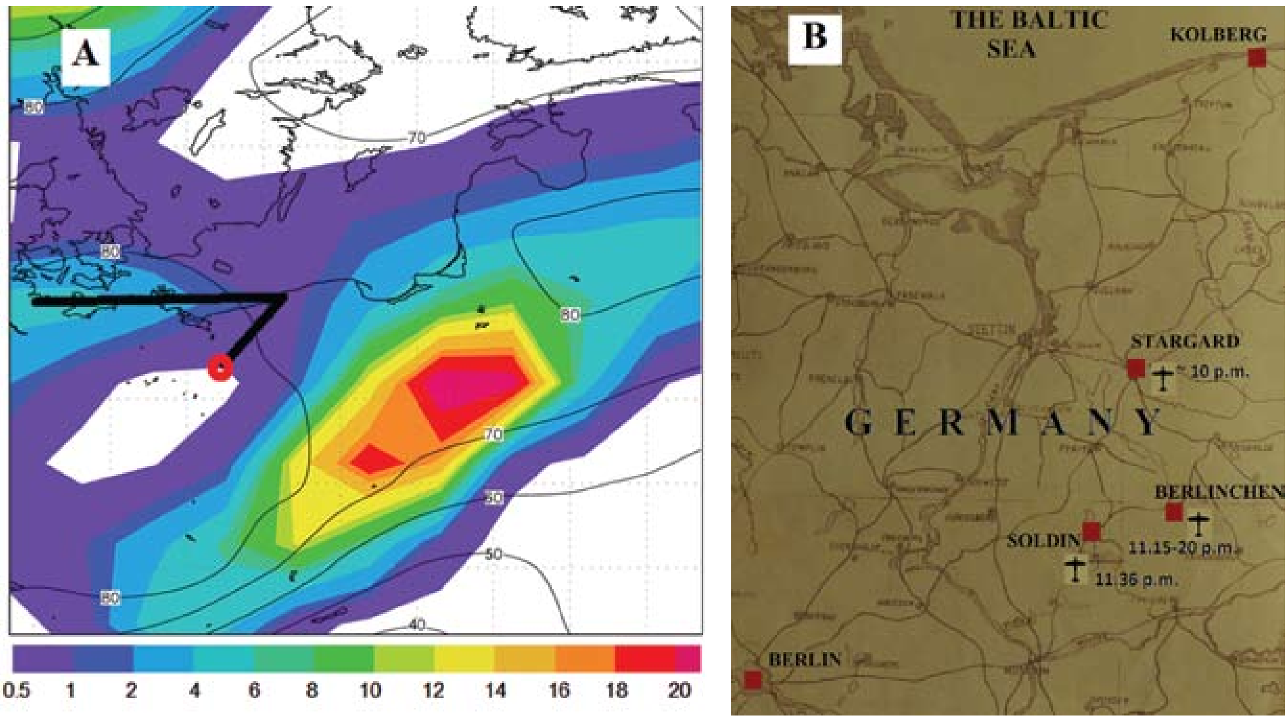

Fig. 6 The mean precipitation amount (mm/6 hours) (colours) and a relative humidity (%) at 900 hPa level (contours) at 18–24 UTC (16 July, 1933). Black line indicates the expected flight path. **A** – the red dot marks the crash site; **B** – the more detailed map of the crash site (near Soldin) area with indicated location of *Lituanica.*

purportedly, direction has changed from west to northwest while speed remained almost unchanged. Nevertheless, the changes in prevailing wind direction usually take place during atmospheric front passage and at the moment of such passage the wind usually become gusty or is accompanied by squall. The mismatches between wind regime described in the report and data derived from weather stations archive may occur due to specific observation time schedule at weather stations: last observations of particular day were used to be made at 6 PM, followed by next observations only in the morning (6 AM) of the next day.

DISCUSSION

According to 20th Century Reanalysis output, the large scale circulation over Northern Atlantic during 15–16 July of 1933 seemed to be "close to normal": Azores High was located within its climatological position while low pressure centres migrate north from it, except the active frontal zone interposed between North America coastline and Azores High; however, this area was beyond the flight route. Both foreign experts, J. H. Kimball and Dr. Soultetus have reported about favourable wind conditions over Atlantic: at most of the flight time the pilots flew downwind, while stronger wind and wind shear fields remained southward from their path. Presumably, that was corrected during the flight, in accordance with visible signs of atmospheric disturbances.

J. H. Kimball attempted to summarize the large–scale atmospheric circulation conditions known for that moment and to assess the contribution of the human factor. Moreover, he pointed out that weather maps were prepared and sent to Mr. S. Darius in time: as the provided data did not contain any extraordinary information about weather conditions, along the flight section neither between New York and Newfoundland, nor over Atlantic and the North Sea, except the narrow poor weather band over Central North Atlantic. This poor weather area started to develop in July 13 eastward from Newfoundland and was well known for the transatlantic flyers. Therefore, J. H. Kimball quite reasonably gave permission to "hop". However, the pilots had to notice wide and high band of the frontal clouds to the southeast of the provided trajectory and could decide to change the course towards the northeast or north.

Weather conditions for the section between British Isles and West Prussia were described in a slightly different mode. The reports of Dr. Soultetus and S. Olšauskas were mainly focused on weather conditions prevailing in Germany at the moment of plane crash. Despite the more professionally coined description by Dr. Soultetus, Mr. S. Olšauskas surpassed his German colleague by adding three detailed synoptic charts (comparing to 20CR data) for the Europe. These charts included accurate position of surface high and low centres, meteorological observations marked by special symbols, isobars etc.

The apparent mismatches of the meteorological information (wind field, precipitation type and intensity, etc.) provided by three different meteorologists could be influenced by following factors: uncertainty about the flight trajectory between Newfoundland and Germany, insufficient available observations over the ocean and North Sea, as well as by absence of conventional meteorological night time observations. The German investigators used the report of Dr. Soultetus, Lithuanians were provided with all three reports. So it is very likely that at least some of the abovementioned distinctive interpretations in their findings were caused by these mismatches.

