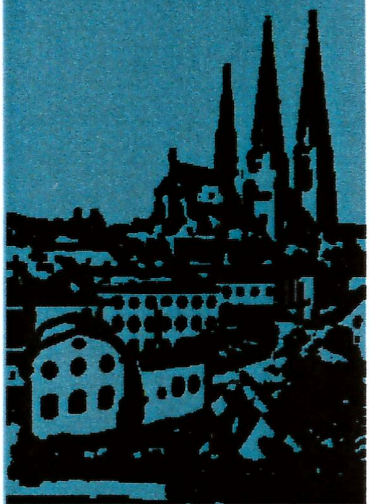
UPPSALA UNIVERSITY
Department of Earth Sciences
Physical Geography

The influence of wind-induced resuspension on sediment accumulation rates

A study of archipelago and offshore areas in the NW Baltic proper



Camilla Andersson

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Supervised by Per Jonsson

Abstract

The processes of sedimentation such as erosion, resuspension, transportation and accumulation are of major importance when handling environmental problems such as pollutants and eutrophication. Redistribution of sediment can induce transport of pollutants, why a greater knowledge of the sediment processes and the factors giving rise to sediment transport is desirable. There are a multiple of factors that could affect sediment processes, such as currents, waves, wind and sea level changes. Wind conditions are one of the major factors influencing oceanographic conditions, why focus is this study is set on the relationship between wind frequencies and sedimentation processes.

The aim of this study is to investigate gross accumulation rates (accumulation of dry substance), foremost in archipelago areas of the NW Baltic Proper, and to some extent an offshore area in the NW Baltic Proper. The thesis suggests time trends in gross accumulation rates to be affected by wind conditions.

Former analyses of water content, Cesium-137, carbon and nitrogen in combination with dating from lamina counting resulted in data on dry substance deposition data from six enclosed bays in the archipelago of the NW Baltic Proper. In order to receive new materiel from an offshore area, field work were performed during the summer of 1999. Analyses were performed in the same way as above. The gross accumulation rates could be calculated and dated in a satisfactory way in the accumulation areas. The offshore area proved to be difficult to interpret, why no conclusions could be made concerning accumulation in deep offshore areas (180-203 m).

Data on wind force and durability from SMHI together with accurate described annual gross accumulation rates allowed plotting the time trends of the two parameters. It proved that a good correlation was seen in wind speed ≥7-9 m/s (r^2=0.5) when using annual core mean values. Former investigations has showed a good correlation at higher wind speeds, ≥14 m/s. It is suggested that in small enclosed bays, fetch are the limiting factor which does not allow wind speeds exceeding ≥7-9 m/s to lower the critical depth at which erosion/resuspension occur. Since great similarities were found between the inner and outer Stockholm archipelago and the archipelago of Södermanland it is indicated that the results are valid for a large part of the NW Baltic Proper archipelago area, provided that the predictions are based on a sufficient number of bays and cores.

Preface and acknowledgements

This report is the result of a 20-p Master of Science thesis in physical geography and sedimentology. The study includes planning, preparation and implementation of a field investigation with the vessel R/V Sunbeam during the summer of 1999. Laboratory work was performed at the department of Earth Sciences, Uppsala University. The study also includes analyse of data from field and laboratory work, wind data from a SMHI (the Swedish Meteorological and Hydrological Institute) weather station and data from former sediment investigations in the Baltic proper during 1996-97, including data from the EUCON project.

I would like to thank my supervisor Per Jonsson for excellent guiding and endless inspiration and of course for being the captain during the fieldwork on Sunbeam. David Fransson has been a great support in field and laboratory as well as a good friend. One person who has been an invaluable help in my fieldwork is Johan Persson, who also has provided me with material as maps and data from investigations in the archipelago areas. Pia Holmberg has been a great help in my laboratory work as well as in giving advises concerning analyse of data. Finally, I would like to send a thank you to my study mates, especially Ulf Jonsell, Håkan Samuelsson and Åsa Johansson, always being there for a coffee break, needed or not.

Front-page photograph by Johan Persson

TABLE OF CONTENTS

1 Introduction

An increased knowledge about the sediment processes (chemical, physical and biological) is of major importance in environmental research in the Baltic Sea area. Many years of sedimentation studies has concluded that sediments are excellent sources of information concerning the processes proceeding both in the water mass as well as in the surrounding environment. The sediments act as an archive of the environment history of the Baltic Sea, helping us to get a clearer picture of processes such as redistribution of sediments, discharges, transport and concentrations of pollutants, intrusion of salt water and benthic fauna condition.

The discharge of phosphor and nitrogen to the Baltic Sea has increased since the beginning of the twentieth century (Larsson *et al.*, 1985 and HELCOM, 1990) which has lead to increased levels of nitrate and phosphate in the Baltic proper and the Bothnian Sea. According to HELCOM (1981), the increased discharge of nutrients is one of the most important causes to the increase in primary production in the Baltic Sea during the last decades. There is clear evidence that coastal areas, especially archipelago areas situated near large cities, have been eutrophieated through e.g. wastewater discharges containing easily oxidised organic matter and nutrients. As a result of the increased eutrophication, oxygen concentrations in the deep water of the Baltic proper have decreased during the twentieth century (HELCOM, 1990). More than one third of the Baltic Sea seafloor area suffers today of oxygen deficiency (Wulff *et al.*, 1990), which has contributed to a substantial reduction of the macrobenthic fauna in deep (>80 m) areas. In most marine areas the macrobenthic fauna is abundant in the boundary layer between surface sediment and deep water. The fauna bioturbate the sediments and thus wipe out time trends in sedimentation as well as rapid changes in pollution load. This is the case in most parts of the Bothnian Bay and Bothnian Sea seafloor. As mentioned above, a major part of the seafloor in the Baltic proper has during the last decades been exposed to a rapid reduction of macrobenthic fauna, which leads to preservation of the laminae in the sediments. The laminae is considered to be annual (Eckhéll *et al.*, 2000), with a light varve corresponding to deposition during the winter and a darker, nearly black, organic rich varve deposited during the summer. The preservation of laminae due to oxygen deficiency may have a major influence on the sedimentation of organic pollutants and metals. For example, cadmium and copper can form strong sulphide complexes in anoxic environments.

We know that the Baltic Sea is exposed to a numerous varieties of pollution and that sediments are good indicators of how these pollutants spread geographically and historically. Field sampling and laboratory analyses are good but expensive methods to receive information on sediment processes, which give strength to the idea of developing models of geographical variations in erosion, resuspension and dry substance accumulation of sediments. Factors influencing resuspension are e.g. morphometry of the area, fetch, wave base, deep currents and winds. Wind forces influence wave action and currents and may have a major influence on time trends of sedimentation. Wind force and sediment accumulations are key factors considered in this paper.

1.1 Aim

With the introduction above as background it is obvious that modelling of sediment processes and sediment transport is an important method to receive knowledge of how pollutants in sediments can be resuspended, transported and deposited. This study is an attempt to identify time trends and possible correlation between gross accumulation rates (accumulation of dry substance) and variations in wind conditions. The intention was at first to investigate only an offshore area of great depth (180-200 m). As it proved to be difficult to date these cores in a satisfactory way, focus was changed to enclosed bays in the NW Baltic proper archipelago, another area not completely investigated earlier.

The comprehensive questions at issue in this thesis are:

1) How are gross accumulation rates in the Baltic Sea affected by wind forces in archipelago and offshore areas of varying depths?
2) How could the possible correlation be explained in terms of sediment processes?

The methods used are:

i) interpretation of material and data from previous investigations concerning sediment accumulation in the NW Baltic Proper archipelago,
ii) field mapping and sampling in an offshore area (depth 180-200 m),
iii) laboratory analyses of sediment key parameters,
iv) analyses of time trends in gross accumulation rates in offshore and archipelago areas,
v) data handling to identify possible correlation's between gross accumulation rates and wind data.

As possible correlation's between dry substance deposition and wind frequencies earlier has been investigated by Eckhéll *et al.* (2000) in an marine area of 95-135 m, this study considered an marine area of greater depth (180-200 m) to investigate if their hypothesis was valid for a greater depth interval. The investigation areas in the NW Baltic Proper archipelago (six bays) were selected with the intention to represent a mean of all enclosed bays in the archipelago area from Roslagen in the north to St Anna in the south. A good correlation between wind frequency and dry substance accumulation have been found in St Anna archipelago (Persson and Jonsson, 2000). The aim of this thesis is to investigate if and how the wind conditions can effect gross accumulation in other archipelago areas.

2 Theoretical background

In order to understand the complex relationship between environmental problems as eutrophication and pollution and the processes of sediment dynamics, many parameters must be taken in consideration. The importance of sediments as environment for living organisms, the resuspension and deposition of sediment and how wind frequencies can be coupled to sediment redistribution are some of these factors. Here will follow a short introduction to some important and essential concepts and ideas concerning oceanography and sediment dynamics.

2.1 Physical properties of the Baltic Sea

A clear connection is seen between the processes of sedimentation and the environment in which the sedimentation takes place. In order to understand the environment of the Baltic Proper offshore areas as well as the coastal bays, some basic knowledge concerning whole of the Baltic Sea is of importance. Topography, salinity and oxygen content are some of the factors coupled to sedimentation and environmental issues.

2.1.1 Topography of the Baltic Sea

Although the Baltic Sea is a shallow sea, the morphology of the seafloor is very diverse. The topography of the Baltic Sea is made up of a series of basins connected to each other by sills. The main features are of pre-glacial origin, with the troughs in most cases filled with Quaternary deposits.

One common way to divide the Baltic Sea into five sub-basins is (Fig. 2.1): the Bothnian Bay, the Bothnian Sea, the Gulf of Finland, the Gulf of Riga and the Baltic Proper (Voipio, 1981). The depths of the depressions are various, from e.g. a depth of 116 m in the Gdansk depression to a depth of 459 m in the Landsort depression, the deepest basin in the Baltic Sea. In spite of the considerable depths of some of the basins, mean depth of the Baltic Proper is only 65 m. Bays at the Baltic Sea coast are

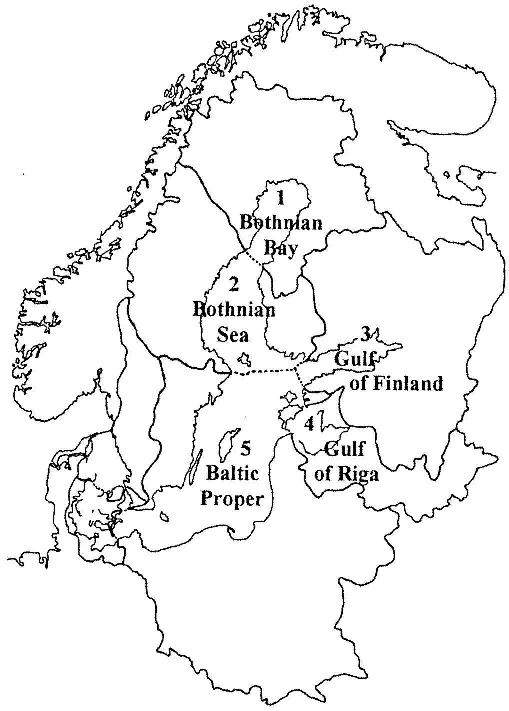


Figure 2.1: Drainage basin and subregions of the Baltic Sea; the Bothnian Bay (1), the Bothnian Sea (2), the Gulf of Finland (3), the Gulf of Riga (4) and the Baltic proper (5) (Modified from Voipio, 1981).

of various depth and have various distinguished sills.

2.1.2 Salinity of the Baltic Sea

In the major part of the Baltic Sea a permanent halocline prevails at a depth of 60-70 m (Voipio, 1981). The variations of salinity in the surface water are mostly quite small (6-7 ‰), while salinity in the deep water can vary between 7 ‰ (the Bothnian Sea) and 13 ‰ (the Baltic Proper). At larger saltwater intrusions, a secondary halocline form in the deep basins at 70-140 m, where bottom water salinity may reach 11-13 ‰, as the case in major parts of the Western Gotland basin where the offshore investigation area is situated. The secondary halocline however weakens by turbulence and diffusion and can partly or totally disappear (Fonselius, 1995).

During spring a thermocline develops. The thermocline increases in thickness until autumn, and can reach a depth of approximately 30 m before the autumn circulation disperses the temperature differences. The thermocline is eventually wiped out, and in January/February water has the same salinity and temperature from the surface to the depth of the permanent halocline. The thermocline in the Baltic proper never reaches the depth of the halocline.

