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Influence of salinity and suspended matter on benthos of an Arctic tidal flat

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An Arctic tidal flat in Spitsbergen (Svalbard Archipelago) was studied along a transect from the river on the landward side to the adjacent fjord in July 1996 and 1997. The concentration of suspended particulate matter ranged from 500 mg l^{-1} in the river to 50–200 mg l^{-1} over the tidal flat and to less than 20 mg l^{-1} in the surface water of the fjord. Sedimentation rates ranged from 10 g m^{-2} d^{-1} close to the river mouth to 60 g m^{-2} d^{-1} on the tidal flat and reached maximum values of over 500 g m^{-2} d^{-1} just across the tidal flat break, characterized by a sharp salinity and depth gradient. Macrozoobenthos biomass increased from 1 g ww m^{-2} in the tidal flat to over 50 g ww m^{-2} in the fjord basin. The number of macrobenthos species increased from 3 to 70 across the steep depth/salinity gradient. Diversity was little different between stations exposed to heavy and low sedimentation in the fjord. The critical zone of environmental change appears to be very narrow and is situated just on the tidal shelf break, where zoobenthos changes as sharply as the salinity/depth gradients.

Key words: Arctic, benthos, biodiversity, sedimentation, tidal flats.

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Introduction

The Arctic littoral has been commonly regarded in the past as an uninhabited ecological zone because of ice scouring (Thorson, 1933; Gurjanova, 1968). While the hard-bottom littoral has been described in several papers (e.g. Ellis, 1955; Ellis and Wilce, 1961; Weslawski *et al.*, 1997), less attention has been paid to the soft-bottom tidal flats. Mud flats are common in the Arctic, and studies have been carried out on Spitsbergen (Legezynska *et al.*, 1984; Ambrose and Leinaas, 1989; Rózycki and Gruszczynski, 1991) revealing a rich and diversified fauna. These tidal flats represent examples of a heavily disturbed environment for benthos, since the shallow water sediment is frozen for 6–8 months each year. There is evidence that the tidal flats are inhabited by a non-permanent community, which depends on the supply from the nearest sublittoral area (Weslawski and Szymelfenig, 1999). Arctic rivers forming estuaries and extensive deltas are known to sustain brackish water communities comprising specialized epibenthic and nectobenthic species, mainly amphipods (Zenkevitsch, 1963). Our aim was to follow the environmental gradient created by a small river on Spitsbergen at 78°N and to check how the communities are influenced by salinity, suspended matter, and sedimentation gradients.

Study area

The Adventfjorden tidal flat is situated at 78°13′N and 15°38′E in the innermost part of a branch of Isfjorden, Spitsbergen (Fig. 1). The flat extends for about 2.5 km SW–NE and over 1 km NW–SE. In the central part, elevation changes less than 1 m over a distance of 1 km (0.1% slope). The seaward margin forms a steep underwater slope, where depth changes by 40 m within less than 500 m (8–10% slope). There are two large lateral sedimentary pools filled with watery silty sediment (Moskugslaguna on the northern side and an unnamed pool in the south). The flat is shaped by a varying number of shallow river branches usually arranged as