Summarising information available in all three meteorological reports, the weather information sent to pilots prior to take–off, and an assessed meteorological fields extracted from 20CR dataset, we can conclude that complicated weather conditions prevailed over Eastern Europe during late hours in July 16, 1933 and bad weather signs were clearly visible ahead of the planned flight route. The *Lituanica* was not equipped with the radio, so pilots S. Darius and S. Girėnas were not supplied with in–flight information. That is, they had to make their decisions by compiling a pre–flight weather information and visible observations en–route. On the final stage of their flight, the piloits were forced by an adverse weather to radically change heading and abandon their general flight plan. It is likely that initially they hoped to go round the storm clouds from south. Shortly they realized that the scale of storm clouds is much larger than localized system of convective clouds. They could estimate that a system like this could span hundreds of miles. Therefore, they decided to land in Germany (presumably, in Berlin, but more likely as soon as possible) and looked for an area with at least better visibility conditions, i. e. where the wider breaks in a uniform and continuous cloud cover could be seen. Weather conditions had changed in this particular area in the afternoon and night of July 16: cooler and drier air mass was followed by rain and was favourable for quite thick radiation ground fog formation (2–5 meters). A fog like this is almost transparent from the birds–eye perspective. But when the pilots kept low interception angle just a few meters above the top level of the fog, it became a "a grey soup" with no visual reference to the ground.

If the German and Lithuanian investigators had reported the impact of weather conditions on a flight of *Lituanica* referring only to abovementioned reports and had no other appreciable qualitative information, then the differences in their interpretations of weather conditions (and consequently affected conclusions regarding the cause of the crash) could be explained as follows.

Professional information provided by German expert was more detailed than the one of the Lithuanian meteorologist. Additionally prevailing low cloudiness in the late hours of July 16 was reported by several meteorological stations located in West Prussia, while detailed synoptic charts (synoptic schemes according current understanding) were presented in the annex of Lithuanian report and special symbols and signs indicated similar weather conditions in July 16 as well as in the morning of July 17.

Finally, one question was left unexamined. The German meteorologist has mentioned a difference in atmospheric pressure in sites where *Lituanica* took–off and crashed – respectively, 761 and 755 mm. Dr. Soultetus claimed that the pressure in New York was by 6 mm higher than near Soldin and consequently the aircraft altimeter indicated the higher absolute altitude by 70 meters. However, it is not entirely clear whether the German meteorologist meant the pressure (755 mm) at sea level or at crash site. It is very likely that the pressure at sea level was indicated (according to reanalysis the sea level pressure was 756.7 mm at zero UTC). Also, it is necessary to draw attention to the absolute altitude difference (about 7 m above sea level at the New York airport and about 70 m at the crash site), i.e. very similar height difference with the aforementioned. If Dr. Soultetus indicated pressure at sea level, the altimeter was indicating somewhat correct height above the surface. If Dr. Soultetus indicated pressure at the crash site, then the altimeter of crashed plane had to stop at the 60–70 m mark. In any case, this resulted in even more difficult conditions for landing. On the other hand, in theory, the pilots were able to realize the terrain height (they had a map with the marked line of the primary flight path, which almost crossed the catastrophe location). But practically it was difficult or, more likely, impossible to being assessed in a stressful situation (dark and cramped cabin, fatigue, possible lack of fuel, absence of landing lights, no in–flight information, etc.). It could be argued (only by guessing) that a highly experienced flyer like Captain S. Darius (who was *Lituanica's* first pilot and main navigator) had to understand and assess situation sufficiently ant that in a life-or-death situation the pilots' decision making just could not be entirely tied up to altimeter readings. And so, finally, it has to be assumed that the unknown terrain altitude and atmospheric pressure was just one of the reasons that had led to the crash of *Lituanica*.

CONCLUSIONS

During the *Lituanica* flight from July 15 to 17, 1933, the large scale atmospheric circulation over North Atlantic was "near normal" – no anomalous airflow patterns were detected using given synoptic charts and 20 century reanalysis fields. Much more complicated weather conditions prevailed over Europe: low cloudiness over North Sea and Northern Germany and active atmospheric front from southern Baltic to Carpathians mountains.

An actual flight path of *Lituanica* could have been changed significantly at several points by precautionary weather decision making by Captain S. Darius, who was the first pilot and chief navigator of the transatlantic flight. The reanalysis data did not contradict the statements by official investigators who claimed that: a) *Lituanica* could pass the British Islands being unnoticed because of the thick clouds (German Report); b) the airplane possibly had crossed the narrow northern edge of Scotland (Lithuanian Act of Investigation).

The findings of the study append more detailed information to the three references by the American, German and Lithuanian meteorologists, which were provided to the official investigators in 1933. Accordingly, it explains the differences in assumptions made by the German and Lithuanian officials. It also clears up the vagueness in the Lithuanian officials' conclusion about a "very bad weather" at the vicinity of the crash: weather conditions could hardly be a reason to a worsened "crisis", which allegedly had led to a forced landing near Soldin.

According to this research, the most likely cause of the *Lituanica* crash could be a poor visibility due to low clouds and probable foggy conditions under clouds at the nighttime hours, and a human factor, that is, presumably faulty orientation in space.

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Diatom-based estimation of sea surface salinity in the south Baltic Sea and Kattegat

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Abstract The new diatom-based sea-surface salinity (SSS) estimation has been applied to a collection of 27 taxa in 48 present-day sediment and surface water samples recovered in the Baltic Sea and Kattegat. The sediment core 303610-12 (2005) from the Eastern Gotland was chosen for the study of the Holocene sequence spanning the past 8160 yrs BP. The Artificial Neuronal Network (ANN) method provided an estimation of spring (March-April) SSS values ranging between 7.04-8.25 ‰. The low amplitude of salinity change might be caused by mixing of fresh water with upper surface layer of the Baltic Sea due to high precipitation and riverine input. These findings were compared with independent geochemical proxies for salinity (K, Ti and S) derived from XRF Core Scanner record. Significant correlation between salinity and sulphur records and an inverse correlation between K and Ti demonstrate that the ANN method, when combined with quantitative and qualitative analyses of diatoms, provides a useful tool for palaeo-salinity reconstructions from the Holocene sediments of the Baltic Sea.

