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Seasonal and spatial variations of sedimentary matter and diatom transport in the Klaipėda Strait (Eastern Baltic)

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Abstract The exchange of sediment between the Baltic Sea and the Curonian Lagoon was studied in the Klaipėda Strait from 1994 to 2008 using special sediment traps. The examination of trap samples demonstrates that migrating sedimentary matter, i.e. the concentration and composition of sediment fluxes in the strait, varies widely. Seasonal and spatial variations of sediment fluxes directly depend upon the hydrometeorological situation. The most intensive vertical flux according to mean values is recorded in the port gate water area of the strait during spring and winter seasons and also in the western passage of the Curonian Lagoon in the autumn. The smallest sediment fluxes are determined in the Malkų Bay. Grain sizes of transported sediments vary from silty-clayey mud up to fine sand. The dominating sediment fraction is 0.05-0.01 mm. The grain size of sedimentary matter is associated with the intensity of sediment transport. The more intensive sediment fluxes transport much coarser matter, and when the intensity decreases the amount of finely dispersed matter relatively increases. Variation in numbers of marine, brackish, and freshwater diatom specimens reflects the relative mixing of Baltic Sea marine and Curonian Lagoon fresh water together with transported sediments in the strait.

Keywords *Sediment vertical flux, diatoms, Klaipėda Strait, Curonian Lagoon, Baltic Sea..*

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INTRODUCTION

Studies on sediment transport are important in water environments where exchange water of different origin (frequently marine and fresh water). Emerged currents bring resuspended and produced in water column particles in both directions via straits. Especially important is obtain data and knowledge about intensity of sediment fluxes in strait and circumstances that influence sediment transport. Most studies on sediment fluxes were performed analysing sediment trap material (Bárcena *et al*. 2004; Johannesen *et al*. 2005; Roos *et al*. 2006; Pospelova *et al*. 2010). Sediment trap construction usually is not uniform for different environments. It depends mostly on flow velocities (White 1990). However, the main objective is sediment material investigation of sediment traps applying different methods (grain size, fluxes, microalgaes) for studies of environmental processes in strait.

Understanding environmental change and the circulation via the Klaipėda Strait of sedimentary matter between the relatively large water basins of the Baltic Sea and the Curonian Lagoon requires both qualitative and quantitative information. Sediment composition, seasonal intensity of sediment fluxes in the Klaipėda Strait provides knowledge about flow and sedimentary matter exchange between brackish and freshwater basins. Especially important role in this connection is the contribution of diatom analyses. Diatoms are major primary producers in a variety of modern aquatic environments, particularly in waters of middle and high latitude settings (Berger, Wefer 1991). Although, fossilized diatom frustules accumulation in the sediment core occurs at only 2.8% of the rate of accumulation in the sediment trap, taxonomic studies are valuable for reconstruction of palaeoenvironments (Kato *et al*. 2003).

The Baltic Sea has a relatively small volume of water mass in comparison to its large surface area (425.4 $x10^3$ km^2). Freshwater inflow into the basin is very significant and water salinity is not high in the Baltic Sea (decreasing from 30-32‰ near the Danish Straits to 7-8‰ in the central part of the sea). The Curonian Lagoon is in the south–eastern part of the Baltic Sea (Fig. 1). This lagoon has a triangular shape, shallow (average depth 3.8 m) and its water surface area is about 1550 km^2 (Žaromskis 1996). The Klaipėda Strait connects the Curonian Lagoon with the Baltic Sea and the exchange of water and sedimentary matter between the Curonian Lagoon and the Baltic Sea occurs in both directions.