2.1.3 Oxygen content of the Baltic Sea

A constant exchange of gases between the surface water and the atmosphere lead to an equilibrium between the gas pressure in the atmosphere and the concentration in the surface water (HELCOM, 1990). One of these gases that are physically solved in the water is oxygen. Oxygen is consumed in respiration processes and by oxidation of dead organic matter in the water. Salinity as well as temperature affects the concentration of oxygen in the surface water. In the oceans, the concentration of oxygen decreases with depth. In the Baltic Sea, which has a permanent halocline, the limit between the oxygen saturated surface water and the oxygen poor deep water, is especially distinguished. The oxidation of dead organic matter can be explained by the following formula:

$$CH_2 + O_2 \rightarrow CO_2 + H_2O$$

With an increased primary production and eutrophication, the large amount of organic material brought to the deep water will contribute to a reduction in oxygen content. During stagnant conditions, the oxygen demand for decomposition in the deep water is too high to be supplied by oxygen from the surface water at the same rate. The permanent halocline even more complicates the vertical water exchange. As a result of oxygen deficiency in the deep water, the decomposition will proceed by other processes as reduction of nitrate and sulphur (Fonselius, 1995). The reduction of nitrate involves formation of nitrogen gas (N_2), which has no major environmental effect on the Baltic Sea as water normally contain a large amount of nitrogen gas. However as the nitrate has been consumed, a process including reduction of sulphate begins. This means that sulphate-reducing bacteria's at the sediment surface start using oxygen from sulphate ions (SO_4^{2-}) and thereby reduce them to sulphide ions:

$$2\,CH_2O + SO_4^{2-} + 2\,H_3O^+ \rightarrow$$
$$2\,CO_2 + S^{2-} + 2\,H_3O^+ + 2\,H_2O$$

No higher living forms can exist in an environment with a high content of the poisonous gas hydrogen sulphide. The benthic fauna is wiped out and fish avoid the area, which becomes "a dead marine desert", as Fonselius (1995) name such an environment.

That is, the formation of hydrogen sulphide is closely coupled to the release of nutrients to the Baltic Sea, increased primary production, the permanent halocline and the oxygen deficient deep water. The deep water of the Baltic Proper can be exchanged by intrusion of salt water through the Danish straits. The salt water has a higher oxygen content and a higher density, which lead to a lift-up of the hydrogen sulphide-rich water and intrusion of oxygen-rich water into the basins, which can improve the conditions for the benthic fauna. The salt-water intrusions are rare events, the latest great intrusion to heave the long lasting stagnation in the Baltic Proper occurred during the early 1990s (Fonselius, 1995).

Today, more than one third of the Baltic Sea suffers from oxygen deficiency (Wulff *et al.*, 1990). According to a number of investigations carried out in the NW Baltic Proper (Anonymous 1996, 1997, 1998 and 1999), many bays in the archipelago from Roslagen in the north to St Anna archipelago in the south, include large seafloor areas where hydrogen sulphide (H_2S) is formed as a result of low oxygen concentrations. Some offshore areas are "naturally" laminated (Jonsson *et al.*, 1990), but during the last decades large areas has become laminated due to the extinction of the benthic fauna (Fig. 2.2).

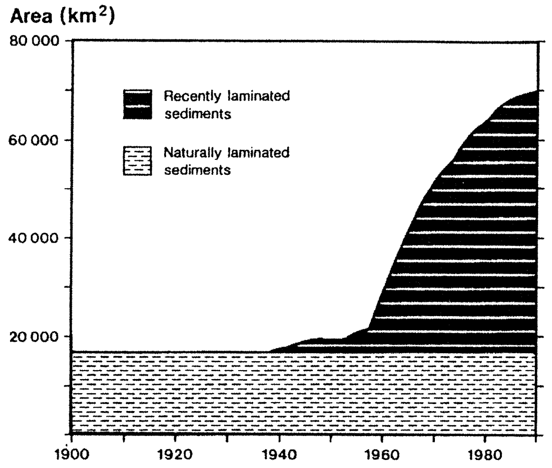


Figure 2.2: The development of laminated sediment in the Baltic Sea has dramatically increased in the last decades. One possible explanation is the increased eutrophication, which contributes to formation of hydrogen sulphide (H_2S) (From Jonsson et al., 1990).

2.2 Currents and wave action

Two of the key factors in sediment dynamics are influences by waves and currents (Fig. 2.3). Both waves and currents can be induced by wind, these processes are further explained below.

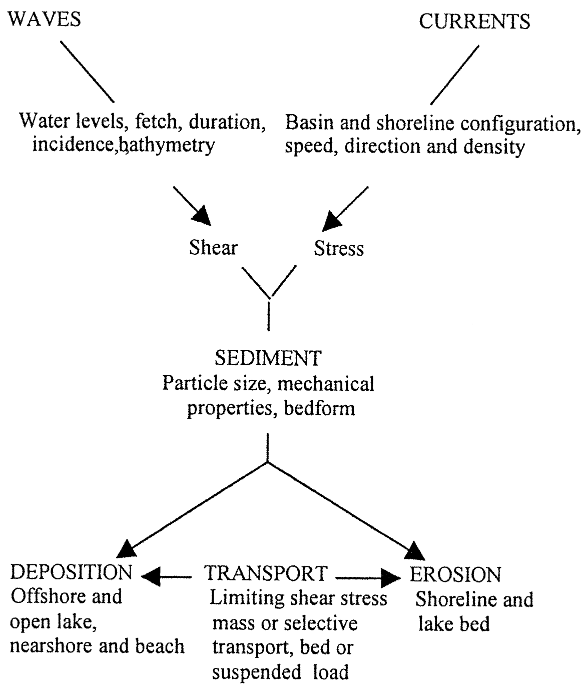


Figure 2.3: Illustrating the influence waves and currents can have on sediment processes (From Håkanson and Jansson, 1983).

2.2.1 *Wave action*

Håkanson (1977) presents two ways in which waves can interact with bottom sediments, referring to Sly (1973): (1) as breaking waves in the beach zone, and (2) as waves in that zone affected only by orbital velocities of water motion (beyond the breaker zone). The orbit of a wave is illustrated by figure 2.4, which illustrates the water particle movements in circular orbits, the diameter of the orbit decreasing by depth. Waves with these circular orbits

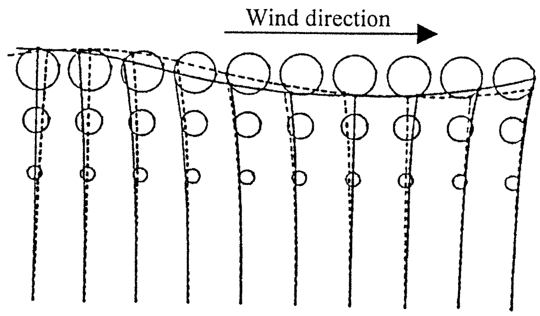


Figure 2.4: Short wave orbits, created by wind energy. Wave energy (orbit diameter) decreases with depth (From Fonselius, 1995).

are called short waves (Fonselius, 1995) and are normally created by wind action. Waves created by earthquakes or underwater explosion of volcanoes have more flattened orbits and the water flow forward and back in a horizontal movement. These waves are called long waves. Formation of waves in an archipelago area strongly depend on the morphometry, a subject who will be further discussed in the following chapter.

A wave may be described by defining wave height, wavelength, wave period and slope as illustrated by figure 2.5. By the discussion above on short, wind-induced waves, it comes clear that wavelength are the most important wave energy factor influencing sediment dynamics. As understood by the discussion on short wave orbits, the wavelength controls the depth at which the orbital motion may be effective. An increase of wave length and wave height result in a corresponding lowering of the wave base. The wave base or "the critical depth" separates areas of transportation from areas of accumulation (Håkanson,

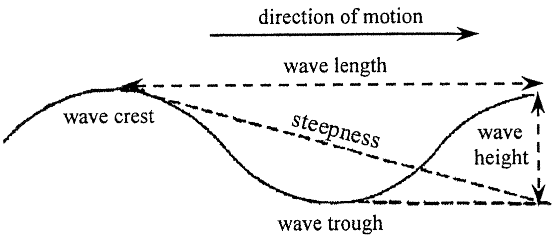


Figure 2.5: Definitions of a wave. Illustrating the relationship between wave length and wave height (From Fonselius, 1995).

1982), and will be further discussed in chapter 2.4 on resuspension.

2.2.2 Currents

Currents are mainly induced by the solar energy flow, which causes differences in density and water level. This process sets water in movement horizontally and vertically when trying to equalise the differences. Wind is another factor, which through friction induce surface currents. These wind-induced currents are theoretically described by a Swedish oceanograph, V.W Ekman. His model of wind-induced currents, show a reduction of current energy by depth, due to friction and the Coriolis effect (Fonselius, 1995). Anti-clockwise rotating cells can describe the mean surface current situation in the Baltic Sea. The Baltic Proper constitutes one of these large cells (Fig. 2.6).

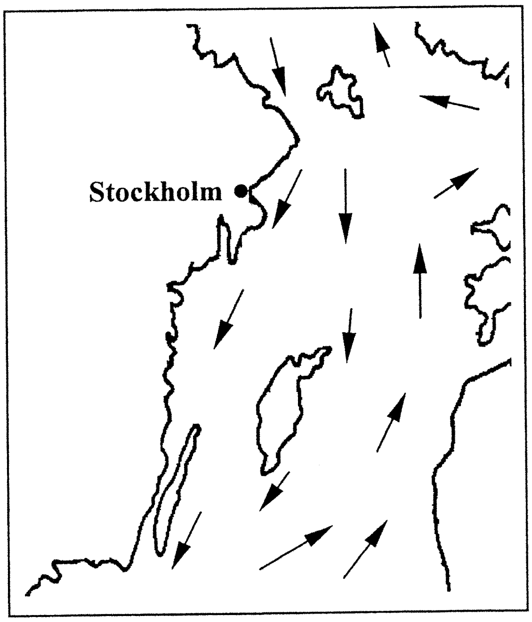


Figure 2.6: The mean surface current situation in the Baltic Proper. The large-scale current pattern can be of importance to sediment processes (Modified from Olsson, 1978).

This large-scale current pattern is of course of importance to the processes of sediment erosion and accumulation. Though, the types of currents that may be of most importance in redistribution of sediment are turbidity currents, episodic down-slope movements of sediment-laden water. This type of currents can redistribute large amounts of sediment compared to the wind-induced surface currents influenced by the Ekman effect. But still, the wind-influenced current can also be of importance in shallow areas.

2.2.3 Sea level variations

Today the southernmost coastline of the Baltic Sea is weakly transgressive (about 1 mm/year) due to crustal submerge. In the northern Öresund equilibrium prevail and the northern part of the Baltic Sea is regressive (about 8 mm/year in the Bothnian Bay) due to crustal uplift (Fig. 2.7). According to Fonselius (1995), the volume of the Baltic Sea decreases by 1-2 km^3/year as a result of the sea level change. Though,

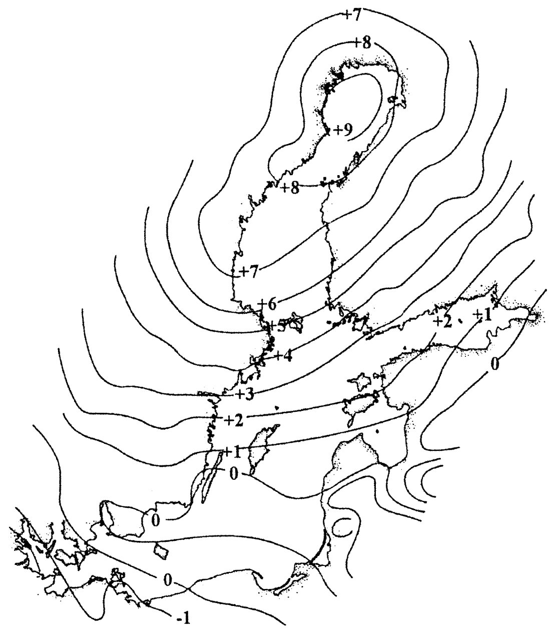


Figure 2.7: Isobases (mm a^{-1}) illustrating a quantification of the sea level variations due to crustal uplift (and submerge). (Modified from Fonselius, 1981).

this study does not take into consideration the impact of crustal uplift, tide or any sea level variations. As the influence crustal uplift does not contribute to any rapid changes in sea level variations and as tides in the Baltic Sea only is a few centimetres (Fonselius, 1995), these factors are believed to be of minor importance in this study.