Keywords *• diatoms (Bacillariophyta) • artificial neuronal network • salinity reconstruction • reference data set*

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INTRODUCTION

The Holocene Baltic Sea history is bound to sea level changes and isostatic rebound of the Fennoskandia affecting water mass exchange with the Atlantic Ocean that influence environmental conditions in the Baltic Sea basin (Svenson 1991; Bjorck 1995; Harff *et al.* 2001). The Littorina Sea transgression ca. 8500 cal. yrs BP was the most drastic environmental change expressed in terms of salinity increase (Jensen *et al.* 1999; Emeis *et al.* 2003). Inflow of saline waters resulted in a change of a freshwater Ancylus Lake into a brackish-marine water of the Littorina Sea. This caused drastic increase in the sea surface salinity since the last deglaciation (15–17 psu after Willumsen *et al.* 2012). Since the Littorina Sea transgression the Baltic Sea basin has been permanently connected with the Atlantic Ocean through the Danish straits. The intensity and frequency of saline, dense and rich in nutrients water inflows are coupled with the positive index of North Atlantic Oscillation which strength eastward direction of humid air masses. This, in consequence enhance marine inflows into the Baltic Sea (Alheit, Hagen 1997; Harff *et al.* 2011). One of the well proven proxies used to track changes in salinity and to reconstruct them through the Baltic Sea evolution stages is analysis of diatomaceous microfossils preserved in the well dated sediments of the sedimentary basins.

Diatoms are valuable bioindicators due to the abundant occurrence, short life cycle and high vulnerability to environmental parameters. They are sensitive tool often applied for short-term environmental reconstructions (Witkowski 1994; Snoeijs *et al.* 1999; Gersonde, Zielinski 2000; Emeis *et al.* 2003; Gersonde *et al.* 2003). Quantitative and qualitative analysis of diatom assemblages can be used as a proxy of water salinity or temperature in which they dwell. Moreover, based on diatomological analysis trophic status, oxygen saturation, water depth or water circulation pattern, including climate changes and anthropogenic impact can be estimated (Van Dam *et al.* 1994).

Qualitative diatom evaluation has been applied as primary mode of salinity reconstructions in the Baltic Sea Holocene history (Abelmann 1985; Gustafsson, Westman 2002). Chemical methods based on $\delta\ ^{13}C$ / $\delta\ ^{12}C$ ratio in organic matter from surface sediments or on chemical measurements of sediments have been important in previous studies on salinity reconstructions from the Baltic Sea. Isotopic studies took into account deeper water masses, below the halocline indicating higher salinity and greater salinity amplitudes during the Holocene (Emeis *et al.* 2003; Leipe *et al.* 2008). The chemical measurements have been performed on concentration of Boron (Sohlenius *et al.* 1996) and Bromine (Grigoriev *et al.* 2011). It resulted in correlation with water salinity and allowed quantitative reconstruction of palaeosalinity changes particularly during the Littorina Sea and Post-Littorina Sea periods.

Assumptions of this study include water stratification triggered by the inflow of dense saline bottom waters and large freshwater discharge due to riverine waters enhanced by precipitation which affect upper part of the water column (Voipio 1981; HELCOM 2010; Harff *et al.* 2011). Thus, the sea water surface seems to be sensitive to salinity changes.

The goal of this paper is to develop a diatom-based reference data set that in combination with a sophisticated statistical method of ANN can be useful for sea surface salinity reconstructions. Potentially high sensitivity of the surface water in the Baltic Sea to salinity changes provides an opportunity to reconstruct SSS fluctuations with high resolution during the Holocene. For this purpose the paper here presents correlations between observed and estimated salinities in selected areas of the Baltic Sea. Furthermore, assess applicability of the new diatom reference data set based on test SSS reconstructions in the sediment core 303610-12 encompassing sediments from an early-mid Holocene is shown here.

MATERIAL AND METHODS

A total of forty-eight samples were retrieved with the purpose of diatomological analysis based on forty-four present-day surface sediment samples made accessible by the Polish Geological Institute-Polish Research Institute (Marine Geology Branch in Gdańsk-Oliwa) and four surface water samples from PANGEA (Data Publisher for Earth & Environmental Science). Samples were collected from the Kattegat, Pomeranian Bay, Hell Peninsula offshore, Gdańsk Bay, and East Gotland Basin with use of box corer and plankton net (Fig. 1; Table 1).

The 114 Holocene sediment samples (spanning the last 8160 yrs BP) used for testing an applicability of diatom-based reference data set have been recovered from core 303610-12 at location of 57.28°N, 20.11°E (Eastern Gotland Basin; Harff *et al.* 2011). The diatomaceous composition of the core 303610-12 has been studied in the Palaeooceanology Unit at the Faculty of Geosciences, University of Szczecin. The 3.9 m postglacial sediment core have been subdivided into six zones (B1-B6) based on the con-