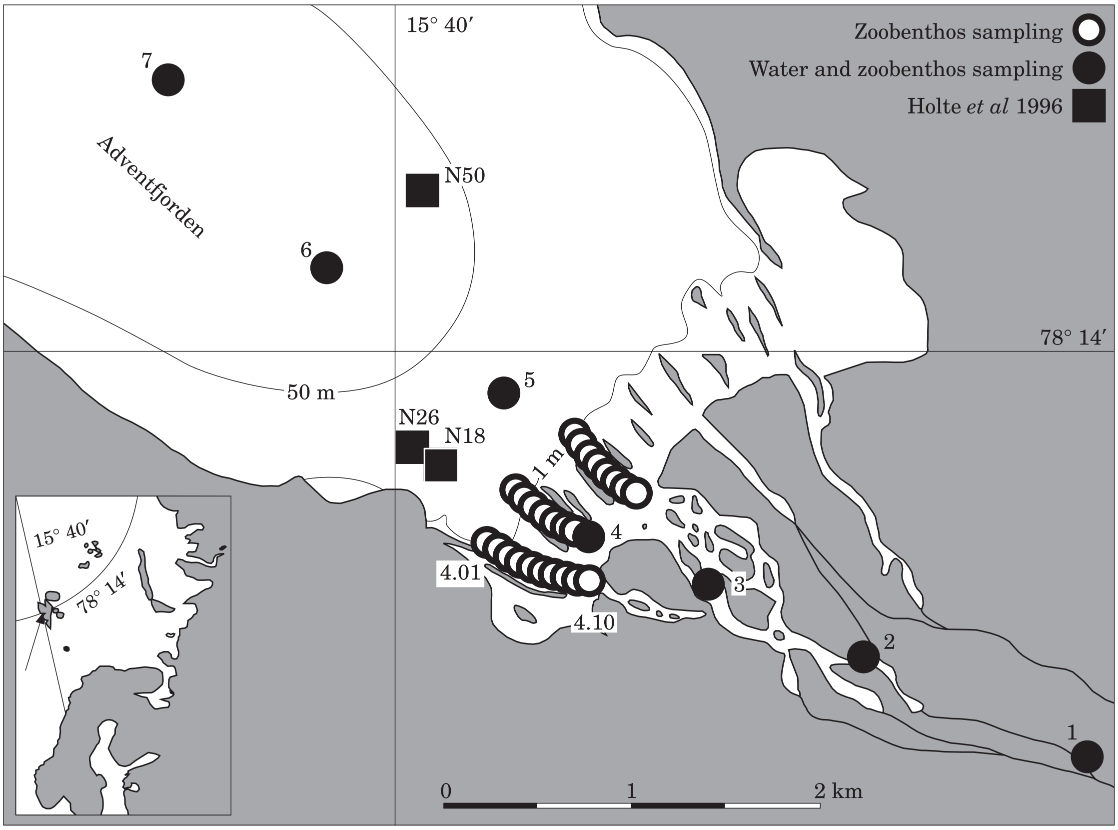

Figure 1. Map of the sampling area in Adventfjorden and stations.

three to four main outflows. The Adventelva is one of the largest rivers in the Svalbard archipelago flowing about 35 km through Adventdalen and collecting a number of tributaries. The distance to the open sea (via Isfjorden) is about 150 km. Tides are regular, M2, semidiurnal with a maximum amplitude of 190 cm. Air temperature ranges from 2 to 8°C, with easterly winds below 10 m s^{-1} in July 1996 and 1997. Ice generally starts to form in late October in freshwater ponds in the eastern part of the tidal flat. The average winter ice thickness ranges from 45 to 80 cm over the central part of the fjord and from 80 to 110 cm on the tidal flat. The disintegration of fast ice took place in early June in both 1996 and 1997.

Materials and methods

Samples were collected in July 1996 and 1997. A grid of 200 × 200 m squares was used to cover the approximately 10 km^2 area for estimating suspended loads and sediment deposition in the bay. Data from the nearest sampling point were extrapolated to the grid squares. Stations 1, 2, and 3 were situated in the river bed, station 4 on the tidal flat, and stations 5, 6, and 7 in the fjord basin.

Salinity was measured *in situ* with a mini CTD sonde (Bergen Sensor Data). Temperature data (range 2–3°C in both river and adjacent fjord) did not reveal a clear signal or pattern and therefore were not used. Suspended particulate matter (SPM) was collected from 1 dm^3 of water, filtered on Whatman GF/F glass fibre 0.7 µm filters, and dried at 60°C for 24 h. After weighing, samples were burnt at 450°C to obtain mineral matter weight and organic matter loss. Three samples were collected from each site every second day, always during low tide. The depths of SPM sampling in the fjord were 0, 5, and 40 m, while in the shallow river only a sample from the surface was taken.

Instantaneous river run-off was estimated during July 1997 by a survey of outflow dimensions and flow measurements (Table 1). Since the observations were limited only to a few days in July, the pattern of seasonal river discharge was taken from the scanty literature available on Svalbard rivers. According to hydrological data presented in Brazdil *et al.* (1988), Gokhman and Khodakov (1986), Hagen and Lefauconnier (1993), and Weslawski *et al.* (1995), the July discharge represents

Table 1. Estimates of Adventelva annual run-off, based on own measurements from July 1997 and seasonal patterns from the literature (see text).

Measurements (July)	Range	Mean
Flow speed (m s^{-1})	3–5	4
No. of outflows	4	4
Width of outflows (m)	2–10	4
Depth of outflows (m)	0.1–0.7	0.4
Estimated run-off (m^3 s^{-1})		26
Monthly run-off (10^6 m^3)		
June (28% annual)		42
July (45% annual)		67
August (21% annual)		31
September (6% annual)		9
Total	70–280	149

40–50% of annual runoff. Assuming a value of 45% and based on the actual measurements from July, monthly and annual discharge was estimated (Table 1).