The Klaipėda Strait is 12 km in length. Its width at the port gate is 385 m, but it reaches almost 1500 m in the southern part, where the strait joins the Curonian

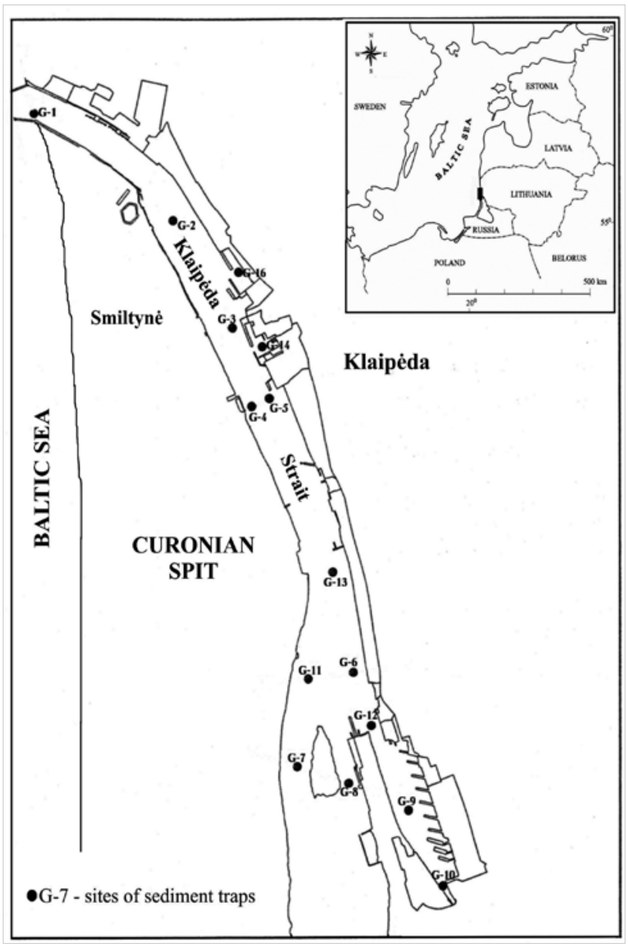

Fig. 1. Sampling sites in the Klaipėda Strait. Compiled by S. Gulbinskas and G. Vaikutienė, 2009.

Lagoon. Water outflow from the lagoon to the Baltic Sea is 27.655 km^3/year; the volume of reverse flow is 6.125 km^3/year (Jakimavičius, Kovalenkovienė 2010). According to average long–term data the ratio between fresh water flow from the lagoon and brackish water inflow from the sea is 4.5. The proportions of sedimentary matter supplied from these two water bodies seem to be similar. Extreme current velocities and alteration in their direction occur during abrupt and strong changes in hydrometeorological situation, usually in the autumn and winter seasons (Gailiušis *et al*. 1992; Galkus, Jokšas 1997; Pustelnikovas, Salučka 1999; Gailiušis *et al*. 2002; Kriaučiūnienė *et al*. 2006). For this reason, flow velocities and transport of sedimentary matter in the Klaipėda Strait changes is also variable over time.

The main objective of our investigation is to reveal the spatial and seasonal variations of the sedimentary matter circulation between different aquatic systems on the basis of transported matter concentration and diatom studies. For this purpose research of sediment fluxes and diatom assemblages was made using numerous sediment traps material.

METHODS AND MATERIAL

Samples of the transported material were obtained using sediment traps. They were made of plastic tubes, 14 cm in diameter, 1.2 m high and with a collecting area of 154 cm^2. Vertical sediment flux was documented in the port gate water area (G-1), the main transit part of the Klaipėda Strait (G-2, G-3, G-4, G-5, G-13), in the eastern part of the strait with very intensive human activities (G-6, G-12), including the Malkų Bay (G-9, G-10) and other semi–closed bays (G-14, G-16), as well as at the strait–lagoon junction, i.e. its western (G-7) and eastern (G-8) passages (Fig. 1). Sediment traps were moored at a depth of 3 m from the bottom. Sediment samples were collected at approximately one week four times per year, in order to collect sediment matter transported during different seasons. Such examination in the Klaipėda Strait was carried out during 1994–2008.

The rate of vertical sediment flux was calculated as the sedimentary material collected in the traps per their exposition time (g/cm^2/day). All in all 265 measurements have been done. Grain size composition of transported matter was analysed using sieving and pipette methods. The sediments were classified using decimal grain size scale (Bezrukov, Lisitzin 1960).