Other sea level variations than tides are mostly depending on wind conditions. The greatest variations in seawater level occur during autumn and winter when wind frequencies are highest. In bays of the Baltic Sea, sea level can change rapidly. The variations in sea level can reach values of one or some meters, which in case of sea level rise gives rise to new areas of erosion. In the opposite way, a lowering of sea level would reduce the area of accumulation/ deposition by making new areas (earlier accumulation areas) exposed to the wave base and with that exposed to erosion and resuspension. Sea level variations such as these are not considered in this study but are an interesting factor to take into consideration in future studies.

2.3 Morphometry of coastal areas

As stated by Persson (1999), different coastal areas respond differently to one and the same load of pollutants. It is therefore important to find a model of describing a coastal area by some standard parameters. Persson (1999) present a model with three main groups of morphometric parameters:

- *size*, e.g. total water area and bottom area
- *form*, e.g. mean depth, mean slope and form factor
- *special parameters*, e.g. topographic openness and filter factor

All of these factors influence the way in which wind, wave and currents may redistribute sediments. The six bays investigated in this study have been picked out to represent various sizes, form and other characteristics. This is an attempt to get a sufficient spread of different environments in order to be able to consider the morphometric parameters as being non-significant for the thesis. Still, some morphometric parameters are discussed and adopted in the following section concerning resuspension.

2.4 Transport of sediment - resuspension

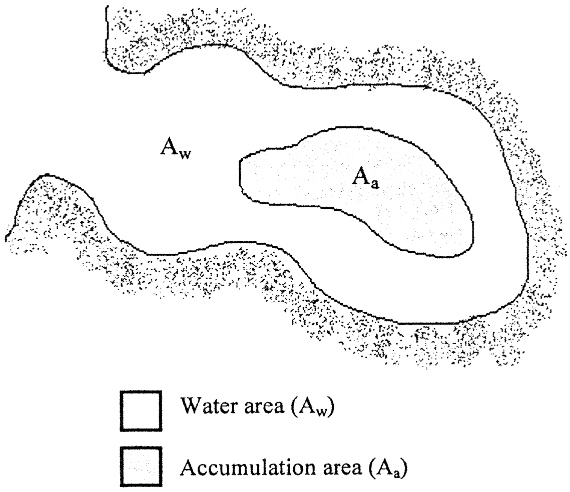
Sediment dynamics include erosion, transportation and deposition. The main sources of settling particulate matter are planctonic production, allochtonous input and sediment resuspension. Erosion, resuspension and transport by sediment can be described by a number of parameters as filter factor, fetch, wave energy, wind energy and sediment focussing. These parameters are explained more detailed below. High resuspension activity due to wind/wave effects are particularly important in large, shallow lakes and bays (Håkanson, 1982).

2.4.1 Classification of seafloor

This study use the classification of Håkanson´s (1983) three different types of seafloor (fine material is here defined as medium silt with grain sizes less than 0.006 mm):

- *Accumulation areas* where fine materials can be deposited continuously.
- *Transportation areas* where there is a discontinuous deposition of fine material, that is deposition is interrupted by resuspension/transportation.
- *Erosion areas* where there is no deposition of fine material.

The deposition rates in both the archipelago and marine environment vary naturally due to a number of important factors e.g., topography, stratification, fetch and wind (Brydsten, 1993). All these factors influence the relative proportion of A-areas in the investigation area (Håkanson and Jansson, 1983). To be able to compare accumulation rates between areas with different proportion of A-areas, accumulation has to be normalised for sediment focussing in the area (Fig 2.8). The sediment focussing factor (water area/A-bottom area) is based on the initial mapping of seafloor in the study area, where the different seafloor types can be interpreted from sonar stripes.



Sediment focusing factor = A_w/A_a

Figure 2.8: Illustrating the sediment focussing factor in a bay as the total water area divided by the accumulation area.

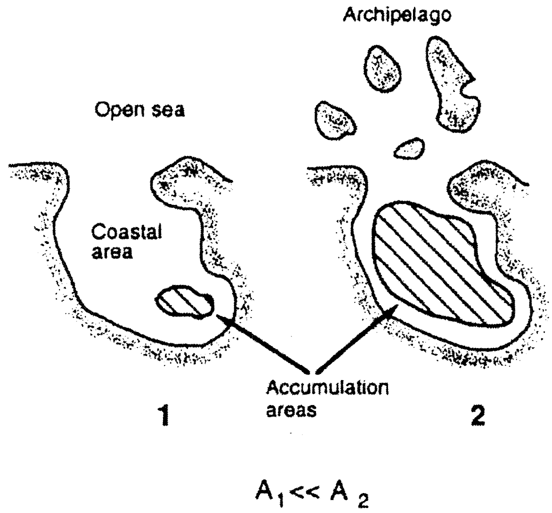


Figure 2.9: The amount of wind and wave action reaching bay 1 are larger than the one reaching bay 2 (different filter factor), which influences the area of accumulation (From Persson, 1999).

When the focusing factor is taken into account, the mean gross deposition rates can be calculated as gram per square meter water surface per year (Persson and Jonsson, 2000) and by that it is possible to in a correct way compare deposition calculations in different bays with each other.

2.4.2 Factors influencing resuspension

Many factors influence sediment dynamics. Wind, wave and currents have already been discussed, as well as morphological parameters.

A morphometry parameter discussed by Persson (1999) is the filter factor (Ff). It quantifies the amount of wind- and wave energy that may affect the ecosystem from surrounding coastal areas. That is, a dense archipelago diminishes the areas of transportation and increases the accumulation areas (Fig 2.9). The effective fetch (L_f) is another important factor in resuspension processes. An increased effective fetch may lead to a pronounced increase of the mean wave height, with a corresponding deepening of the wave base. As earlier discussed, the wave base or "the critical depth" separates areas of transportation from areas of accumulation. By analysing fetch today and historically, we can simulate the effect on wave height at a certain fetch and wind speed. Resuspension lead to redistribution of large amounts of fine material, the erosion- and transport areas increase proportionally to the seafloor area that is exposed to the deeper wave base. A rough distinction between erosion, transportation and accumulation areas can be received in the so-called ETA-diagram (Fig. 2.10), constructed by Håkanson (1977).

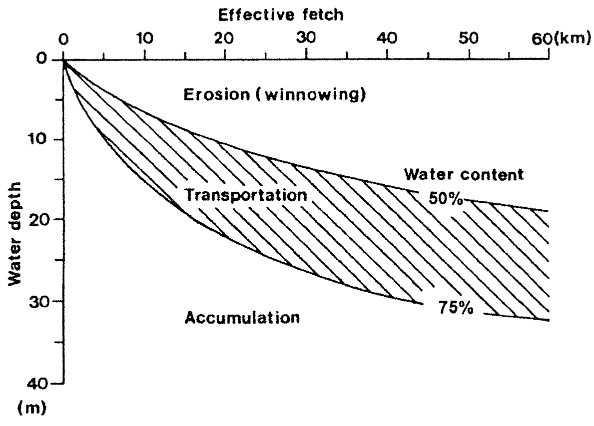


Figure 2.10: The seafloor can roughly be divided into erosion-, transportation- and accumulation areas by knowledge of the water depth and the effective fetch. (From Håkanson, 1977).

2.4.3 Effects of resuspension

An important question concerning resuspension is which environmental effect sediment resuspension could have. Weyhenmeyer (1996) list a number of possible effects on water, sediment and organisms. For example:

- *increase in total and particulate nutrient concentrations and metal concentrations,*
- *increase in concentrations of organic pollutants (e.g. HCBs and TCB),*
- *increase in concentrations of radiocesium in fish,*
- *increase of algal production due to increased concentrations of soluble nutrients,*
- *decrease of algal production through light attenuation,*
- *source of nutrition to filter-feeding organisms.*

In the same way as sediment resuspension act as a source of nutrients and contribute to the release of contaminants to the water column, it can also act as a sink for nutrients and contaminants as nutrients and contaminants move from the water column due to settling of particles.

3 The investigation area – physical settings

3.1 NW Baltic Proper

There are numerous ways to divide the Baltic Sea into smaller areas. The subdivision in smaller basins is based on hydrographical data as depth of sills and shallow areas, which limit the water exchange and produce natural sub basins. The offshore investigation area is situated in the NW Baltic Proper, more specified in the West Gotland Basin (Fig. 3.1). The 11,3 km^2 area of investigation (Laxen 1) has a depth range of 180 to 203 m and is situated close to the earlier investigated P23 area (Eckhéll *et al.*, 2000).

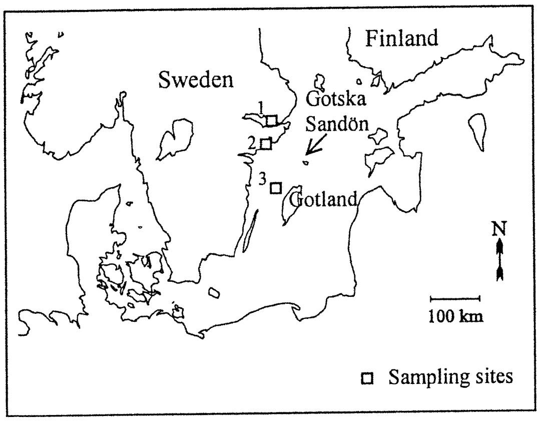


Figure 3.1: The investigation areas; 1 - Stockholm archipelago, 2 - Södermanland archipelago and 3 – Laxen 1, the marine area. Gotska Sandön, where the weather station is placed, is also marked in the figure.

3.2 Six bays in the archipelago of the NW Baltic Proper

The investigation area of the NW Baltic Proper archipelago comprises a large number of bays. For this study, a total of six bays have been used, of which five in the Stockholm archipelago and one in the Södermanland archipelago (Tab. 3.1 and Fig. 3.2–3.5). The bays are of various depths, elongation and orientation and are exposed to different sources of human impact. A brief geographical description of the six bays follows.

Table 3.1: The archipelago investigation areas and the depth of the 17 sampling sites.

Area	Bay	Core	Year *	Depth (m)
Stockholm inner archipelago	Erstaviken	B	1996	57
	"	C	"	56
	"	D	"	67.5
	"	E	"	71.5
	Ö Saxarfjärden	A	1996	67
	"	B	"	64
	Älgöfjärden	B	1997	27.5
	"	E	"	35
Stockholm outer archipelago	Gälnan	B	1996	20
	"	C	"	23
	"	D	"	24.5
	Edöfjärden	B	1997	26.5
	"	G	"	37
Södermanland archipelago	Näslandsfjärden	A	1996	39
	"	B	"	35.5
	"	C	"	27
	"	D	"	19.5

* Year of sampling

3.2.1 The inner Stockholm archipelago

Ö. Saxarfjärden (Fig. 3.2-1 and 3.5a)

The bay is mainly orientated NNW-SSE and has an area of 26,8 km^2. 58 % (15,5 km^2) of the seafloor is classified as accumulation area. A major part of the seafloor is flat with depths varying between 50 and 60 m, with a maximum depth of 67 m. The sills are distinct with depths of about 30 m.

Älgöfjärden (Fig. 3.2-2 and 3.5b)

The elongated bay has its main orientation O-V and SV-SO. Maximum depth is about 40 m. Two narrow sounds lead in to the bay, which easily could be interpreted as limiting the water exchange. Though, the northern sound, Vindö sound, has a threshold of 20 m and is known to be very current. The accumulation area is estimated to 48 % (5,6 km^2) of the total bay area of 11,6 km^2. There are a large number of private households and agriculture in the surroundings, contributing to discharges to the bay. In some cases the wastewater discharge directly into the adjacent watercourses. Discharges come also from the local wastewater plant.

Erstaviken (Fig. 3.2-3 and 3.5c)
Erstaviken is an elongated bay orientated NW to SE. A sill of depth 25-35 m decreases the water exchange with outer areas. The maximum depth of the bay is 75 m and the water area is 18 km^2 of which 45 % (8 km^2) is classified as accumulation area. There are no larger direct sources of discharge to water in the area. Some wastewater is discharged to the drainage basin from private households. As the soil layers in the surrounding area are thin, there is a possible risk for leakage of wastewater to the ground water as well as to Erstaviken. A larger agriculture including livestock is placed at the inner part of the bay.