Sedimentation rates on the tidal flat and in the river were measured with small sediment traps (aspect ratio 7:1; 7 cm diameter) mounted on bamboo sticks and placed at seven stations along the upper valley (4 km from the river mouth) through the tidal flat and down to the fjord basin. The traps were deployed during low tide and collected the next day. Sedimentation in the fjord was measured with larger traps (aspect ratio 7:1; 10 cm in diameter) deployed at 0, 10, and 40 m for 24 h (Zajaczkowski, 1997). Three replicates of double traps from each station were taken. The slope of the tidal flat/river area caused differences in immersion period between traps, which was taken into consideration. Data are given in g dw m^{-2} d^{-1}.

Surface sediment samples (upper 2 cm) were taken with a Van Veen grab (fjord stations) or directly from the flat at low tide. Sediment samples were dried, weighed, burnt at 450°C, and weighed again to establish organic matter loss. Subsamples were granulometrically analysed on a set of geological sieves.

Meiobenthos was collected with steel tubes (2 cm diameter) inserted 5 cm into the sediment along three profiles of 1 km length, every 100 m (sub-stations 4.1 to 4.10; Fig. 1). Triplicate, non-sliced samples were mixed together, preserved in a 4% formaldehyde solution, stained with Bengal Rose and sieved on 0.5, 0.2, 0.1, and 0.06 mm screens. Animals passing through the 0.5 mm screen were regarded as meiofauna, identified to higher taxonomic levels, counted and measured. Biomass was calculated according to formulas presented in Feller and Warwick (1988).

Intertidal macrofauna was collected with a plastic tube (30 cm diameter) inserted 10 cm into the sediment during low tide. Triplicate samples were washed on a 0.5 mm screen, preserved in a 4% formaldehyde solution and analysed 3 months later in the laboratory. Sublittoral samples from the fjord basin were collected from three Van Veen (0.04 m^2) replicates. The fauna was sieved through a 0.5 mm mesh and formalin wet weight was determined within 2 mg of accuracy. The PRIMER

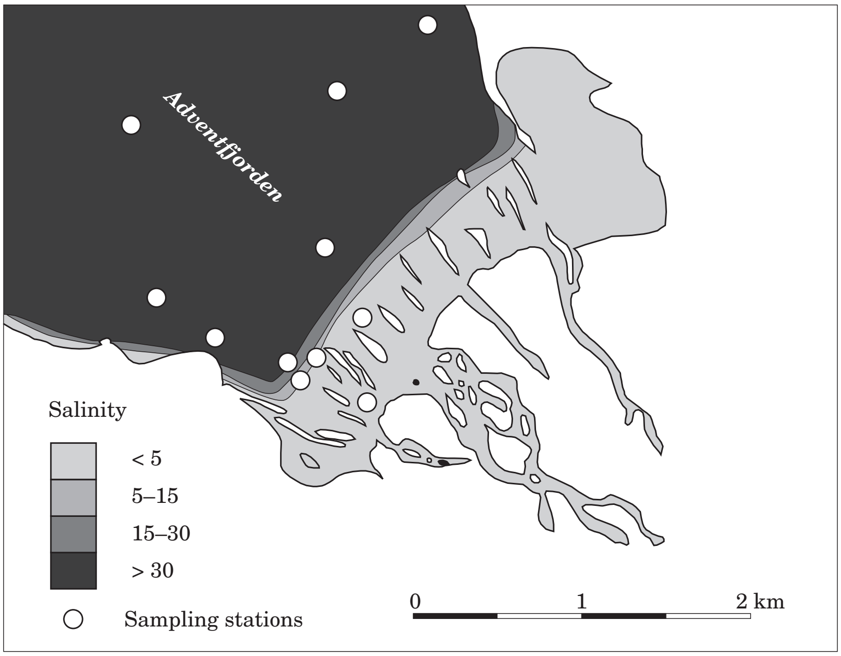

Figure 2. Distribution of near-bottom salinity at low water, July 1996.