Diatom composition was studied in 24 samples obtained from sediment traps. The laboratory preparation of sediment samples for diatom analysis was prepared following R.W.Battarbee (1986). Carbonates were eliminated using hydrochloric acid, and concentrated hydrogen peroxide was used to destroy the organic matter. The clay particles were eliminated by decanting after the preliminary boiling of sediments in sodium pyrophosphate (10%) water solution. Slides for microscopic analysis were prepared using *Naphrax"* mounting. Diatom species were identified using taxonomic works (Krammer, Lange–Bertalot 1986–1991).

The succession of the most frequent and ecologically important taxa is presented as percentages of the total sum of identified diatoms. In order to describe water salinity, diatom species were divided according to their salinity requirements into marine and brackish (water salinity 0.2–30‰) and freshwater diatoms. Also three habitat groups of diatoms were distiguished: planktonic, benthic and epiphytic (Van Dam *et al*. 1994; Barinova *et al*. 2006) and presented the programs *TILIA* and *TILIA−GRAPH* (Grimm 1992).

RESULTS AND DISCUSSION

Sedimentary matter

Previous results, obtained using sedimentary traps, have shown that the intensity of sedimentation in the Klaipėda Strait is highly variable (Trimonis, Gulbinskas 1999 a,b). The long–term measurements of this present study reveal that the range of vertical sediment flux is very large – from 2 up to18621 g/cm^2/day (Table 1). These rates were recorded in spring – the minimal value in the Malkų Bay (G-9), and the maximum in the port gate water area (G-1). The extremely high vertical flux, which was calculated from sediments in traps, differs from real accumulation on the bottom. The main reason is that every portion of transported material, which gets into the trap, is accumulating. But on the bottom sediments are re–suspended very actively and it doesn't permit large accumulation. Very intensive vertical sediment fluxes were measured in the port gate water area during the winter–spring period (February–March; Fig. 2). Another area of the intensive transportation of the sediments in the strait is the western passage of the Curonian Lagoon (G-7). There the rates in April and November are 13053-10795 g/cm^2/day. It reflects the hydrometeorological changes, sometimes short–term, when the major changes in current directions and velocities occur. The port gate water area and western passage of the lagoon are especially impacted because of the large water masses involved. It is probable that in such dynamic areas the sediment trap data are increased by resuspended sediments from the bottom.

The intensity of sediment fluxes in the main navigation part of the Klaipėda Strait varies to a lesser degree, 19-5199 g/cm^2/day. The highest intensity was measured at the sites G-2 (3341 g/cm^2/day), G-3 (1535 g/cm^2/day) and G-4 (5199 g/cm^2/day) in November, which is characterized as a period of frequent hydrodynamic changes. The parameters for each monthly time–period do not depend only on the natural factors since water turbidity in the strait occasionally increases because of human impact, such as dredging in the navigation channel.

The eastern passage of the lagoon (G-8) also has dynamic conditions, including and highly variable sediment inflow from the Curonian Lagoon (Table 1, Fig. 2). The lowest vertical fluxes are characteristic of the Malkų Bay (G-9, G-10), where sedimentation conditions are less influenced by current changes typical of the strait.

The seasonal variations of sedimentation reflect the mean parameters of the short–term values. These averages were calculated one site of the Klaipėda Strait (Table 1, Fig. 3). The highest seasonal sediment flux average is in the port gate water area in winter 3919 g/

Table 1. Intensity of vertical sediment fluxes (g/cm^2/day) in the Klaipėda Strait (1994–2008). Compiled by E. Trimonis, 2009.