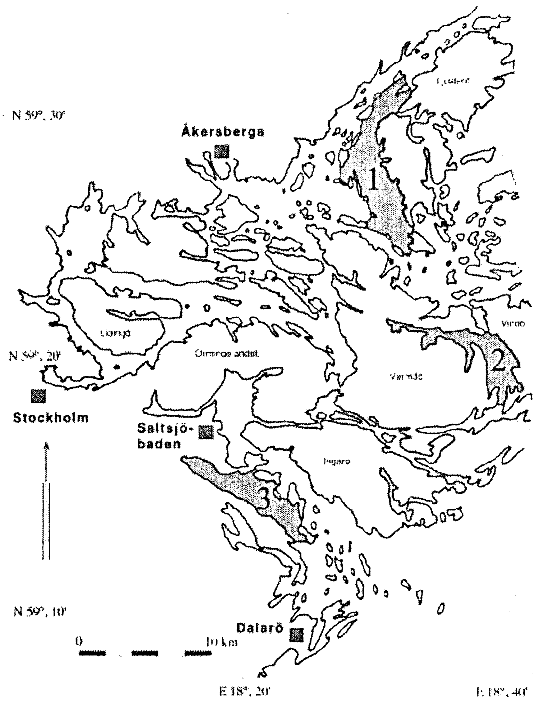


Figure 3.2: The inner Stockholm archipelago; 1 – Östra Saxarfjärden, 2 – Älgöfjärden, 3 – Erstaviken. (Modified from Persson, 2000).

3.2.2 The outer Stockholm archipelago

Edöfjärden (Fig. 3.3-5 and 3.5d)
The elongated bay has its main orientation in direction NO-SV. The topography is very rough and divides the bay into six basins of various sizes. The largest basin covers most of the bay area. The bay has an area of totally 16,7 km^2 of which 40% (6,7 km^2) is classified as accumulation area. Greatest depth of the bay is 37 m. Human impact is quite small as most of the settlements in the surroundings are weekend cottages.

Gälnan (Fig. 3.3-4 and 3.5e)
Gälnan has its main orientation NO-SV. The accumulation area stands for 51 % (26,7 km^2) of the total water area of 32,4 km^2. The bay is shallow with depth of 12-18 m in most of the area, and a maximum depth of about 30 m. No larger industries or sewage treatment works are placed in the area, which contributes to the quite small direct human impact on Gälnan. The settlement in the area is mostly made up of weekend cottages.

Figure 3.3: The outer Stockholm archipelago; 4 –Gälnan, 5 – Edöfjärden. (Modified from Persson, 2000).

3.2.3 The archipelago of Södermanland

Näslandsfjärden (Fig. 3.4-6 and 3.5f)
Näslandsfjärden is an N-S orientated bay in the archipelago of Södermanland, south of Stockholm. The bay has a water area of 14 km^2, of which 49 % (6,8 km^2) is classified as accumulation area. A large part of the bay has a depth greater than 25 m, with shallower areas at the northern part. Greatest dept of the bay is 40 m.

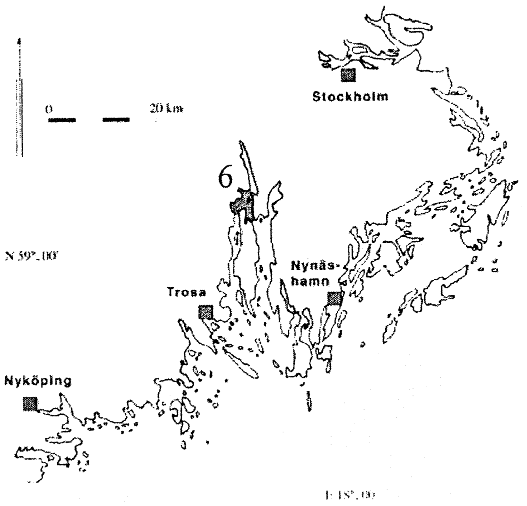


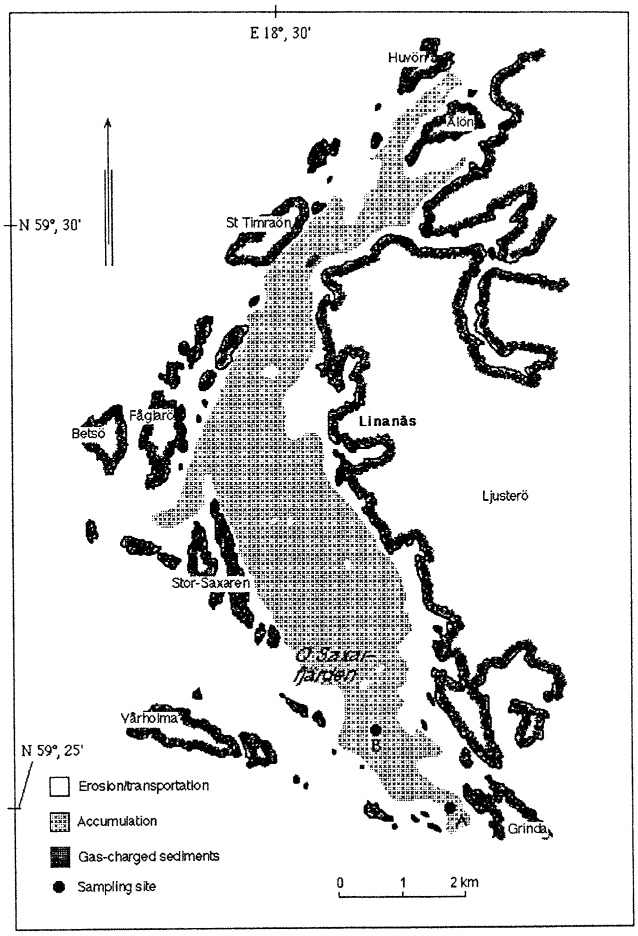
Figure 3.4: The archipelago of Södermanland; 6 – Näslandsfjärden. (Modified from Persson, 2000).

Figure 3.5 a-b: Illustrating the six investigated bays in detail.

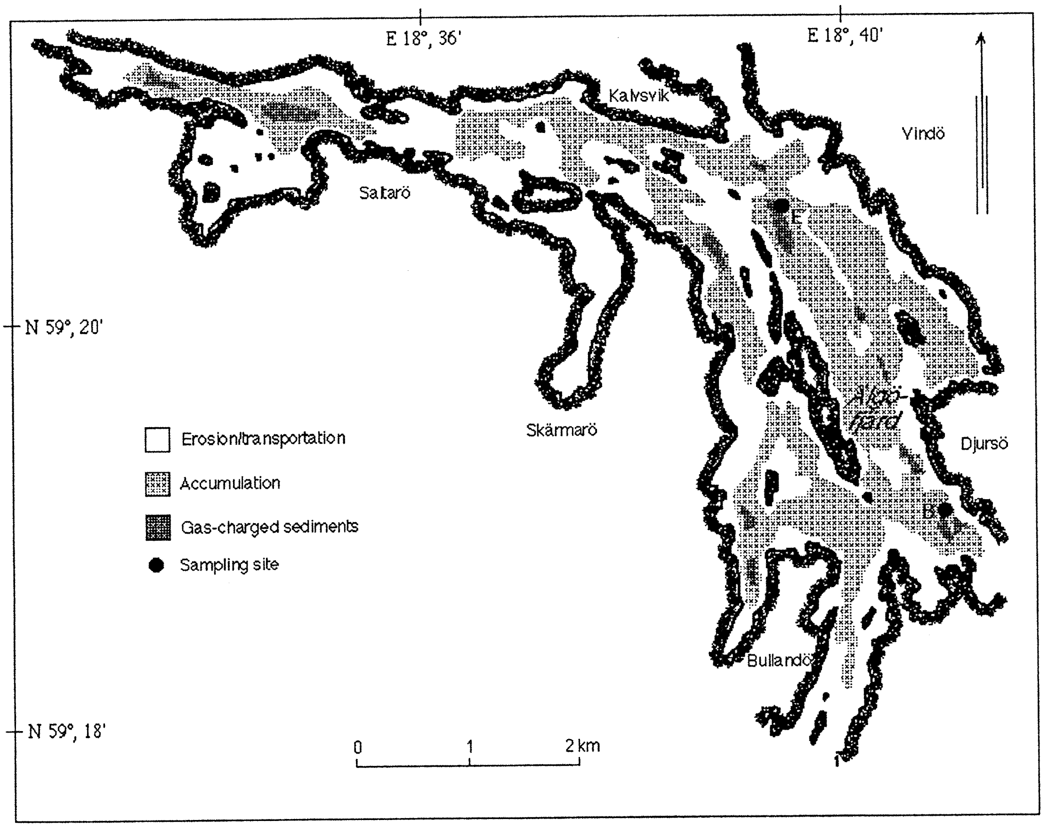
a) Östra Saxarfjärden,

b) Älgöfjärden,

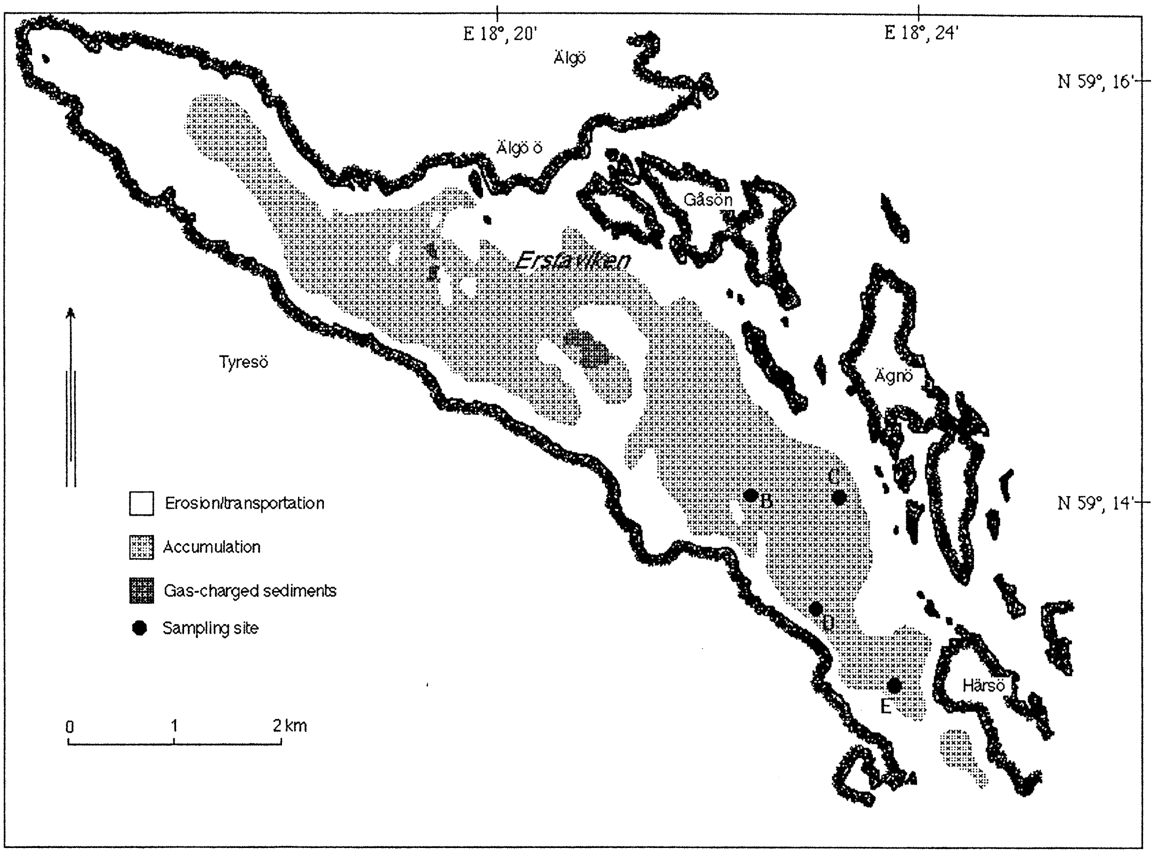
The sampling stations are marked with points. (Modified from Persson, 2000).



a)



b)



c)