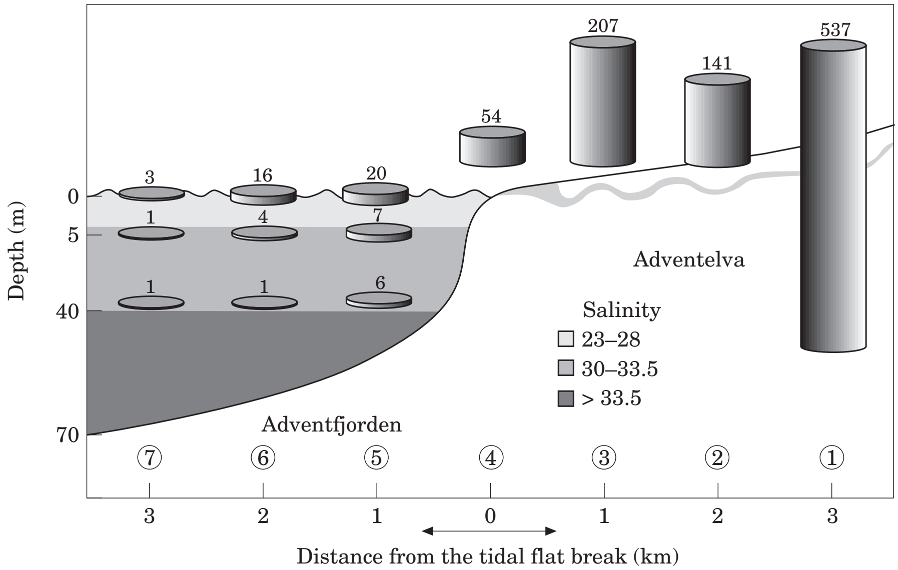

Figure 3. Amount of suspended mineral matter (mg dm^{-3}) during low tide, 27 July 1997.

(1997) software package was used for calculating the Shannon Wiener index (log e), species number richness, and evenness indices.

Results

At low tide, near-bottom salinity changed rapidly from 5 to 30 across the tidal flat break within a short distance (Fig. 2). Surface salinity gradients were not that sharp and changed with the tidal cycle. However, a low-salinity layer (below 28) restricted to the upper 5 m was observed even on the outermost fjord station 7 (Fig. 3).

Table 2. Percent of organic matter in suspended particulate matter (SPM) collected from water samples by area, July 1997.

	River	Tidal flat	Fjord
No. of samples	9	28	9
Minimum	4.5	6	0
Maximum	8.6	33.6	3.8
Mean	7	14.2	0.8
s.d.	1.2	6.8	1.40

Another sharp drop was observed in total SPM concentration in the surface waters over the tidal flat when the tidal flat break was crossed, reaching very low values at the most offshore station (Fig. 3). The average share of organic matter in SPM doubled when moving from the river to the tidal flat and was sharply reduced in the fjord (Table 2). Allowing for an annual discharge of the Adventelva in the range of 70–280 10^6 m^3 and for a duration of the season of 122 days with an average of 200–500 mg l^{-1} SPM, conservative estimates of sediment transport range between 20 000 and 80 000 t per year (Table 3).

Sedimentation rates suddenly increased from low values in the river and on the tidal flat to extremely high values at the tidal flat break, and decreased again to low values at the outer station (Fig. 4). At the landward border of the tidal flat (station 1), where river and tidal

Table 3. Compilation of data on run-off and SPM loads from Svalbard rivers (minimum and maximum estimates given in parentheses).

	Season	Run-off		SPM load		Author
	d	m^3 s^{-1}	10^6 m^3 yr^{-1}	10^3 t yr^{-1}	mg l^{-1}	
Mimer	174	2.2 (?–31)	32			Gokhman and Khodakov, 1986
Bayelva	120	3	31	14	1000	Hagen and Leafuconnier, 1993
Brattegelva	176	0.05 (?–2)	6	6	1000	Brazdil *et al.*, 1988
Breenelva	120	6 (2–20)				Brazdil *et al.*, 1988
Erikbreenelva		0.12	1	7	2000	Vatne *et al.*, 1992
Adventelva	122	26 (5–56)	70–279	22–82	200–500	Own data