Site		Season			
		spring	summer	autumn	winter
		g/cm^2/day	g/cm^2/day	g/cm^2/day	g/cm^2/day
G-1	a	16–18621	153–1040	23–6355	79–14142
	b	2712	364	1787	3919
G-2	a	19–1486	101–617	19–3341	41–205
	b	562	293	848	123
G-3	a	88–1004	201–830	21–1535	57–1638
	b	451	393	591	540
G-4	a	23–1133	140–1350	24–5199	68–2148
	b	349	396	1037	870
G-5	a	37–880	208–382	132–1225	24–764
	b	373	268	672	333
G-6	a	46–433	148–309	16–547	144–1796
	b	243	232	420	601
G-7	a	7–13053	213–731	6–10795	514–912
	b	1576	446	2233	713
G-8	a	3–9259	105–646	10–3043	33–855
	b	1008	350	730	311
G-9	a	2–406	13–950	30–245	–
	b	131	238	117	103
G-10	a	187–241	–	64–128	443–448
	b	207	257	96	446

a – limit of flux intensity; b – mean value.

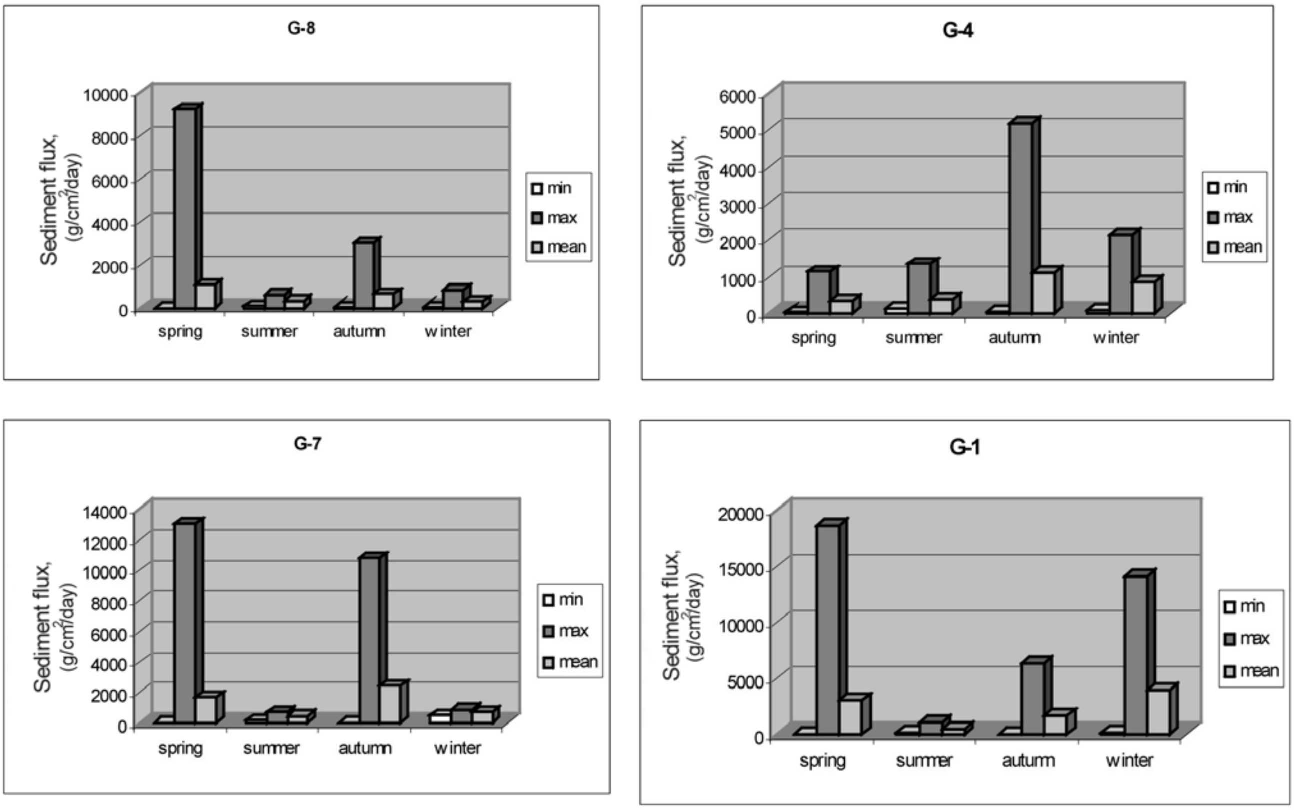

Fig. 2. Vertical sediment flux variations in the year seasons. G-8, eastern, and G-7, western passages of the Curonian Lagoon; G-4, central part of the Klaipėda Strait; G-1, port gate water area. Compiled by E. Trimonis, 2009.