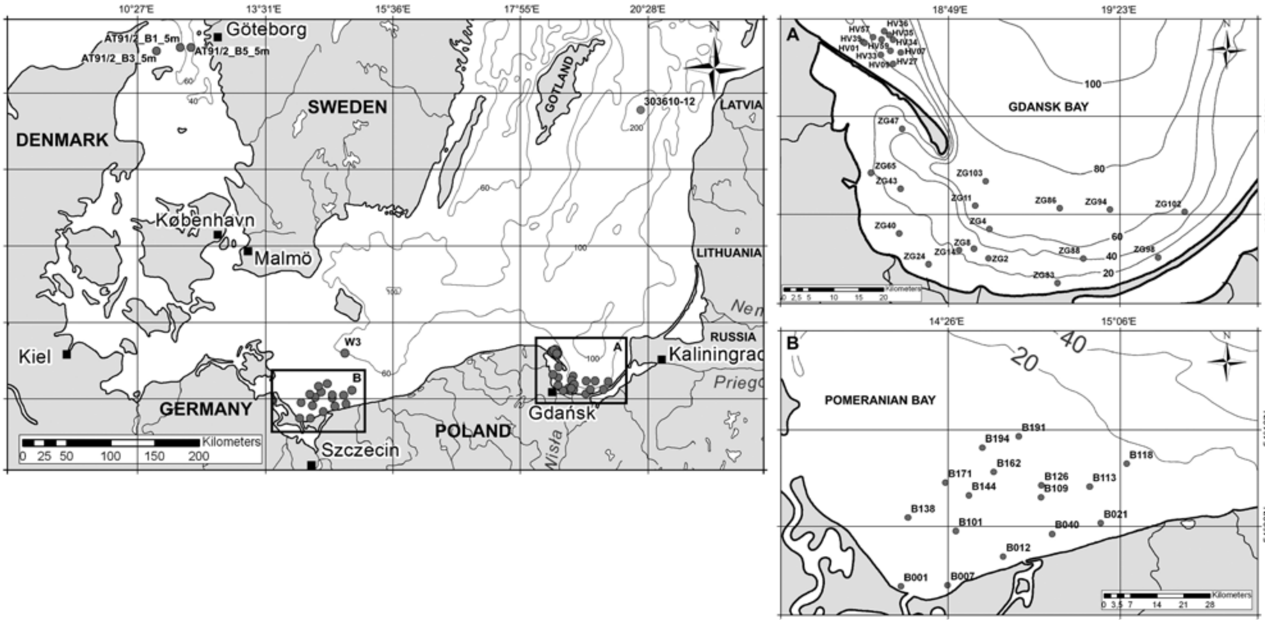

Fig. 1 Location map showing distribution of selected samples for diatom reference data set in Kattegat (AT), Gdansk Bay (ZG), offshore Hell Peninsula (HV), Pomeranian Bay (B), and Eastern Gotland Basin (core 303610-12). Compiled by B. Kotrys, 2014 (after W. Jeglinski, 2014, unpubl.).

Table 1 Codes of samples used for diatom reference data set, their coordinates (decimal latitude and longitude) and depths below sea level (m, b. s. l.)

Sample	Latitude	Longitude	Sample depth (m, b. s. l.)	Studied area
AT91/2_B1_5m	57.55000	11.52500	5	Kattegat
AT91/2_B3_5m	57.53330	11.32500	5	
AT91/2_B5_5m	57.46500	10.90000	5	
B001	53.93537	14.25665	6,9	Pommeranian Bay
B007	53.94830	14.44157	11,2	
B012	54.02777	14.65353	10,8	
B021	54.12632	15.03191	16,4	
B040	54.09136	14.84109	14,1	
B101	54.07751	14.45408	12,8	
B109	54.17494	14.78398	16	
B113	54.21012	14.97507	11,8	
B118	54.27174	15.11528	15,5	
B126	54.20338	14.78116	16	
B138	54.09835	14.25774	13,9	
B144	54.16440	14.49345	13,5	
B162	54.22488	14.58457	15,1	
B171	54.18922	14.39377	13,1	
B191	54.31368	14.67254	10	
B194	54.27992	14.52950	13,6	
W-3	54.63799	14.93805	60,0	Bornholm Basin
HV01	54.78573	18.55843	16,4	Hell Peninsula
HV07	54.76185	18.62259	19,9	
HV09	54.74779	18.65478	21,8	
HV27	54.79113	18.61618	23,1	
HV33	54.76863	18.67789	29,7	
HV34	54.79141	18.65263	28,8	
HV35	54.79971	18.63995	29,0	
HV36	54.80634	18.62357	27,1	
HV39	54.78361	18.56451	16,3	
HV57	54.79457	18.58986	21,1	
HV59	54.76557	18.65084	23,6	
ZG102	54.49540	19.57158	47,2	Gdansk Bay
ZG103	54.54187	18.95361	67,6	
ZG11	54.49690	18.92278	64,3	
ZG14	54.41596	18.87669	20,2	
ZG2	54.40229	18.96934	24,5	
ZG24	54.38886	18.78434	12,7	
ZG4	54.45547	18.96930	61,9	
ZG40	54.44259	18.69151	12,2	
ZG43	54.52350	18.69090	28,1	
ZG47	54.63138	18.69009	43,9	
ZG65	54.55018	18.59794	14,2	
ZG8	54.41599	18.92293	30,1	
ZG83	54.36194	19.18473	9,2	
ZG86	54.49679	19.18534	71,4	
ZG88	54.40674	19.26198	38,6	
ZG94	54.49644	19.34004	70,4	
ZG98	54.41205	19.49252	7,9	

tinuously measured physico-lithological properties. Zonation from B1 to B6 represents Littorina Sea to recent Baltic Sea stages which are dominated mainly by laminated sediments (Harff *et al.* 2011).

To process of cleaning the surface sediment began with application of hydrogen peroxide and hydrochloric acid (HCl) heated to 170°C and were then decanted ten times. For the preparation of microscopic slides with randomly dispersed diatom valves sediment residuals were diluted with demineralized water to an amount of 300 ml. Defined amount of suspension was carefully dispersed on the cover glass with an automatic pipette. The water was slowly removed from the cover glass dish by evaporation. After complete removal of the water the cover glass was mounted with Naphrax.

Light microscopic analyses were conducted with a Nikon Optiphot-2 microscope with at a magnification of 1000x. Generally ca. 300 diatom valves were identified and counted per sample. Based on the qualitative counting results and ecological characteristics particular diatom taxa diatoms were analysed in terms of habitat and salinity.

For the purpose of salinity estimations it was decided to use the Artificial Neuronal Network technique (ANN; Malmgren, Nordlund 1997). In spite of rare usage of ANN in micropalaeontological studies, however, it provides good results considered to be better estimate than statistical methods as for example Imbrie and Kipp Method (IKM) or Modern Analogue Technique (MAT; Chen *et al.* 2005). Particularly when the limited reference data set restricted mainly to the southern Baltic Sea is considered this method seems to be suitable for palaeosalinity estimations (Kotrys 2012).