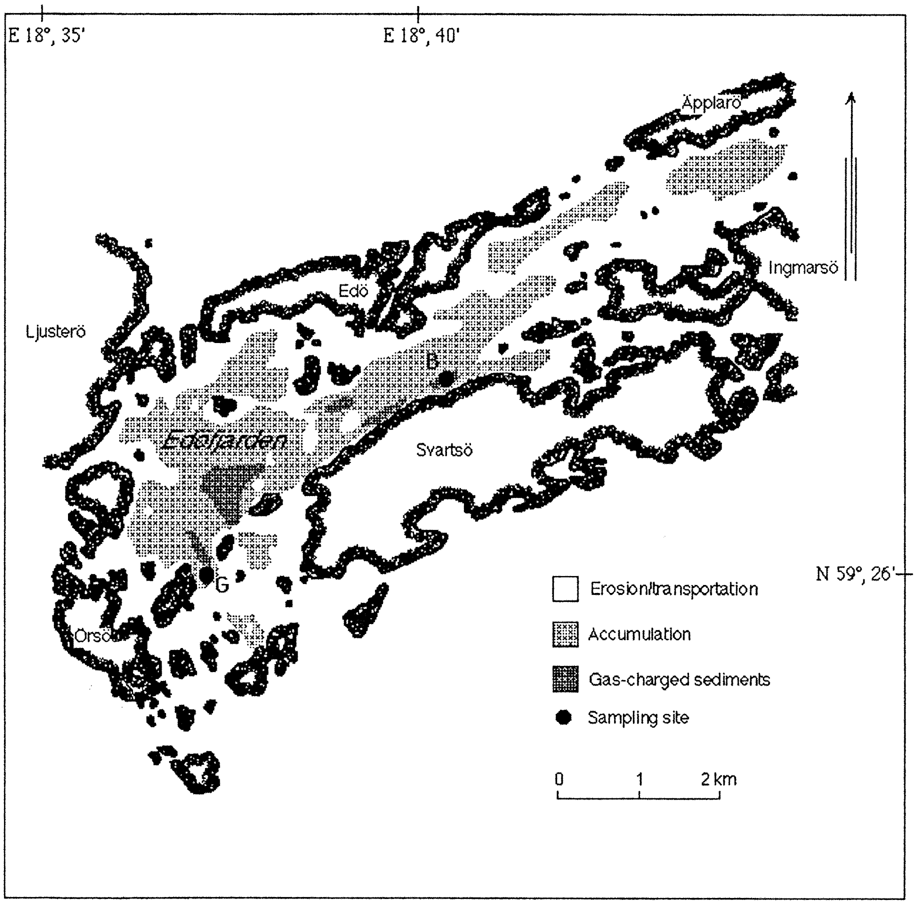
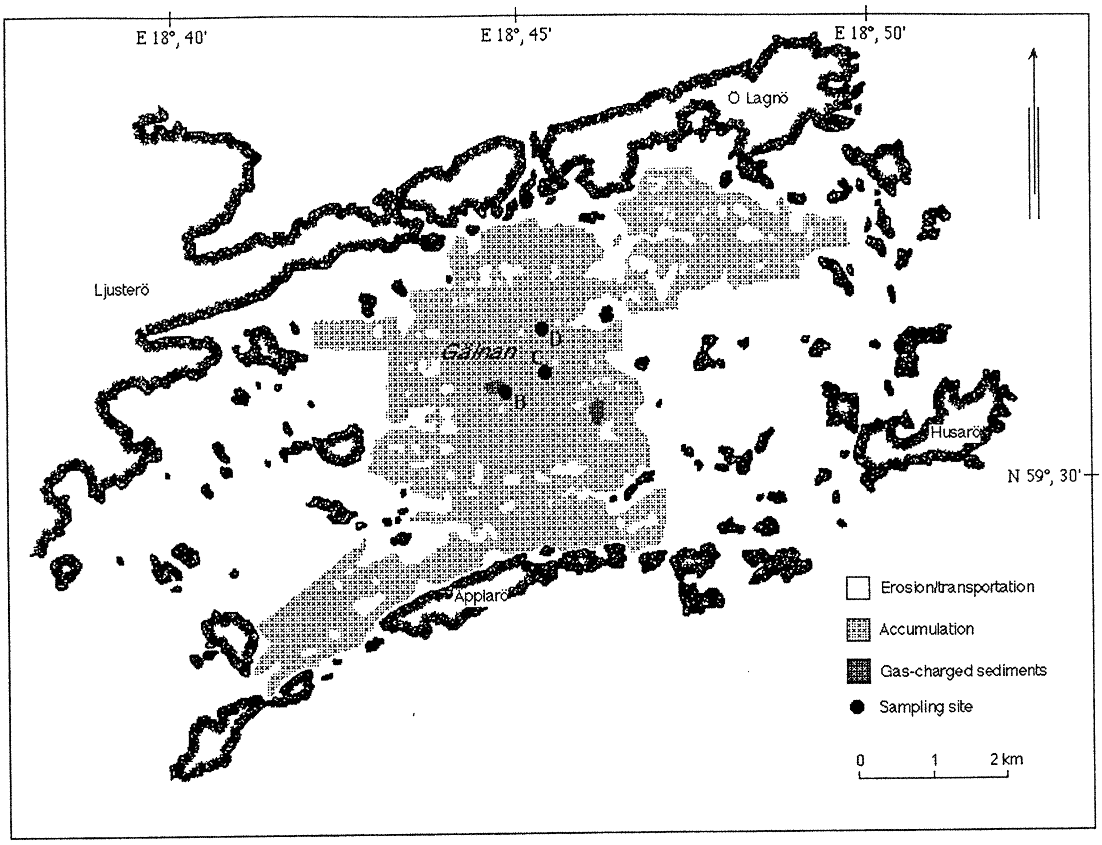


Figure 3.5 c-d: Illustrating the six investigated bays in detail.
c) Erstaviken,
d) Edöfjärden,
The sampling stations are marked with points. (Modified from Persson, 2000).

d)



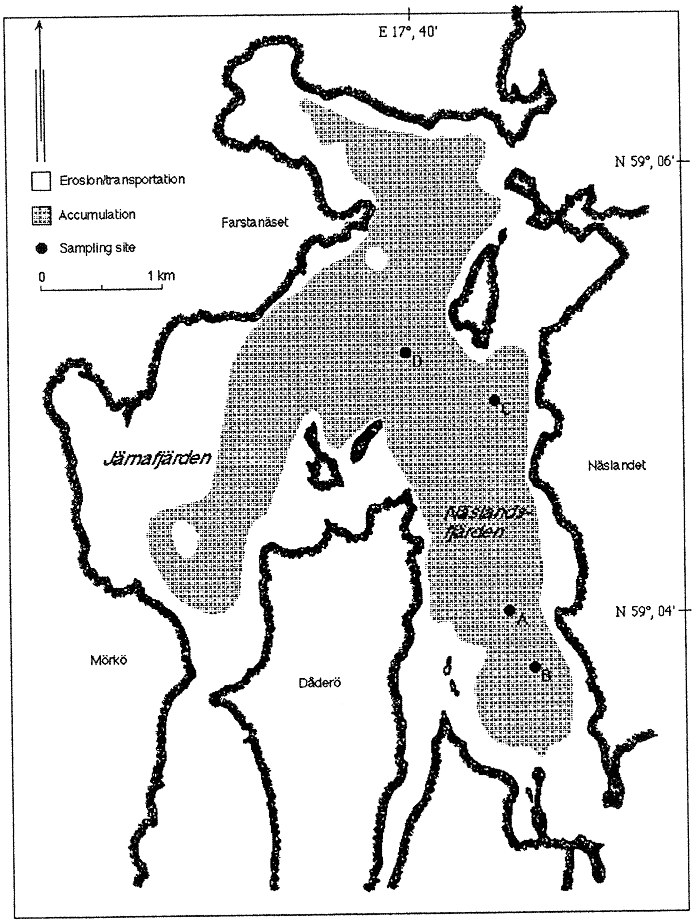
e)

Figure 3.5 e-f: Illustrating the six investigated bays in detail.

e) Gälnan,

f) Näslandsfjärden

The sampling stations are marked with points. (Modified from Persson, 2000).



f)

4 Methods

The thesis include two investigation areas; one offshore area based on field studies and one study of archipelago environments based on data from earlier analysed cores from the Stockholm archipelago. Since both field and laboratory work was performed in a similar way in the two investigation areas, using the same equipment in field and in the laboratory, the following description of the methods used is valid for both areas.

4.1 Field work

Field work was performed in June 1999 for investigation of the offshore area. The field work in the archipelago area had earlier been performed during the summers of 1996 and 1997. All fieldwork was conducted from R/V Sunbeam. Global Positioning System (GPS) with an accuracy of generally <30 m was used for positioning.

The offshore investigation area (Laxen 1) has an area of 11,3 km^2. Four transects of each 2 nautical miles were distributed over this same area, with a distance of 0,4 nautical miles between each transect. In the same way, transects were distributed in the six bays. The ship was cruising along the transects, mapping the seafloor with a side-scan sonar, an echogram and a sediment echosounder. The side-scan sonar gives a picture of the surficial distribution of different seafloor types. Pale colours indicate soft sediments (A-areas) and darker colours hard sediment (E- or T-areas). The sediment echosounder provides a vertical picture of the seafloor sediment layers.

The equipment used was an EG&G Environmental Equipment Model 260 Image Correcting Side Scan Sonar (100 kHz frequency) and a 272-TD-Saf-T-Link Tow Fish (Fig. 4.1). A low-frequency sediment echosounder (O.R.E Geopulser Pinger 14 kHz) was used to get a vertical view of the sediment layers and an echogram was used as help during the sampling procedure. The information received from the mapping was used to make a preliminary interpretation of

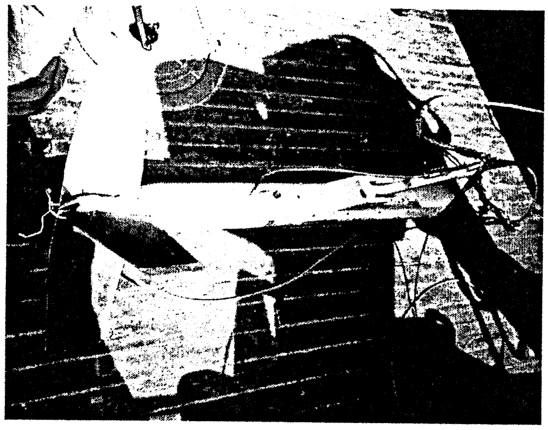


Figure 4.1: The Side Scan Sonar Tow Fish used for mapping of the seafloor. Photo by author 1998.

the bottom topography, type of seafloor and to make a selection of suitable sites for sampling. In the offshore area, five cores (A-E) were sampled with a Gemini core sampler (Fig. 4.2). The most important advantage with this sampler is that we receive two similar twin cores, which allows two opportunities for analyses in the laboratory.

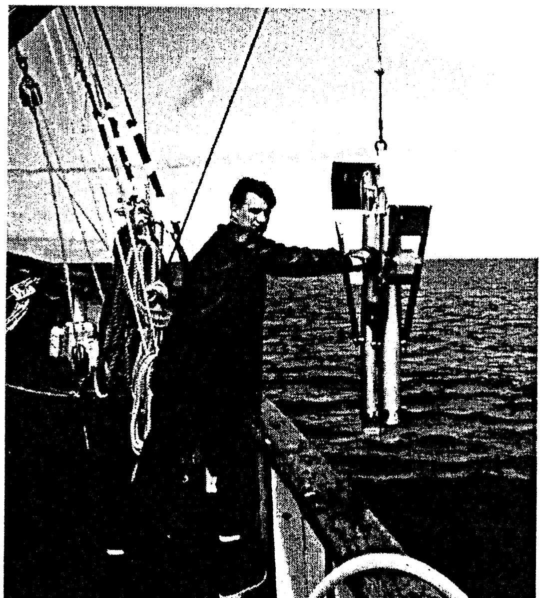


Figure 4.2: The Gemini core sampler. Photo by author 1999.

A large number of cores were taken in the six investigated bays during 1996-97, of which 17 cores are used in this study. The sampling was performed with great care not to disturb the sediment surface.

The cores were stored at +4-6°C until preparatory work took place in the laboratory.