cm^2/day, and the lowest is 96 g/cm^2/day in autumn near the Wilhelm Channel in the Malkų Bay. The seasonal variations show that maximum mean values of the flux intensities are in the port gate water area during spring (2712 g/cm^2/day) and winter (3919 g/cm^2/day) and in the western passage of the lagoon during summer (446 g/cm^2/day) and autumn (2233 g/cm^2/day). So, the most intensive sediment transport in the strait is going on during spring and winter. But the autumn period (especially November) is very similar in that it has extreme weather changes, which are reflected in water turbulence and sedimentation rates. The smallest changes of the sedimentary flux intensities take place during summer–from 232 up to 446 g/cm^2/day.

Transported sediment shows large variations in grain size. The data have revealed that suspended sediments change from site to site in the strait and over time at the same places. The sediments transported in the strait are often dominated by fine silt (0.05-0.01 mm), but coarse silty mud (Md 0.1-0.05 mm) is transported during some shorter time periods. Fine sand material (Md 0.25-0.1 mm) more frequently predominates in the port gate water area and in the western passage of the lagoon, where the sediment fluxes are greatest. In some cases fine sand sediments are transported in the eastern passage of the Curonian Lagoon (G-8), when the sediment flux was very intensive there. Similar results are noted at the G-3, G-4 and G-5 sites.

Silty–clayey mud (fraction <0.01 mm makes 50-70%) were rarely collected in the traps. Fine–grained sediment of this character was most frequent in and near the Malkų Bay (G-6), such results were obtained in the lagoon passages during the summer season, when the intensity of sedimentation is low (105-470 g/cm^2/day).

Grain size is very diverse in the port gate water area, changing from fine silty mud to fine sand. Still larger variation in grain size spectrum is characteristic of sediments in the Curonian Lagoon passages (G-7 and G-8). In connection with variable sedimentation rates, the transported particle sizes change from silty–clayey mud to fine sand, coarsest during high sedimentation periods.

Diatoms

Relatively large numbers of diatoms were found in all analysed sediment trap samples. Totally 114 diatom species and 32 genera were identified in the sediment samples from the Klaipėda Strait. Diatoms make about 50-90% of total microalgae abundance in phytoplankton of the Curonian Lagoon in spring (Olenina 1998). However, large amounts of diatoms were found in trap sediment samples collected during all seasons, not only in spring. There were abundant diatoms detected in the samples from the strait water area even in winter and summer: G-1 (02.1997), G-1 (07.1997), when diatom reproduction in water is low. Evidently, large amounts of diatoms were trapped

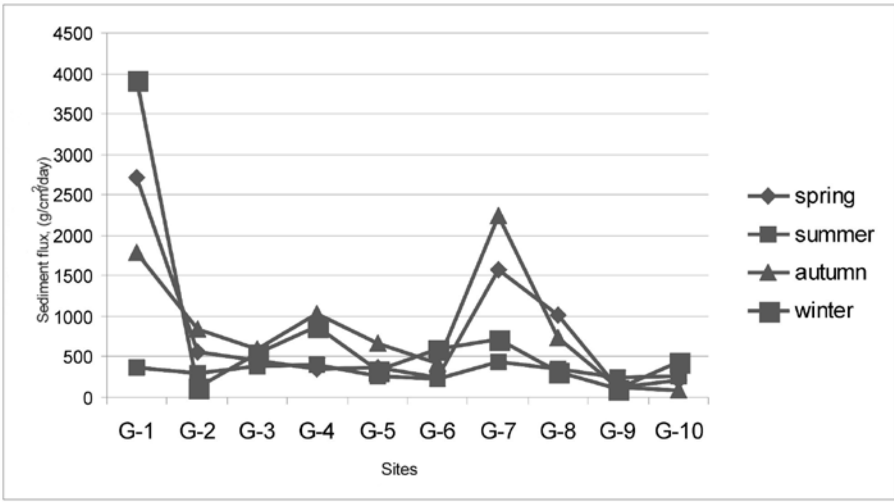

Fig. 3. Vertical sediment fluxes in the Klaipėda Strait in the year seasons. Compiled by E. Trimonis, 2009.

together with resuspended sediments.