The first description of principles for training the ANN was established in 1940 (Wasserman 1989). The ANN was found to be applicable for gas and oil exploration, in military techniques, in medicine or economy. For palaeoceanographic purposes the ANN was initially tested and applied by Malmgren and Nordlund (1997).

The learning sequence known as back propagation or propagation of error of ANN, which was applied to these studies, is processed by an algorithm that works by what is known as supervised training (Malmgren, Nordlund 1997). Firstly an input is transferred for a forward pass through the network. The network output is compared to the assumed output, which is specified by the computer simulation (as supervisor), and the error for all the neurons in the output layer is calculated. The essential mechanism behind back propagation is that the error is propagated backward to earlier layers so that a gradient descent algorithm can be applied (Malmgren, Nordlund 1997; Malmgren *et al.* 2001; Cortese *et al.* 2005; Kucera *et al.* 2005).

To perform the ANN salinity estimations on the basis of changes in diatom assemblages NeuroGenetic Optimizer (NGO, version 2.6.130, ©BioComp Systems, Inc.) software developed by Malmgren, Nordlund (1997) was applied. This software provided the best results from ANN tests conducted in a study by Cortese *et al.* (2005). They tested by means of a radiolarian reference data set and summer sea surface temperature the two different ANN programs: the NeuroGenetic Optimizer (NGO; ©BioComp Systems, Inc.) and the iModel (©BioComp Systems, Inc.). The most accurate data were produced by the NGO. Cortese *et al.* (2005) found, based on three test runs, that the NGO generated slightly lower error rates than the iModel.

REFERENCE DATA SET

A basic assumption to develop a reliable reference data set and perform sea surface salinity (SSS) reconstructions was that the composition of microfossil assemblages (e.g. diatoms) preserved in the surface sediment record corresponds with the present-day oceanographic parameters (e.g. salinity) and that this relation remained unchanged during the studied geological time period. The main principles of constructing of a microfossil-based reference data set for palaeoreconstructions are (1) the proper selection of surface water environmental parameters (e.g. salinity), and (2) the proper selection of microfossil species used as proxies for palaeoreconstructions (e.g. Cortese, Abelmann 2002). Following these principals salinity data from hydrographic data bank of Pan-European infrastructure for Ocean, Marine Data management (SeaDataNet) and European Marine Observation and Data Network (EMODNET Chemistry) have been used. Surface salinity data was extracted with application of the online OceanBrowser (access date 05. 2013).

The application of present day hydrographic data and surface sediment samples guarantees that the palaeosalinity estimations are based on reliable reference data set representing the modem environment condition. Palaeosalinity estimations were restricted to spring conditions when diatoms peak production occurs (Wasmund *et al.* 1998). The applied hydrographic data represent salinity values averaged over a time period spanning April-May. Salinity data were taken from two meters water depth. Values from this depth reflect surface water conditions that are sensible to short-term salinity changes that can occur in the marine water.

On the basis of the OMNIDIA ver. 3 software, which has a database (Omnis7) with information on more than 11 000 species, we selected surface and bottom water dwelling taxa that representing fresh,

fresh brackish, brackish fresh, brackish and brackish marine water environmental conditions. From the total of 265 taxa recorded in the analysed sample set, 27 planktonic taxa were chosen to be included in the reference data set (Table 2).

The selection of taxa was carried out as follows: surface water dwelling taxa were selected that demonstrate a clear geographic relationship with the surface water salinity pattern in the study area; only taxa that can be doubtless identified on the basis of unequivocal taxonomic description and documentation to guarantee that the species abundance pattern revealed from the analysed reference data set and down-core assemblages that can be related to each other in terms of ecology were selected; included were only diatoms from sediment samples containing well preserved and silicified specimens; to balance the weight between fresh, brackish, brackish fresh, brackish and brackish marine diatoms a comparable number of taxa representing each above mentioned group was included in the data set used herein; taxa inhabiting deeper waters have been eliminated from the data set; taxa representing no-analog species in the geological record have not been considered.

A no-analogue situation is where the maximum abundance of a specific diatom taxa from a down-core record exceeds its maximum abundance from a reference data set. This problem can have its source in selective dissolution or in different marine conditions that do not occur in the present day sea water and therefore such species must not be considered for quantitative reconstructions of palaeoenvironment (e.g. Ablemann, Gowing 1997; Cortese, Abelmann 2002; Kotrys 2012). In order to decrease the ratio between diatom taxa of high and low abundance the reference data set was logarithmically transferred (Kotrys 2012).

TESTING THE ARTIFICIAL NEURONAL NETWORK

For the purpose of testing the diatom reference data set and estimate down core spring SSS of the NGO ANN had to be properly calibrated. For the estimation of prediction error the Root Mean Square Error of Prediction (RMSEP) was applied. The RMSEP is the square root of the sum of the squared differences between the observed and predicted values for all observations in the test set divided by the number of such observations, to estimate the prediction error (Kotrys 2012). A minimum of 50 network training passes were applied with the cut-off for network training passes was set up to 1000. The network employed 27 inputs and 2 hidden layers.