4.2 Laboratory work

4.2.1 Sub sampling

Three cores (A, C and D) were picked out from the offshore area, for analyses of water content, total organic carbon (TOC) and Cesium^{137}. These parameters had already been analysed on all 17 cores from the archipelago (except for Cesium^{137} on Älgöfjärden B). The cores were first frozen for approximately two hours and then split up vertically, described and photographed. The photographs were used for counting of varves, one part of the dating process. In Appendix 1, two representative cores are displayed, one from the offshore area and one from the archipelago. Dating of the cores was based on the assumption that each lamina couplet (light-dark; varve) represents one year (Jonsson, 1992). Before slicing, the thickness of each varve was carefully measured as the distance between two light bands.

Sub-sampling was proceeded by slicing the core into varves, each by each to receive a one-year resolution of analysed data. In the offshore area this implied slicing the cores in approximately millimetre thick samples. The archipelago cores had already had been analysed in 1996-97, and the sub-sampling was made by each or every other centimeter, not by each lamina. In those cases, minute lamina counting from photographs was performed, which in combination with core descriptions from 1996-97 resulted in a dating of each lamina. Based on sampling depths within the cores, results from radiometric dating and results from laboratory analyses, water content and TOC could be interpolated for each year also concerning the archipelago cores.

4.2.2 Dating of sediments

Varve thickness was in detail examined in computer (Photoshop) based on photographs of the cores. This programme enables adjustment of contrasts and colours, which makes interpretation of lamina easier. The number of varves and their thickness was noted for comparison with analyses of ^{137}Cs. Varve counting was performed on all 17 cores from the archipelago and three cores from the offshore area. All cores, except for Älgöfjärden B, were also radiometrically dated by ^{137}Cs.

4.2.3 Water content

All samples were freeze dried for 72 hours to determine the water content. The samples were weighed and the water content was calculated in percent of the total weight of the sample. The water content is used when calculating the dry substance.

4.2.4 Total organic carbon

Analyse of total organic carbon and nitrogen was performed at the department of limnology, Uppsala University. A small amount (5-10 g) of the dried sediment was put in a lead capsule and weighed with an electrobalance scale "CHANMODEL 4700". The capsules were analysed with "LECO CHNS-932" to determine total organic carbon (TOC), nitrogen and sulphur by oxidation of the samples. The amounts of TOC, N and S were received as percent of the dry weight.

4.3 Calculations

4.3.1 TOC – LOI regression

The *loss on ignition* (LOI) is a measure of the organic content in lake and marine sediment and is usually presented in weight percent of the dry substance. When heating the dried sediment at 550°C during two hours, the organic material will incinerate. As the heating also can cause inorganic losses as evaporation of chemically bound water and split of carbonates, the loss on ignition is not the exact equivalent to organic content. According to Håkanson and Jansson (1983), the loss on ignition can be determined by the following formula:

$$IG = \frac{W_s - W_r}{W_s} \cdot 100 = \frac{gds - gir}{gds} \cdot 100$$

where
IG = loss on ignition in percent of the weight of the solid particles (W_s);
W_s = weight of the solid particles;
W_r = weight of the inorganic residue;
gds = g dry substance;
gir = g inorganic residue.

The *total organic carbon* (TOC) is a measure of how large amount of the total organic material that is made up of carbon respectively other organic matter. The correlation between TOC and LOI is usually very good (Håkanson and Jansson, 1983). Such a regression was constructed by Persson and Jonsson (2000) based on a large empirical material (n=298) derived from the analyses of cores from the offshore NW Baltic Proper). This means that if total organic carbon in a certain area is known, loss on ignition can be calculated by plotting the regression between the two parameters, based on earlier analysis of sediment in a similar area.

4.3.2 Dry substance accumulation

To calculate the annual dry substance accumulation, the thickness of the annual lamina has to be known. The dry substance deposition is calculated according to the following formula, in Håkanson and Jansson, 1983:

$$v_d = Y \cdot ds \cdot \rho \cdot 100$$

where
v_d = dry substance deposition ($g/m^2/yr$)
Y = lamina thickness (cm)
ds = dry substance (%)
ρ = bulk density (g/cm^3 wet substance)

Dry substance is determined by:

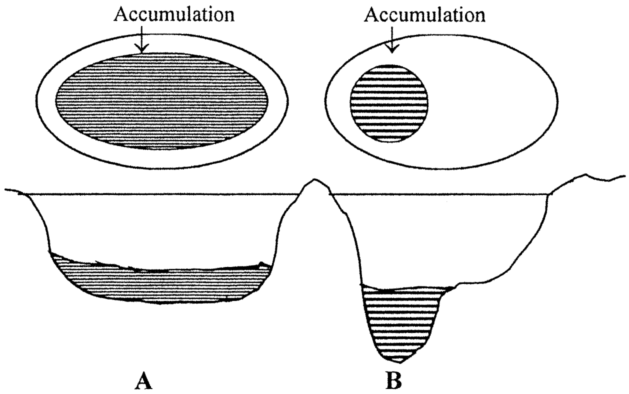
$$ds\ (\%) = 100 - W$$

The bulk density is the density of the wet sample and is given by:

$$\rho = \frac{100 \cdot \rho_m}{100 + (W + LOI_o)(\rho_m - 1)}$$

where
ρ_m = density of the solid particles (g/cm^3)
LOI_0 = loss on ignition in % of the total wet weight

The density of the solid particles varies depending on the elements in the sediment. Since clay, quarts and other elements with similar density usually build up the sediment, ρ_m is as a general rule set as 2,6 g/cm^3 (Håkanson and Jansson, 1983). Where analyse data was not available for each lamina, values of dry substance and density (from LOI) was interpolated by the known visual dating of the sediments. In those cases where loss on was not determined, LOI was calculated from regression between LOI and TOC.



	A	B
Accumulation area:	80 %	20 %
Sediment focusing factor: $= \frac{\text{water area}}{\text{acc. area}}$	1.25	5
Accumulation rate: (g m^{-2} acc seafloor area yr^{-1})	1250	5000
Accumulation rate: (g m^{-2} surface water area yr^{-1})	1000	1000

Figure 4.4: Illustrating the importance of including the sediment focussing factor in deposition calculations. The accumulation rates in the accumulation areas differ evidently, but when these values were corrected for sediment focusing it stood out that lake A and B has the same accumulation rate per m² water area per year. The difference is particularly clear in lake B, where the accumulation rate differs by a factor of five depending on weather deposition is corrected or not.

A comparison of sediment accumulation between two different areas can not be done without normalising for sediment focussing. The basis for this type of normalisation is that the area where accumulation of fine particles occur has been quantified; the accumulation area. The procedure of normalisation for sediment focussing (Fig. 4.4) is simply a way to calculate the obtained accumulation rates in accumulation areas to represent the entire water area. In the illustrated example (Fig. 4.4) a much higher accumulation rate expressed in relation to accumulation area is registered in the shallow bay compared to the deep bay. However, if the sediment accumulation is normalised to water area, accumulation rates can be compared.

4.4 Wind data

The wind data set used is collected at the SMHI (Swedish Meteorological and Hydrological Institute) weather station at Gotska sandön (Fig. 3.1) and includes data from 1951 to 1997. The station is placed 50 meter above sea level, at Lat: N 64° 79,35′, Long: 16° 98,11′. Continuous measurements of wind speed have been performed since 1951.

The data consist of measurements of mean wind speed, defined as the mean wind speed (0-57 m/s) over a time period of ten minutes. The data set used in this study is built up by yearly number of occasions (10 minute periods) of a certain wind speed, 0 - 57 m/s. These data allows us to calculate the yearly variations in wind frequency with a resolution of 1 m/s. The data set is considered homogenous as the weather station has not been moved and no larger buildings has been set up in the surroundings, factors with can influence the quality on the collected data.

Concerning the offshore area, data from Gotska sandön were the most suitable to use as it is the best geographically situated station. It is placed near the investigation area, and in a position exposed for similar wind conditions as the investigation area. For the Stockholm archipelago there were three other possible stations to take into consideration: Örskär, Bromma and Söderarm. Örskär is located too far north to be suitable for this study. Bromma lies on mainland and should probably be best suited for only the inner archipelago. However, urbanisation in the area during the last decades (buildings surrounding the weather station) may have influenced the data in a negative way. Söderarm is maybe the best located station of the three mentioned above, but as its placement over sea level has changed throughout the years the data set could be to shattered to be relevant. This leaves us with the weather station on Gotska sandön to be the most suitable alternative also for the NW Baltic proper archipelago. Moreover, the aim of this study is to find if the thesis is valid not only for the Stockholm archipelago, but for the whole coastline of the NW Baltic Proper, a factor which also contributes to the selection of Gotska sandön weather station.

5 Results and discussion

5.1 Loss on ignition (LOI) and total organic carbon (TOC)

5.1.1 Offshore area

Persson and Jonsson (2000) has from a large empirical material received a LOI:C ratio of approximately 2,2 for the NW Baltic Proper. When data from other parts of the Baltic Sea were included, a similar correlation was received. The LOI:C ratio were nearly identical, 2,1-2,2. The linear relationship was used for calculating the loss on ignition for core C.

5.1.2 Archipelago area

Normally, TOC and LOI are well-correlated (Håkanson and Jansson, 1983). When analysing an empirical material derived of 62 cores (379 samples) from 13 bays in the archipelago of the NW Baltic Proper (Tab. 5.1, Fig. 5.1) a fairly good correlation (r^2=0,76) was obtained. The reason to why the correlation not is higher is probably linked to that the bays show a large geographical and morphological spread.

Table 5.1: Cores used for correlation between LOI and TOC.

Area	Bay	No. cores
Roslagen archipelago	Singöfjärden	9
	Norrtäljeviken	3
Stockholm inner archipelago	Ö Saxarfjärden	3
	Älgöfjärden	3
	Farstaviken	3
	Baggensfjärden	13
Stockolm outer archipelago	Edöfjärden	5
	Möja söderfjärd	3
	Kanholmsfjärden	1
	Bulleröfjärden	7
Södermanland archipelago	Näslandsfjärden	4
St Anna archipelago	Gropviken	3
	Kullskärsdjupet	5
	Total	62

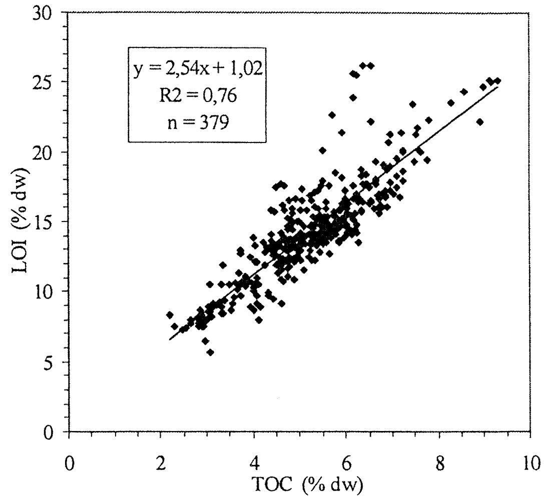


Figure 5.1: Correlation between LOI and TOC received from archipelago areas in the NW Baltic Proper.

The LOI:C ratio received was ca. 2.7, substantially higher than for the offshore area. Since a majority of the cores in this study have been analysed only for total organic carbon, the regression was constructed in order to be able to calculate loss on ignition. The equation in figure 5.1 has been used to determine LOI for 13 of the 17 cores; needed to calculate dry substance deposition (see section 4.3.1 and 4.3.2).

5.1.3 Comparison between offshore and archipelago surface sediment

As the LOI:C ratio differed considerably between the offshore and archipelago area, a comparison between surface sediment in the two environments was made in order to see if the differences could be explained. One way to visually describe the differences is to plot the TOC-LOI correlation for the surficial sediments (Figure 5.2).

Both areas showed a high correlation between TOC and LOI. However, the slope of the regressions were quite different showing that the organic part of sediment in the offshore area consists of a higher content of carbon (TOC) than sediment in the archipelago area. This is an interesting phenomenon, which may be explained by the composition of the deposited material.

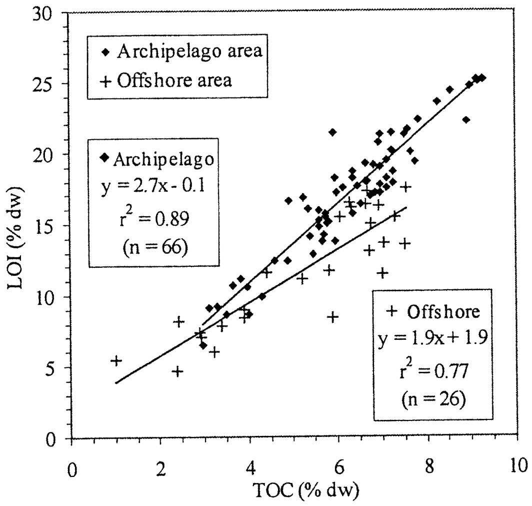


Figure 5.2: The relationship between LOI and TOC in surficial sediment from the archipelago and the offshore area.