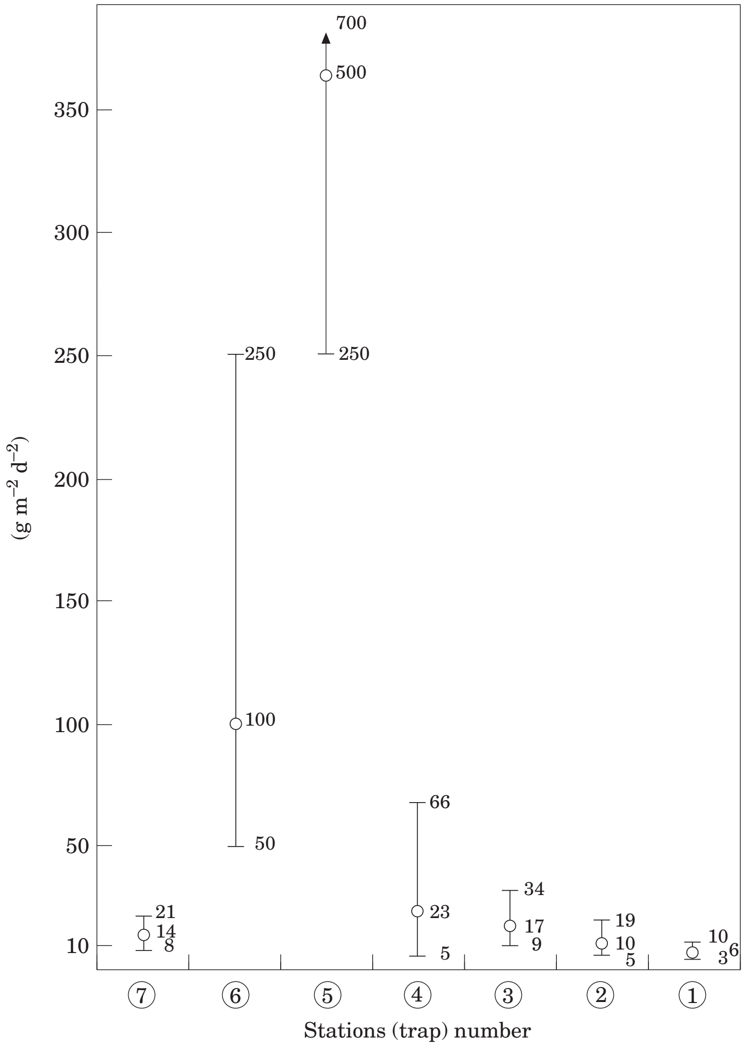

Figure 4. Minimum, mean, and maximum values of sedimentation rates (g m^{-2} d^{-1}) on the tidal flat (stations 1 to 4; 5 July 1996) combined with data from Adventfjorden (stations 5–7; 4 August 1996).

currents are strongest, sedimentation rate was lowest. Rates increased slightly towards the flat break, which was associated with the water becoming less turbid. Estimates of the amount of mineral matter settling in the area investigated indicate that 61% of the 63 000 t deposited annually is deposited in the area of station 5 (Table 4). Considering the estimated amount of sediment transported with the river (maximum 80 000 t), resuspension and additional supply from another river, we suggest that a very small part of SPM is transported out of the fjord.

The surface sediments of the tidal flat consist of medium sand and small stones covered with a thin layer of silt. The coarse fraction (grains over 0.063 mm) of surface sediments range from 40% to 80%, while organic matter content in the sediment ranged from 2.2% to 5.0% (Table 5).

Meiobenthos density and biomass distributions showed no clear pattern along the transect, although high values were observed locally in the middle of the tidal flat (up to 533 ind. 10 cm^{-2}; Fig. 5). The Nematoda/Harpacticoida ratio was also patchy, with more Nematoda observed close to the tidal flat break.

In the river bed, Chironomidae larvae were found only occasionally, while Oligochaeta and the crustaceans *Onisimus littoralis* and *Gammarus setosus* were recorded. In contrast, 66 taxa were encountered in the fjord beyond the tidal flat break (Table 6). Density and biomass changed accordingly from the tidal flat to the fjord from 50 to 6500 ind m^{-2} and from 1 to 50 g ww m^{-2}, respectively. The tidal flat biomass was dominated by *O. littoralis*, ranging up to 450 ind m^{-2} in density (13 g ww m^{-2} in biomass). Despite the relative species richness of the fjord benthos samples, only five species

Table 4. Estimates of sedimentation rate by station (s; kg m^2 d^{-1}), number of squares represented by each station (n; 0.04 km^2), and deposition of sediment (D; tonnes) on tidal flat in July (45% of total) and during the season (120 d).

Station	s	n	D	
			July	Season
1	0.006	16	115	
2 and 3	0.014	22	370	
4	0.023	12	331	
Tidal flat			816	1813
5	0.5	28	16 800	
6	0.1	81	9720	
7	0.01	90	1080	
Fjord			27 600	61 333

Table 5. Average percentage organic matter (OM), coarse sands, and silt (ranges in parentheses) in bottom sediments on the tidal flat (stations 4.1–4.9) and in Adventfjorden (data from Holthe *et al.*, 1996).