Variations in the proportions of marine, brackish and freshwater diatoms reflect mixing of marine (from the Baltic Sea) and fresh (from the Curonian Lagoon) water, together with transported sediments, in the Klaipėda Strait. Three different diatom complexes (according to prevailing diatom group) are distinguished in the sediment samples from the traps: marine–brackish, freshwater and mixed complex.

Marine and brackish diatoms (>50% total diatoms) prevail in the samples of G-1 (11.2001), G-3 (11.2001), G-7 (11.2001), G-8 (10.1997), G-8 (10.2008), G-13 (10.2008), and G-14 (10.2008). Brackish planktonic *Actinocyclus normanii* diatoms prevail (sometimes up to 80%) in all sediment samples listed above (Fig. 4). *Actinocyclus normanii* is a freshwater species with brackish–water affinity, occurring in coastal waters throughout the Baltic Sea near freshwater discharges (Snoeijs, Vilbaste 1994). This species was found widespread in the surface sediments of the Lithuanian coastal area of the Baltic Sea and mentioned as typical for eutrophic waters (Bubinas *et al*. 1998). Some other marine and brackish species are less than 10%, and *Actinocyclus ehrenbergii*, *Thalassiosira lacustris*, *T. oestrupii* are most frequent in analysed sediment trap samples. *Thalassiosira oestrupii* is characteristic of the Litorina Sea sediments, while *T. lacustris* is associated with the Postlitorina Sea in the SE Baltic Sea area (Snoeijs, Vilbaste 1994; Vaikutienė 2004). The occurrence of these mentioned two species in the sediment trap samples suggests that some part of transported material from the sea is redeposited and brought into the lagoon via the strait with brackish water and sediment flux.

Brackish diatoms dominate in most sediment trap samples taken during the autumn months. This can be explained by specific hydrometeorological situation in autumn, when, as a rule, strong western wind increases brackish water inflow into the northern part of the Curonian Lagoon. Brackish diatoms prevail in the samples from the northern part of the strait (G-1, G-3) and in some samples further southwards (G-13, G-7, G-8). Brackish diatom species prevail in bottom sediments of the western part of the Curonian Lagoon also (Vaikutienė 2002). Therefore, it is the evidence that brackish water intrusions can reach rather far southwards into the Curonian Lagoon.

Marine and brackish diatoms are characteristic of the most intensive sedimentation, which occurs in the northern part of the strait during autumn. At that time marine water flows into the strait and reaches the passages leading into the Curonian Lagoon. The vertical sediment flux is usually lower in the passages, though marine and brackish diatoms still dominate in transported sediment material.

Freshwater diatoms (>50% total diatoms) prevail in the samples of G-1 (04.1997), G-1 (05.2001), G-3 (04.1997), G-3 (05.2001), G-7 (05.2001), G-8 (04.1997), and G-9 (05.2001). Freshwater planktonic diatoms *Aulacoseira islandica* (sometimes up to 80%), *A. granulata*, *Stephanodiscus rotula* prevail in these samples. Benthic diatoms were less common, and only some species occasionally constituted 20% (*Opephora martyi*, *Fragilaria inflata* et var. *isvanfyi*, *F. construens* var. *binodis*). The rest of the benthic species were always below 3% of the total diatom sum in samples. All noted above, freshwater diatoms are characteristic of the Curonian Lagoon (Kasperovičienė, Vaikutienė 2007). Large part of annual fresh water outflow from the lagoon takes place in spring (Žaromskis 1996). This is consistent with the prevalence of freshwater diatoms in sediment samples from this season. Diatom analysis in sediment traps in the Klaipėda Strait support data that assemblage of microalgaes in transported sediments depends on season, i. e. depends on the hydrometeorological situation and mainly on current direction (Bárcena *et al*. 2004; Pospelova *et al.* 2010).