The deposited matter consists of material from river input, material from erosion/resuspension and from primary production (Fig. 5.3). The proportions of these materials are various in different areas. The primary production probably contributes to a small part of the total suspended material both in archipelago and in offshore areas. The river input can probably contribute to a large part of the total amount of deposited material, especially in archipelago areas. Eroded and resuspended material can be of importance both in coastal and marine areas, but are probably of greater significance in the archipelago where the material is not spread over such large geographical areas.

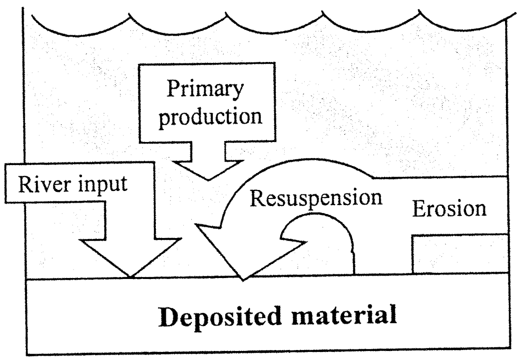


Figure 5.3: Schematic illustration of the components in gross accumulation in a water area.

The differences in LOI:C ratio between archipelago and offshore areas may be explained by the various amounts of input material to the accumulation. The primary production may by this be less contributing to the total deposition in archipelago areas than in marine areas. However, the results are confusing and need further studies to be able to draw any conclusions.

5.2 Dating of sediments

5.2.1 Offshore area

In the offshore area the varves were very thin (normally 0.5-1 mm) and not distinct. This complicated the counting of the lamina and subsequently the process of dating. A first comparison between the result from varve counting of three cores (A, C and D) did not agree with the radiometric dating. The differences were then analysed more in detail and it came clear that there had been a misinterpretation of the varve structure. Some of the thinnest varves were difficult to identify on the photographs. After a more careful laboratory examination of one of the twin cores (Laxen 1:C), a revised lamina counting could be established. With that, a time scale could be achieved which correlated better with the ^{137}Cs dating, but not in a completely satisfactory way.

5.2.2 Archipelago area

The varves in the cores from the six bays had a thickness of 0.4 to 4.2 cm. Lamina counting were performed only from photographs. Since the photos were of high quality and the laminas quite thick, the dating were performed in a satisfactory way. A comparison between the two different methods of dating, the counting of lamina and the radiometric dating with ^{137}Cs, showed that the two methods correspond well, with a variation in dating results of 1986/87 varve (Chernobyl fallout) of one or in a few cases a couple of years. The variations were analysed more thorough and since the varves sometimes can be somewhat difficult to interpret visually, a few corrections in the counting were made with help from the radiometric dating. After these marginal corrections, the dating in general are considered being accurate of the 17 cores.

5.3 Gross accumulation rates

Former investigations (Eckhéll *et al.*, 2000, Persson and Jonsson, 2000) has illustrated that the accumulation rate varies over time in both offshore and archipelago areas. The time patterns in accumulation rates were here further investigated. The gross accumulation rates were calculated in g m^{-2} yr^{-1} for one core in the offshore area and in g m^{-2} water area yr^{-1} for 17 cores in the archipelago. That is, the accumulation in the archipelago was corrected with regard to the sediment focussing factor. The deposited material consists of the input parameters as described in figure 5.3.

5.3.1 Offshore area

As the dating of the marine core could not be performed in a satisfactory way the gross accumulation could not be calculated. The possible time patterns received would not reflect the correct accumulation rates.

5.3.2 Archipelago area

The development of lamination in sediment began at different times in the six bays. In Älgöfjärden lamination appeared in the 1940-50s but in Erstaviken and Saxarfjärden, lamination did not occur until 1970. Therefore, data older than 1964 are not used in this study since less than seven of the 17 cores show clear lamination further back in time. From 1978 and onwards all cores were laminated. The seven cores which were laminated back to 1964 correlate well with the other 10 concerning the period of time 1978-1996/97, why they have been considered to be representative for the years 1964-1978.

Through mapping with Side Scan Sonar and sediment echosounder, the seafloor was investigated and the percentage of accumulation area as well as the sediment focussing factor could be calculated (Tab. 5.2). The accumulation areas make up approximately 40-60 % of the total water area in the bays.

The gross accumulation was calculated in g m^{-2} accumulation area yr^{-1} for all 17 cores. With knowledge of the water area of the bays and the area of accumulation in each bay, the values of gross accumulation were corrected regarding to the sediment focussing factor (see section 4.3.2). When calculations of gross deposition were performed in this way, they allowed comparisons of the six bays by m^{-2} surface water area. The possibility to make these kinds of comparisons is of major importance as the result should be able to be applied on bays with various gross accumulations. The time trends in gross accumulation (corrected by focussing factor) were compared with

Table 5.2: Water areas, accumulation areas, sea floor areas and sediment focussing factor in the investigated archipelago areas.

Area	Bay	Water area (km^2)	Acc. area (km^2)	Acc. area (%)	Focussing factor $= \frac{\text{water area}}{\text{acc. area}}$	Reference*
Stockholm inner archipelago	Erstaviken	17.7	7.9	44.7	2.2	EUCON
	Ö Saxarfjärden	26.8	15.5	57.8	1.7	EUCON
	Älgöfjärden	11.6	5.6	48.0	2.1	Ö-sjö97
Stockholm outer archipelago	Gälnan	32.4	16.7	51.4	1.9	EUCON
	Edöfjärden	16.7	6.7	40.1	2.5	Ö-sjö97
Södermanland archipelago	Näslandsfjärden	13.8	6.8	49.3	2.0	EUCON

* Reference material consist of mapping information and laboratory analysis

each other and with the core mean of all 17 cores (Fig 5.4), to get a picture of the gross accumulation history in the six investigated bays. Bay Östra Saxarfjärden diverge from the others in that it has an overall higher accumulation rate, which is particularly clear in the early 1990s. Opposite to this, all bays show similar patterns with 1,000-2,000 g m^{-2} water area yr^{1} during the 1960s and 70s and a somewhat lower deposition during the 1980s. From the late 1980s the gross accumulation increased and culminated in 1993-94, with a core mean accumulation of approximately 1,600 g m^{-2} water area yr^{1}. The high deposition rates in bay Östra Saxarfjärden may be due to the morphology of the bay.

One important question is though what influences the high gross deposition rates in bay Östra Saxarfjärden could have on core mean. The thick grey line in Figure 5.4 illustrates that core mean features become somewhat different when excluding bay Östra Saxarfjärden, but the main characteristics remain. In addition, this study aims at including all differences in bay morphology to be able to disregard such characteristics when applying the result in other areas. Taking this into consideration, data from Östra Saxarfjärden should not be excluded.

The main time trends in gross accumulation rate are even more evident when accumulation data from each core are described as percentile divergence from its own mean deposition (Fig 5.5). The core mean illustrates the variations in mean accumulation over time. The gross accumulation rate patterns are also here similar when excluding bay Östra Saxarfjärden. Although the accumulation varies by time as illustrated above, it could be interesting to approximate mean accumulation rate per year. By calculating the mean accumulation rate during the last 20 years (1977-1996), an "overall" picture of deposition variations could be established (Tab. 5.3). Bay Östra Saxarfjärden showed the highest mean deposition, three times as high as in bay Älgöfjärden, for example. The large variations in mean deposition between the bays, from 770 to 2,200 g m^{-2} water area yr^{1}, illustrates the expected differentiation in bay characteristics.

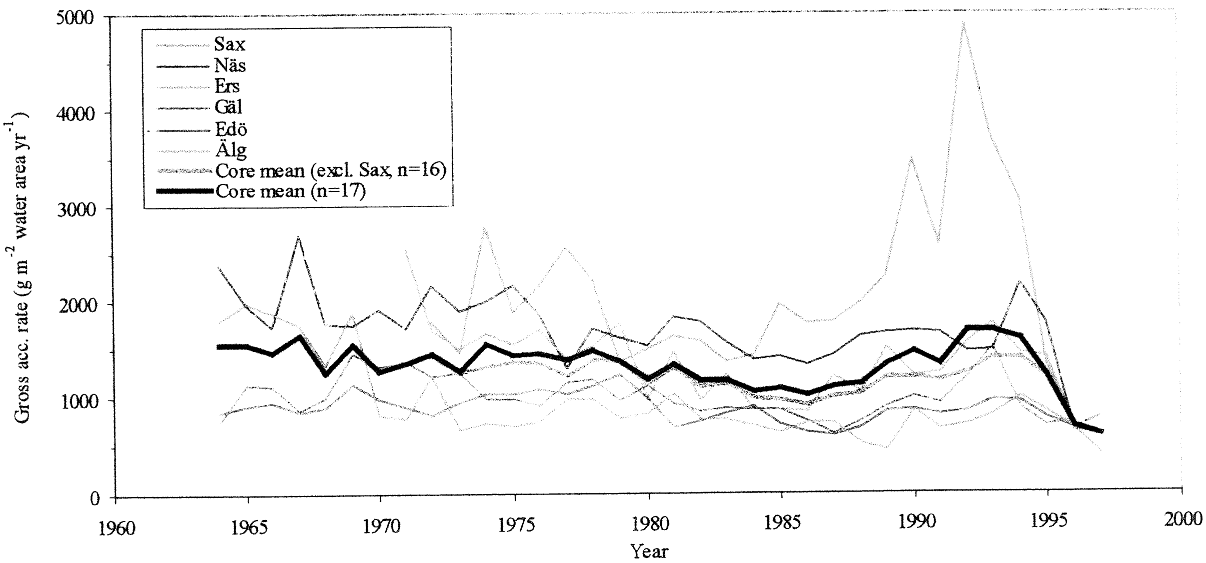


Figure 5.4: Annual gross accumulation rates in the six bays. The thick black line illustrates core mean. The thick grey line illustrates core mean excluding Östra Saxarfjärden.

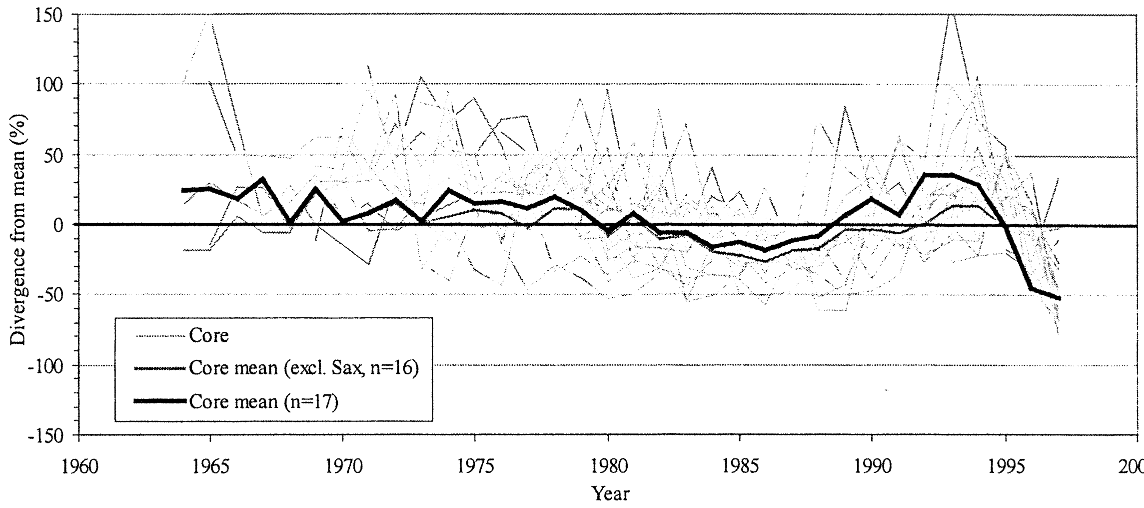


Figure 5.5: Time trends in gross accumulation rates even more pronounced when expressed as divergence from the individual mean.