	OM	Coarse >0.063 mm	Silt <0.063 mm
Tidal flat	3.3 (2.2–5.0)	67 (44–84)	33 (16–56)
Fjord	7.5 (6.3–8.4)	8 (6–13)	92 (87–94)

(polychaetes *Chaetosone/Tharynx* spp., *Cossura longicirrata, Leitoscoloplos* sp., gastropod *Cylichna occulta* and priapulid *Priapulus caudatus*) represented 80% of the density and biomass. Surprisingly, small benthic fish (*Anisarchus medius*) were consistently found in all grab samples collected in 1997 (3 to 5 ind m^{-2}), suggesting the area was an important fish feeding ground.

The macrofauna biodiversity indices of the fjord and tidal flat stations reflect the completely different communities (Table 6). Differences among fjord stations were comparatively low. Biomass was highest at station 5, which was exposed to heavy sedimentation, while diversity was highest at station 7, distant from the disturbing mixing zone. The physical parameters measured (salinity, sedimentation, and depth) and biological parameters change rapidly between stations 4 and 5.

Discussion

The freshwater discharge of the Adventelva is relatively small compared to the average discharge from the Svalbard fjord glaciers (range: 0.4 to 1 km^3 year^{-1}; Beszczynska *et al.*, 1997). Similar rivers at other localities on Spitsbergen were estimated to discharge from 0.001 to 0.03 km^3 of freshwater yearly (Gokhmanov and Khodakov, 1986; Vatne *et al.*, 1992; Hagen and Lefauconnier, 1993). Mixing of the surface brackish water layer with saline near-bottom water is efficient in the wind and current exposed tidal flat area, but diminishes at greater depths, creating sharp salinity gradients at the flat break, as observed in other tidal flats on Spitsbergen as well (Legezynska *et al.*, 1984). Because of extensive shallows and gentle slope, salinity gradients in the near-bottom waters of Siberian rivers are even flatter, salinity ranging from 20 to 30 over large river deltas (Weslawski *et al.*, 1998; Lisitsyn, 1999).

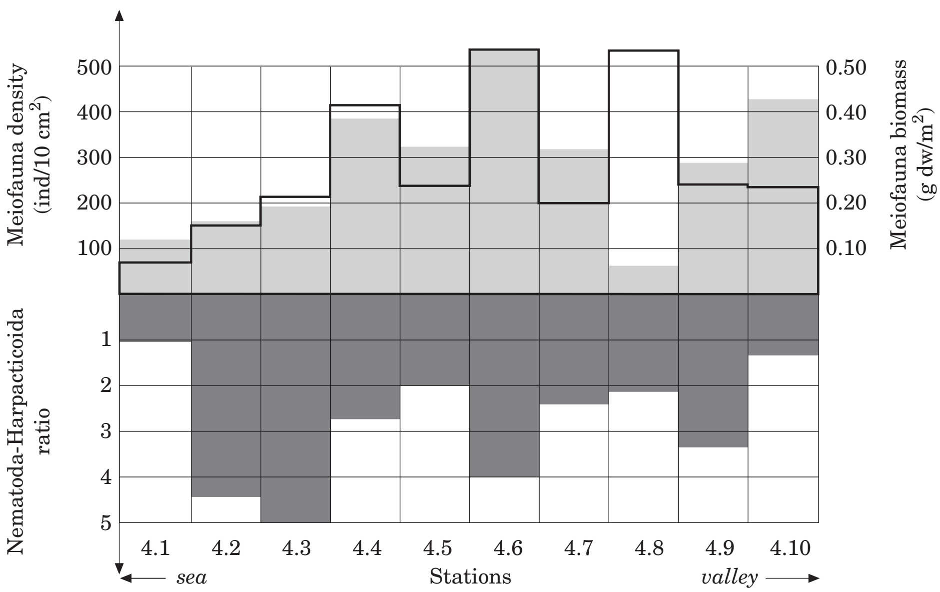

Figure 5. Meiofauna density (solid line), biomass (light grey bars), and Nematoda/Harpacticoida ratio (dark bars) along the tidal flat (mean values from 3 profiles of 10 stations each).