An exceptional situation occurred in late spring in 2008. Sediment fluxes at the sites of G-1 (05.2008), G-6 (05.2008), G-7 (05.2008), G-8 (05.2008), and G-13 (05.2008) were rather small, and instead of planktonic diatoms the freshwater benthic species (*Opephora martyi*, *Fragilaria inflata* et var. *istvanfyi*, *F. construens* var. *binodis*) prevailed. Usually the appearance of benthic diatoms in a deep part of a basin is related to sediment redeposition because of strong currents, but the above–mentioned situation was associated with low sedimentation rates. It can be explained by increased water turbidity and redeposited sediments during the bottom dredging in the strait. Presumably this activity had an influence on the enrichment of transported sediments with benthic freshwater diatoms, when general sediment fluxes remained small.

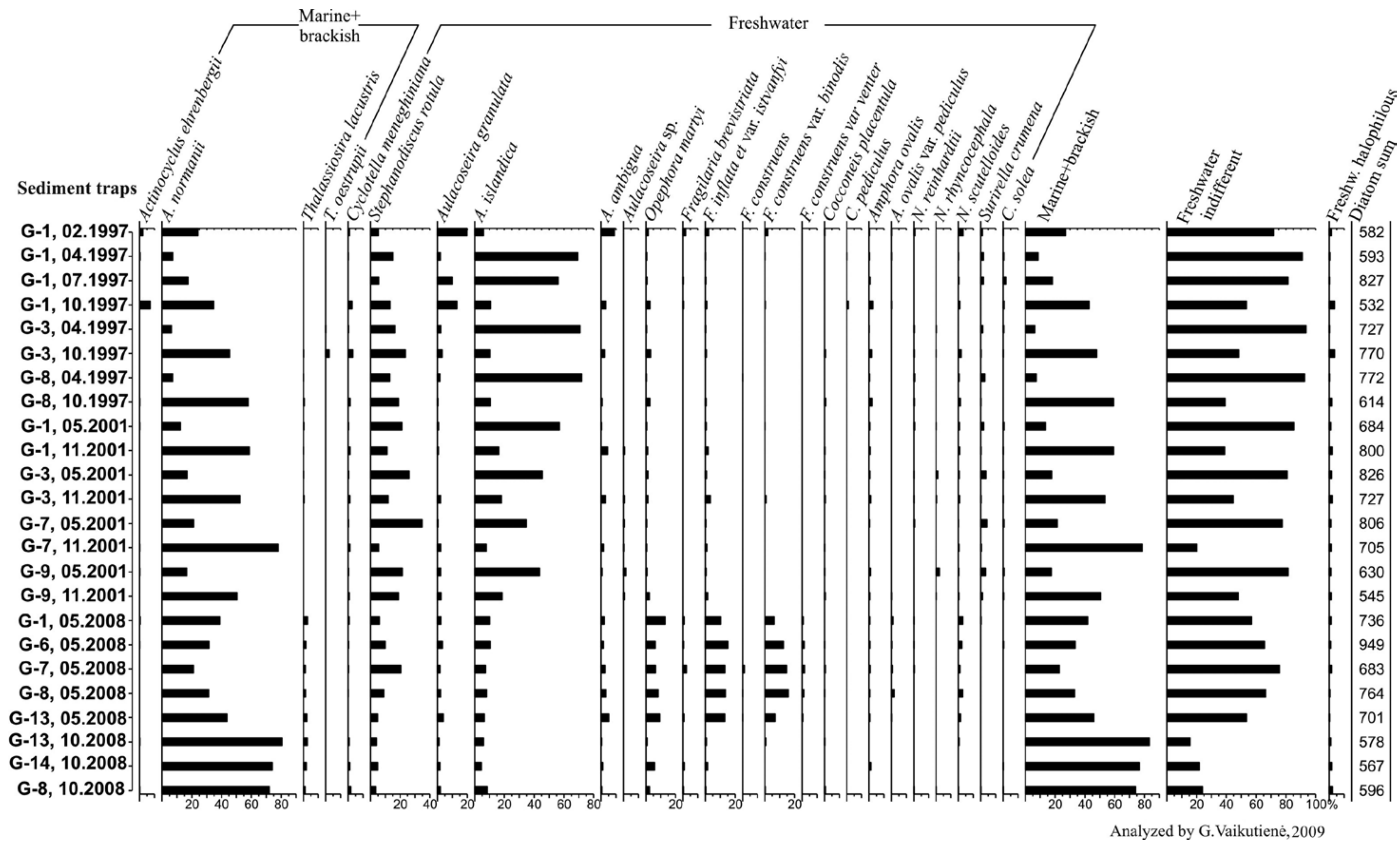

Fig. 4. Prevailing diatom species in sediment trap samples. G-1, number of sediment trap; 02.1997, date of sample collection. Compiled by G. Vaikutienė, 2009.

Mixed diatom complex, when marine–brackish and freshwater diatoms are almost equal, occur in samples of G-1 (10.1997), G-3 (10.1997), G-3 (11.2001), and G-9 (11.2001). Planktonic brackish *Actinocyclus normanii*, *A. ehrenbergii* and freshwater *Stephanodiscus rotula*, *Aulacoseira granulata*, *A. islandica* and *Cyclotella meneghiniana* diatoms are most abundant in the samples, collected in autumn from sites along the strait, as well as in the semi–closed Malkų Bay (site G-9), where current strength is commonly weak and low sedimentation rates are characteristic. Marine-brackish diatom complex usually dominates in most sediment samples taken from sites along the strait in autumn, as marine water inflow prevails at that time. Large numbers of freshwater diatoms in transported sediments can appear because of reworking in connection with strong currents in autumn.

CONCLUSIONS

The long–term (1994–2008) documentation of sediment transport between different basins associated with the Curonian Lagoon shows that sedimentation processes in the marine–lagoon geosystem are very diverse and all components vary widely. Based on the examination of transported sediment quantities and grain size, as well as the analysis of diatom complexes, it can be conclude that:

Concentration and composition of sediment transported in the strait varies over a large spatial and time range. These variations directly depend on hydrometeorology, which is also reflected in water current direction, velocity and changes in the water level. This is especially distinct in the marginal parts of the strait, i.e. the strait–sea, strait–lagoon areas.

The rate of sedimentation is interpreted to be directly correlated with the concentration of suspended matter. The highest vertical sediment fluxes are recorded in the port gate water area and in the western passage of the Curonian Lagoon, while the lowest flux is in the Malkų Bay. Considering seasonal variation, the most intensive sediment transport is characteristic of spring and winter. The lowest variations in sediment flux are observed during summer. But during all seasons, the near–bottom currents considerably influence sedimentation. Although diatom are most prevalent and characteristic in phytoplankton during spring, diatoms have also been abundant in trap samples independent of season. Hence, some diatoms are interpreted to be resuspended from bottom sediments.

The grain size distribution of transported material varies widely – from silty–clayey mud up to fine sand. The dominant sediment is fine silt (Md 0.05-0.01 mm). Changes in grain size are related to the flux intensity, where both increase and decrease together.

Comparison of different diatom assemblages (marine–brackish, freshwater and mixed) shows that in autumn (prevailing marine–brackish diatoms) sediment is transported further southwards into the Curonian Lagoon and its passages. The complexes of freshwater diatoms in trap samples confirm very active outflow of sediments from the lagoon into the strait in spring (April–May).

Sedimentation is highly variable and complicated in the Klaipėda Strait, partly because of environmental changes. Some data show that concentration and composition of transported material at individual sites (areas) could be considerably affected by human impact, such as bottom dredging. A comprehensive estimation of sediment flux in the Klaipėda Strait need to include the interaction of environmental and anthropogenic factors.

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