Table 2 List of diatom taxa selected from surficial samples and plankton net for the reference data set and their ecological demands applied to core 303610-12

Achnanthes taeniata Grunow 1880; brackish marine: from 1.8 to 34 ‰.
Actinocyclus normanii (Gregory); Hustedt 1957; brackish: from 1.8 to 9.0 ‰.
Actinocyclus octonarius var. *crassus* (Smith); Hendey 1954; fresh brackish: <0.9 ‰.
Asterionella glacialis Castracane 1886; brackish marine: from 1.8 to 34 ‰.
Aulacoseira alpigena (Grunow); Krammer 1991; fresh: <0.2 ‰.
Aulacoseira ambigua (Grunow); Simonsen 1979; fresh brackish: <0.9 ‰.
Aulacoseira granulata (Ehrenberg); Simonsen 1979; fresh brackish: <0.9 ‰.
Coscinodiscus radiatus Ehrenberg 1840; brackish marine: from 1.8 to 34 ‰.
Cyclostephanos dubius (Fricke); Round 1987; brackish fresh: from 0.9 to 1.8 ‰.
Cyclostephanos tholiformis Stoermer; Håkansson, Theriot 1987; fresh: <0.2 ‰.
Cyclotella atomus Hustedt 1937; fresh brackish: <0.9 ‰.
Cyclotella choctawhatcheeana Prasad; Neinow, Livingston 1990; brackish: from 1.8 to 9.0 ‰.
Cyclotella meneghiniana Kützing 1844; fresh brackish: <0.9 ‰.
Leptocylindrus danicus Cleve 1889; brackish marine: from 1.8 to 34 ‰.
Leptocylindrus minimus Gran 1915; brackish marine: from 1.8 to 34 ‰.
Nitzschia longissima (Brébisson); Ralfs 1861; brackish marine: from 1.8 to 34 ‰.
Proboscia alata (Brightwell); Sundström 1986; brackish marine: from 1.8 to34 ‰.
Rhizosolenia fragilissima Bergon 1903; brackish marine: from 1.8 to 34 ‰.
Rhizosolenia hebetata Bailey 1856; brackish marine: from 1.8 to 34 ‰.
Skeletonema marinoi Sarno, Zingone 2005; brackish: from 1.8 to 9.0 ‰.
Staurosira elliptica (Schumann); Williams, Round 1987; brackish: from 1.8 to 9.0 ‰.
Stephanodiscus hantzschii Grunow 1880; fresh brackish: <0.9 ‰.
Stephanodiscus parvus Stoermer, Håkansson 1984; fresh brackish: <0.9 ‰.
Thalassiosira baltica (Grunow); Ostenfeld 1901; brackish: from 1.8 to 9.0 ‰.
Thalassiosira eccentrica (Ehrenberg); Cleve 1904; brackish marine: from 1.8 to 34 ‰.
Thalassiosira proschkinae Makarova 1979; brackish: from 1.8 to 9.0 ‰.
Thalassiosira visurgis Hustedt 1957; brackish: from 1.8 to 9.0 ‰.

Before application of ANN the original data were manually divided into two series (24 samples each) according to geographical distribution. This operation was carry out in order to enable the software to use equally mixed samples in training and test sets. For the 48 samples included in the reference data set, 24 samples were used as the training set, and the remaining 24 samples as the test set.

As the selected test set samples are not included in the training procedure, the error rates are based on this set. They therefore provide estimates of the prediction error rate in samples different than those used in the training set (Cortese *et al.* 2005). Thus, obtaining an RMSE of 0.5, if the estimated salinity is 8 ‰, means that the estimated error in palaeosalinity data is at least 0.5 ‰. In other words the lower RMSE is calculated by ANN the lower salinity error for down core reconstructions (Cortese *et al.* 2005).

For greater accuracy, two ANN runs using the NGO, averaging salinity estimates and RMSE from ten best networks was conducted. In the first run the training and test sets were included. Whereas in the second run the test samples were added to the training set and vice versa. In this way 20 best networks based on test and training sets within studied data set have been obtained.

In order to test down core spring SSS estimations based on diatom reference data set a well examined and dated sediment core 303610-12 located at the Eastern Gotland Basin was applied. This record has been analysed and described in detail by Harff *et al.* (2011). Core 303610-12 documents climate and environmental changes of the Baltic area and the North Atlantic region. High quality quantitative diatom analyses and measured concentration of potassium, titanium and sulphur in this core show a potential history salinity fluctuations in time spanning the last 8 kyr (Harff *et al.* 2011).

ESTIMATION FOR DIATOM REFERENCE DATA SET

To evaluate the ability of the ANN to predict salinity, the estimated spring SSS values from each NGO network were plotted against the measured spring SSS. Linear equations gave a satisfactory correlation between estimated and measured salinity values (correlation coefficients R^2=0.9885; Fig. 2). The RMSE of estimations is low 0.628 ‰, meaning that down core salinity can be predicted within relatively low error range.

To show differences between observed and estimated salinity for each sample residuals were calculated (Table 3). The residual at each sample location is defined as the observed value minus the estimated value. This means that positive values are underesti-

Table 3 Differences between estimated and observed salinity values for each surficial sample shown as residuals

Sample	Estimated salinity (‰)	Observed salinity (‰)	Residuals (‰)
AT91/2_B1_5m	21.6923	20.9690	0.7234
AT91/2_B3_5m	21.7025	21.0258	0.6767
AT91/2_B5_5m	21.5725	23.2045	-1.6320
B001	6.1296	5.4804	0.6493
B007	6.5757	6.3711	0.2046
B012	6.8366	6.9181	-0.0815
B021	7.0889	7.3166	-0.2277
B040	7.0261	7.2439	-0.2178
B101	7.3005	6.8667	0.4338
B109	7.3085	7.3599	-0.0514
B113	7.5605	7.5171	0.0434
B118	7.6266	7.5558	0.0708
B126	7.5516	7.4780	0.0736
B138	6.7684	6.8869	-0.1185
B144	7.0643	7.2759	-0.2116
B162	7.1687	7.5072	-0.3384
B171	7.4316	7.4288	0.0029
B191	7.7430	7.6379	0.1051
B194	7.5770	7.6322	-0.0551
HV01	7.3334	7.1808	0.1526
HV07	7.1282	7.1128	0.0154
HV09	6.9843	7.1350	-0.1507
HV27	7.2077	7.2155	-0.0078
HV33	7.2182	7.1398	0.0784
HV34	7.1441	7.2438	-0.0996
HV35	7.0952	7.2438	-0.1486
HV36	6.9970	7.2155	-0.2185
HV39	7.1958	7.1808	0.0150
HV57	7.1368	7.2155	-0.0787
HV59	7.0185	7.1350	-0.1165
W-3	7.6111	7.6473	-0.0362
ZG102	6.3196	6.6685	-0.3489
ZG103	7.0714	6.6119	0.4595
ZG11	6.1823	6.3450	-0.1627
ZG14	5.7606	5.5636	0.1971
ZG2	5.7299	5.4225	0.3074
ZG24	6.1589	5.6715	0.4874
ZG4	6.4416	5.9289	0.5128
ZG40	6.3041	6.2873	0.0168
ZG43	6.0829	6.7472	-0.6643
ZG47	6.9708	7.1603	-0.1895
ZG65	6.4120	6.8387	-0.4267
ZG8	5.7533	5.4225	0.3309
ZG83	5.7290	5.2583	0.4708
ZG86	6.6636	6.4486	0.2150
ZG88	6.1075	5.7821	0.3255
ZG94	6.9101	6.5768	0.3333
ZG98	5.7502	5.7817	-0.0315