Table 6. Macrofauna (individuals m^{-2}) in grab samples from tidal flat and adjacent fjord basin, July 1997, compared with stations from Holthe *et al.*, 1996. Only most abundant species from each data set are presented.

Year	1992	1992	1992	1997	1997	1997	1996	1996	1996
Area	Fjord	Fjord	Fjord	Fjord	Fjord	Fjord	Tidal flat	Tidal flat	Tidal flat
Symbol	N18	N26	N50	5	6	7	4.1	4.5	4.9
Depth (m)	18	26	50	45	55	67	1	0.5	0.5
Axinopsis orbiculata	188	168	5	13	65	155			
Capitella capitata	2213	1160		108	5				
Chaetozone/Tharynx sp.	3373	785	800	1765	640	1120			
Cossura longicirrata	15			1280	98	275			
Cylichna occulta	33	13	315	355	308	470			
Heteromastus filiformis	15	23	8	138	28	180			
Leitoscoloplos sp.	83	30	208	98	145	335			
Nuculoma tenuis	255	333	38		5				
Oligochaeta							150	70	50
Onisimus littoralis							450	75	
n taxa	31	25	31	20	19	22	3	2	1
N m^{-2}	6561	2710	1796	4165	1428	2870	625	145	50
Richness	3.41	3.04	4.00	2.28	2.48	2.64	0.31	0.20	0.00
Shannon-Wienner index	1.36	1.62	1.76	1.56	1.74	1.92	0.71	0.69	0.00
Evenness	0.40	0.50	0.51	0.52	0.59	0.62	0.64	1.00	0.00
Mean biomass (g ww m^{-2})				50	11	12	10	2	1

Glacial streams on Spitsbergen transport large loads of SPM. Szczepanik (1982) and Vatne *et al.* (1992) give a range of 900 to 3800 mg l^{-1} and Elverhoi *et al.* (1980) report 2500 mg l^{-1} in Kongsfjorden. The small glacial river at Erikbreen was estimated to transport some 7000 t of mineral matter during the warm season (Vatne *et al.*, 1992), while less turbid Siberian rivers compared by Bobrovitskaya *et al.* (1996) carry only about 150 mg l^{-1} of sediment. The extreme interannual differences in discharge are noteworthy, e.g. the annual sediment transport of Bayelva ranged from 5000 to 23 000 t between years (Bogen, 1993). According to our observations, the organic matter in Adventelva SPM was provided mainly by tundra fragments (*Sphagnum*, *Saxifraga*, and other higher plants). However, the increase of organic matter in SPM at the tidal flat break may be caused by the production of aggregates of dead marine phytoplankton, mucus, and terrestrial debris due to mixing of fresh water with sea water.

Sediment deposition by large rivers in the Siberian region is small since these are drained by extensive swamps and tundra bogs. Values for these rivers (0.007 to 0.02 kg m^{-2} d^{-1}; Lisitsyn *et al.*, 1994; Bobrovitskaia *et al.*, 1996) contrast data from glacial streams in Baffin Bay, which deposit about 3.5 kg m^{-2} d^{-1} (Syvitsky *et al.*, 1985), or from a New Zealand river supplying a mudflat with 0.4 kg m^{-2} d^{-1} (Grant *et al.*, 1997). In a Scottish sea loch, sedimentation was about 0.05 kg m^{-2} d^{-1} (Overnell and Young, 1995). In this context, the Adventelva belongs to sites with considerable but not extreme sedimentation rates, with values ranging from 0.01 to 0.5 kg m^{-2} d^{-1}. Here, most of the sediment load seems to be deposited just in the frontal zone of the tidal flat break. Data from Siberian rivers show that 80–90% of the organic material is deposited in the zone of fresh and sea water mixing (Lisitsyn *et al.*, 1994; Lisitsyn, 1999). Similar conclusions were drawn after satellite imagery analysis of SPM distribution close to river mouths and glaciers in Svalbard (Weslawski *et al.*, 1998). The 6–8% organic matter concentration in surface sediments reported from the Adventfjorden by Holthe *et al.* (1996) was high compared with other Arctic localities (2–3%; Ambrose *et al.*, 1995), and also compared with our observations of the organic content in the tidal flat sediments nearby (2–5%). This suggests transport (with subsequent deposition) of organic material from the tidal flat to the less turbulent environment of the fjord. The same is true for fine mineral particles (<0.063 mm) deposited mainly beyond the tidal flat, and consequently contributing to over 90% of the surface sediment in Adventfjorden (Holthe *et al.*, 1996).