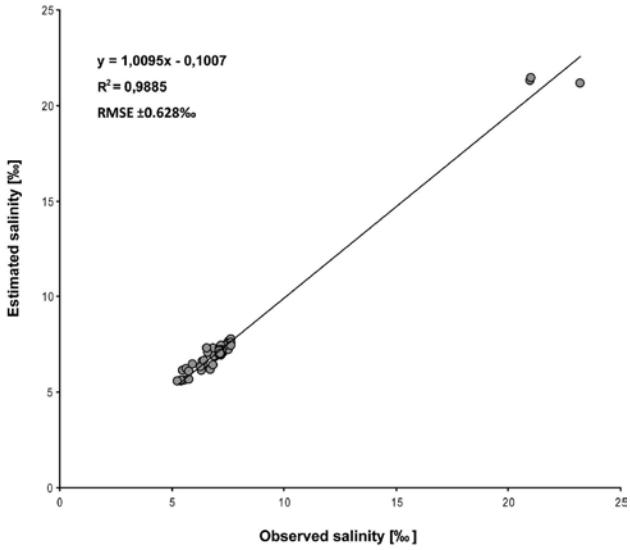

Fig. 2 Observed vs. estimated spring SSS derived from the diatom reference data set used for Artificial Neuronal Network (ANN). Regression line, R2 and RMSE show low differences between estimated and observed salinity values. Dots of low salinity values (between 5 and 10 ‰) represent modern surface sediment samples from the Baltic Sea, and dots of high salinity values (>20 ‰) stand for Kattegat. Compiled by B. Kotrys, 2014.

mating and negative values are overestimating spring SSS. In each network residuals >1.5 ‰ are only noted for one sample recovered from Kattegat. All other values are in the range between -0.9 ‰ and 0.9 ‰, with a general distribution between -0.4 and 0.4 ‰. No conspicuous latitude- longitudinal tendency to underestimate or overestimate salinity is observed.

DOWN CORE SPRING SEA SURFACE SALINITY PREDICTION

The results of palaeosalinity estimation for core 303610-12 show continued record of the last 8 kyr and can be well correlated with other proxies referring to salinity changes in time interval studied. The obtained paleosalinity projection displays slight fluctuations mainly between 8.0 and 7.2 ‰ within the last 8 kyr. The maximum salinity value exceeds 8.1 ‰ and occurs in zone B3 whereas the minimum salinity also occur in zone B3 reaching value >7.1 ‰ (Fig. 3). Within investigated palaeosalinity record of core 303610-12 following Harff *et al.* (2011) six different salinity trends (B1, B2, B3, B4, B5 and B6) are interpreted. During B1 spring SSS record displays conspicuous increase from less than 7.4 ‰ to an average of 7.7 ‰. Within B2 salinity values drop below 7.5 ‰ and increase over 7.7 ‰. Interval of B3 is characterized by rather stable spring SSS with salinity level of about 7.7 ‰. Long lasting decrease of spring SSS is, however, observed in B4. Salinity values drop from an average of 7.7 ‰ to 7.5 ‰ in the upper B4 and then increase substantially. The zone B5 is characterized by high salinity variations. General trend shows salinity increase whereas values oscillate between 8 ‰ and 7.4 ‰. The highest spring SSS amplitude in B4 is 0.6 ‰. Transition from B5 to B6 is marked by high salinity value of 8 ‰. Further salinity trend demonstrates decrease reaching the minimum of >7.4 ‰. The tendency turns over towards higher values in the middle of B6 (7.6 ‰-7.8 ‰).

The reconstructed salinity changes in core 303610-12 show rather low amplitude and low maximum values especially during the Littorina Sea transgression. This is contradictory to the other scientific studies. However, it has been assumed that the upper surface water layer was exposed to higher precipitation and riverine fresh water input to the Baltic Sea in the warm and damp Atlantic period. Therefore, higher salinity of 12-17 ‰ could occur in deeper part of sea water masses.

SPRING SEA SURFACE SALINITY ESTIMATION FOR THE CORE 303610-12

The general trend of analysed palaeosalinity distinctly correlates with diatom percentage curves based on changes in the distribution of planktonic species composition within core 303610-12 (Fig. 3). Higher salinity level is associated with increase of percentage abundance of diatom taxa that belong to brackish and marine environment. Whereas lower spring SSS corresponds to high percentage abundance of fresh and brackish taxa. However, the percentage variations of brackish diatom assemblages in some parts of studied sediment core do not demonstrate substantial similarities to reconstructed salinity. It has been assumed that it may be caused by their wide range of tolerance for high and low salinity level.

Measured concentration of potassium, titanium and sulphur in sediment core which are parallel to inorganic matter increases and identify increase in erosion and sedimentation pattern shifts (Kenna *et al.* 2011), shows similarities with the general trend of spring SSS. The higher down core concentration of K and Ti within zones B2, B4, and B6 may correspond to higher terrestrial discharge that can be triggered by enhanced precipitation (Harff *et al.* 2011). Additionally, together with pelagic deposition concentrations of K can be interpreted as an increase in the importance of aeolian sediment transport. This would lead to less saline surface water that is clearly shown in the spring SSS record (Fig. 3). However, the higher sulphur content in zones B1, B3 and B5 is interpreted as an indicator of anoxic condition (Sternbeck, Sohlenius 1997) which reflect increase of salinity and prevailing halocline. Intervals of higher salinity level reconstructed within the above mentioned zones are well correlated with high sulphur concentration and sections of laminated sediment.