The biomass of meiofauna on the tidal flat (0.6 g m^{-2}) was low compared with the range of values reported from other tidal flats in temperate and cold zones (1 to 6 g dw m^{-2} in France, Escaravage *et al.*, 1989; 1–3 g dw in other Spitsbergen localities, Szymelfenig *et al.*, 1995). Also, much higher densities of 100–300 ind cm^{-2} have been reported for Alaskan and Arctic tidal flats as well (Schizas and Shirley, 1996; Mokijewski, 1992; Szymelfenig *et al.*, 1995). Similarly, the macrofauna biomass was low as well, since for other Arctic tidal flats ranges from 5 to 20 g ww m^{-2} have been reported (Weslawski and Szymelfenig, 1998). A change in biomass from the soft bottom intertidal to the shallow sublittoral ranged from 50 to 150 g ww m^{-2} in a Spitsbergen bay with a weak salinity gradient

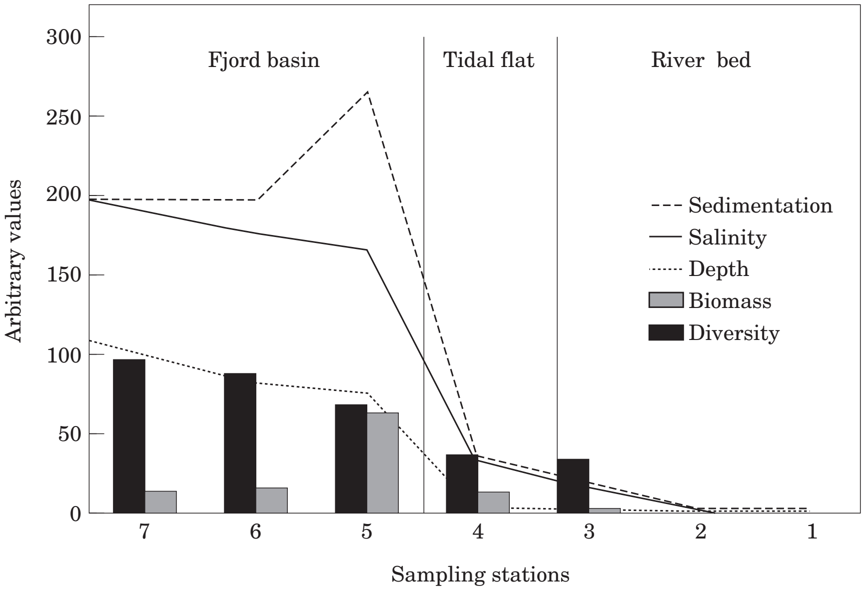

Figure 6. Biomass and diversity of zoobenthos in relation to environmental gradients (arbitrary scale).

(Weslawski *et al.*, 1992). The increase from 5 to 50 g m^{-2} beyond the shelf break presented here suggests that salinity has a major influence on macrobenthos biomass distribution. Impoverishment of macro- and meio-benthos is commonly reported for the inner, brackish parts of tidal estuaries, where a single macrofauna taxon (usually Oligochaeta) tends to dominate (Sconfielti and Marino, 1989; Ysebaert *et al.*, 1993; Soataert *et al.*, 1994). The distinctly higher biomass (and relatively low diversity) observed at station 5 compared with the more offshore stations confirms the specific character of the tidal flat edge area (Fig. 6).

Among some 25 brackish water species reported by Zenkevitsch (1963) from arctic river mouths, at least 6 might be observed in Svalbard (Weslawski and Szymelfenig, 1998). The Adventfjord basin hosts a number of species typical of the soft-bottom Svalbard sublittoral. The dominant species observed here have been reported as the most common ones (Wlodarska-Kowalczuk *et al.*, 1998). The abrupt change in species number across the tidal flat break (3 to 70) contrasts the observation of a more gradual change from 23 to 70 species along the depth gradient from intertidal to shallow subblittoral in Gipsvika (Spitsbergen), where salinity and suspension gradients were very weak (Weslawski *et al.*, 1992). Suspended matter settling in Arctic fjords has been considered by many authors as the principal disturbance factor reducing both biomass and diversity of benthic life (Gorlich *et al.*, 1987; Kendall, 1994; Wlodarska *et al.*, 1998). Other authors stress the importance of the salinity gradient, especially in shallow waters (Burkovskiy and Stolyarov, 1995; Heip and Herman, 1995).

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