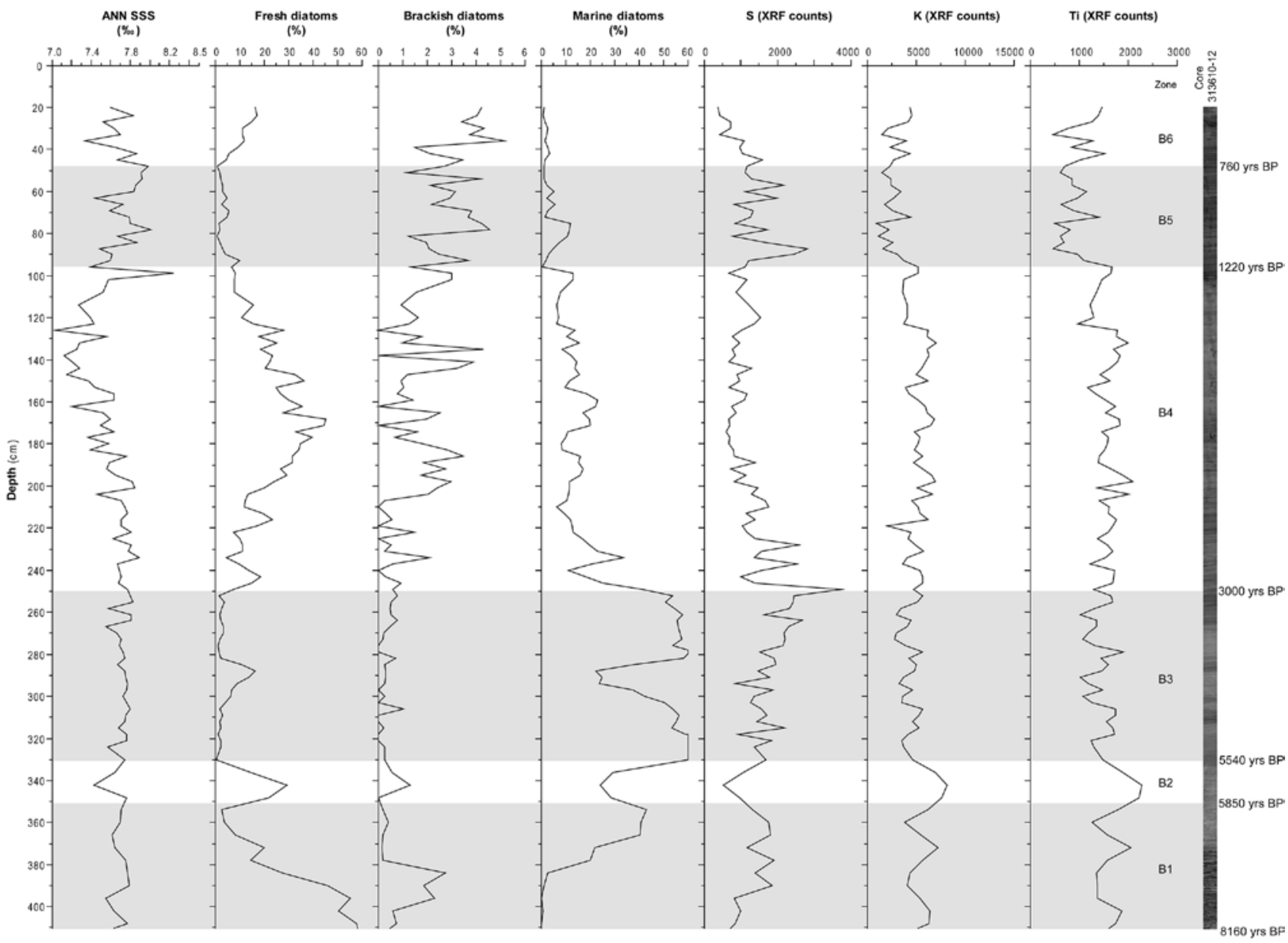

Fig. 3 Compilation of down core reconstructed spring sea surface salinity (SSS; ‰); abundance of fresh, brackish and marine diatoms (%). Content of sulphur (S), potassium (K) and titanium (Ti) at sediment core 303610-12, and physico-stratigraphic zonation from B1 to B6 presenting the post-Littorina to recent Baltic Sea climatic stages is given after Harff *et al.* (2011) ; visualization of sediment core is done by M. Tomczak (2008). Compiled by B. Kotrys, 2014.

CONCLUSIONS

On the basis of the quantitative analysis of diatom assemblages from 48 samples recovered in the Baltic Sea and Kattegat, an artificial neuronal networks for the estimation of the Holocene spring SSS have been developed.

The ANN relies on high-quality surface and net samples, modern hydrographic data and carefully chosen diatom taxa (training set). For the species selection it was considered that ecological information on salinity and habitat demands to ensure that only species classified to specific salinity range that are surface-dwelling are included. The salinity reconstruction has been conducted only for the spring period (from March to April) when the diatom blooms occur.

The spring SSS estimation for core 303610-12 shows salinity range between 7.04 ‰ and 8.25 ‰ at an averaged RMSE of 0.49 ‰ within the last 8160 yrs BP. A comparison of the palaeosalinity record to percentage diatom assemblages variations and excursion of K, Ti and S in core studied shows clear correlation to each other.

The diatom based ANN predictions can be successfully applied to document history of salinity changes of the Baltic Sea. Therefore, it can be useful either to quantify previous studies of sea surface salinity changes in Baltic Sea or where other proxies for Holocene salinity are limited.

In order to improve palaeosalinity investigations there is a need to develop diatom reference data set including samples from other regions of the Baltic Sea. Especially samples from more saline surface water masses are required.

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