Table 5.3: Mean gross accumulation rate for all six bays, calculated on data from the latest 20 years The accumulation rate is expressed as gram per year per square meter accumulation area and water area, respectively.

Bay	Mean acc. rate $g\ m^{-2}$ A-area yr^{-1}	Mean acc. rate $g\ m^{-2}$ water area yr^{-1}
Stockholm inner archipelago		
Erstaviken	2802	1252
Ö Saxarfjärden	3741	2162
Älgöfjärden	1611	773
Stockholm outer archipelago		
Gälnan	1832	942
Edöfjärden	2109	846
Södermland archipelago		
Näslandsfjärden	3160	1558

5.4 Correlation with wind data

The data on gross accumulation rates used in the correlation are the yearly accumulation calculated according to formulas in section 4.3.2. As the data is collected from each core, a correlation can be constructed for each core, for each bay or for all bays together. Most interesting is maybe to compare the six bays to see if the regression is possible to use for other bays in the NW Baltic Proper archipelago. There are several factors that could affect gross deposition, both in coastal and offshore areas, such as morphometry, openness, depth, currents. Another factor is wind. The wind speed, direction, durability and other related characteristics could influence the deposition rate. This study is aiming to define possible correlation between gross deposition and wind frequencies. Wind frequency includes both wind speed and durability, two key factors which both could influence sediment processes.

5.4.1 *Offshore area*

Former investigations in offshore areas (95-135 m) near the Laxen area have found good correlation between gross deposition and wind frequencies (Eckhéll *et al.*, 2000). In that study the best correlation was found at gale force (≥14 m/s).

Whether these results are valid also for deeper offshore areas as the area investigated in this study (180-200 m), are still to be answered since the dating was to scarce to calculate gross accumulation.

5.4.2 *Archipelago areas*

Former investigations have found a good correlation between gross deposition rates and frequency of wind speeds in offshore

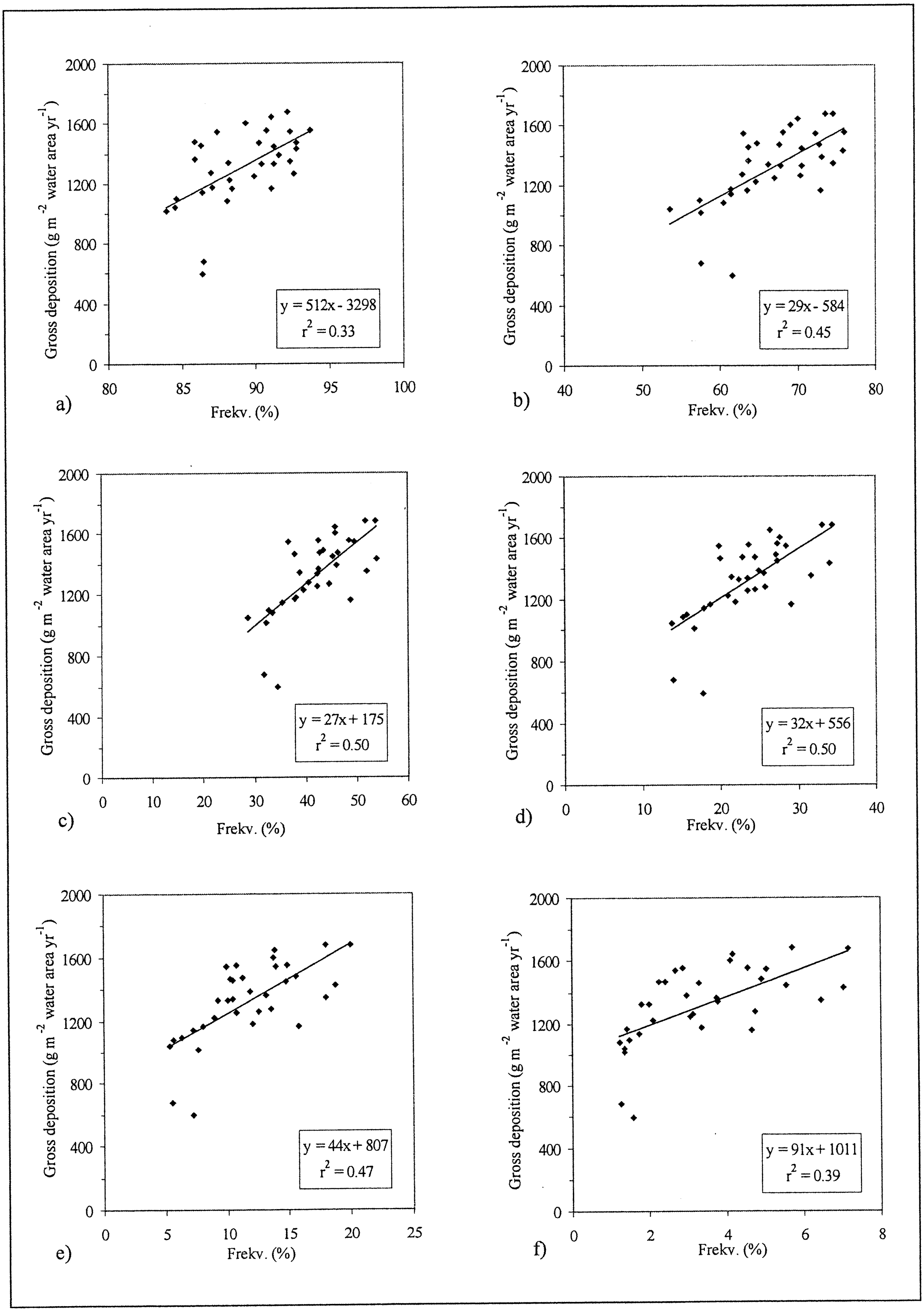


Figure 5.6 a-f: Linear regression between annual gross deposition rate (core mean) and wind frequencies at (a) ≥3 m/s, (b) ≥5 m/s, (c) ≥7 m/s, (d) ≥9 m/s, (e) ≥11 m/s and (f) ≥14 m/s. The best correlation was found at wind speed ≥7-9 m/s.

areas and in St. Anna archipelago (Eckhéll *et al.*, 2000, Persson and Jonsson, 2000). The best correlation was found at ≥14 m/s (gale force). To investigate if similar relationships also appear in other archipelago areas, annual gross accumulation rate from the 17 cores were plotted together with wind data from Gotska sandön. The wind frequencies used were ≥3, ≥5, ≥7, ≥9, ≥11 and ≥14 m/s. The best correlation (r^2 = 0,50) was found in the frequency spectra reaching from ≥7-9 m/s (Fig. 5.6). That is, the best correlation is not received at gale force as in former investigations.

As illustrated by Fig. 5.6, the time trend variations in gross accumulation rates show similarities with the variations in wind frequencies ≥7 m/s. In what way could accumulation rates be affected by wind conditions?

Wind-induced waves and currents influence the wave base, the "critical depth", which sets the level of where erosion and resuspension can occur. Strong winds can increase the wave height and thereby lower the critical depth where erosion/ resuspension occur (Fig. 5.7). That is, the input of eroded and resuspended material to one particular accumulation area can vary with variations of wind frequencies. Deposition rates varies with changes in sediment dynamics and the supply of allochtonous (river input), eroded/ resuspended and organic (primary production) material. The input of allochtonous material and primary production are not so much depending on wind circumstances as the erosion and resuspension of material, which in many cases make up the major part of the deposited material.

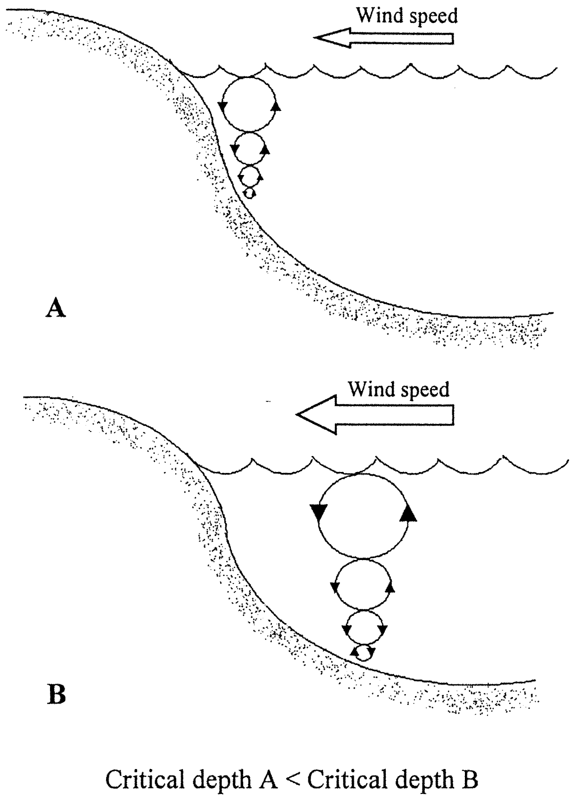


Figure 5.7: In the same area, the critical depth at which erosion/resuspension can occur are deeper at higher wind speeds. That is, in situation B when wind speeds are higher, the wave height increases and the critical depth lowers, which contribute to a higher erosion/resuspension.

During windy years the input from erosion and resuspension could be multiple the input during calm years (Fig. 5.8), which may explain the high gross accumulation rates during windy years. The theory above does not explain why the best correlation was found in wind speed ≥7-9 m/s in the investigated area, and not at gale force (≥14 m/s) as in former investigations. By this theory the gross deposition rates would always be higher at higher wind speeds. In the offshore areas and open archipelago areas this theory could be true, as the fetch has high values, the areas have great depth and other morphological factors are also of less importance. Why gale force and not higher wind speeds gives the best correlation could be a result of the short periods with higher wind speeds prevail. In the archipelago areas, the occurrence of high wind speeds (≥14 m/s) are the same as in offshore areas. Some wind force may be lost depending on the filter factor ("denseness" of the archipelago).

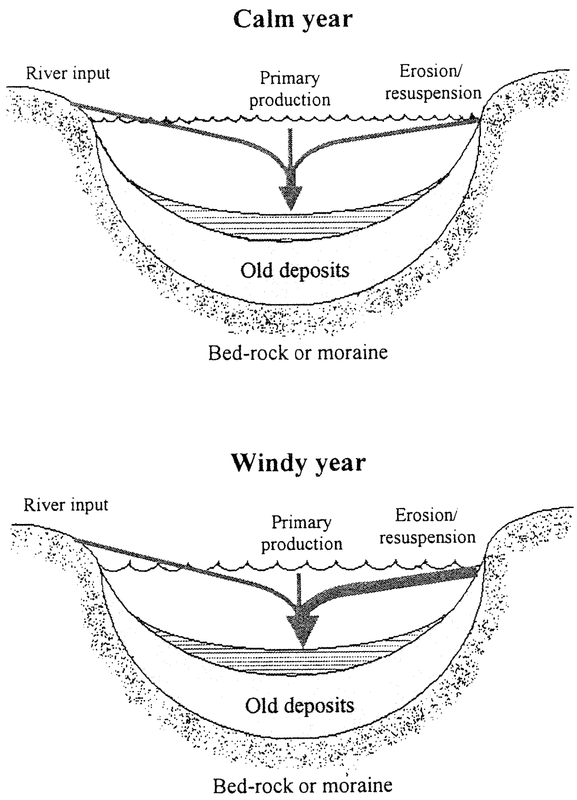


Figure 5.8: The input from erosion/ resuspension can be many times as large in years with strong winds prevailing compared to calm years with lower wind speeds. As the river input and primary production probably are of the same magnitude in both cases, the total gross deposition are higher during years with high wind frequencies.

But the most important morphological factor influencing the critical depth in archipelago areas are probably the fetch. As the bays in the archipelago are quite small and enclosed by a dense archipelago, the high wind speed does not increase wave height more than to a certain limit, which is set by the fetch. Instead, lower wind speeds could have the same influence on erosion and resuspension as the higher wind speeds. As earlier illustrated the time trends of lower wind speeds (≥7-9 m/s) show the best correlation with annually gross accumulation rates. This result may be interpreted as influence of wind forces exceeding 9 m/s is limited by the mean fetch in archipelago areas.

The correlation is further illustrated by Fig. 5.9, where annually core means of gross accumulation rates are plotted with wind frequencies ≥7 m/s. The time trends of the two curves are similar, which give further credibility to the correlation illustrated in figure 5.6 and the theory that a large part of the variation in gross accumulation rate in archipelago areas is governed by wind/wave action.

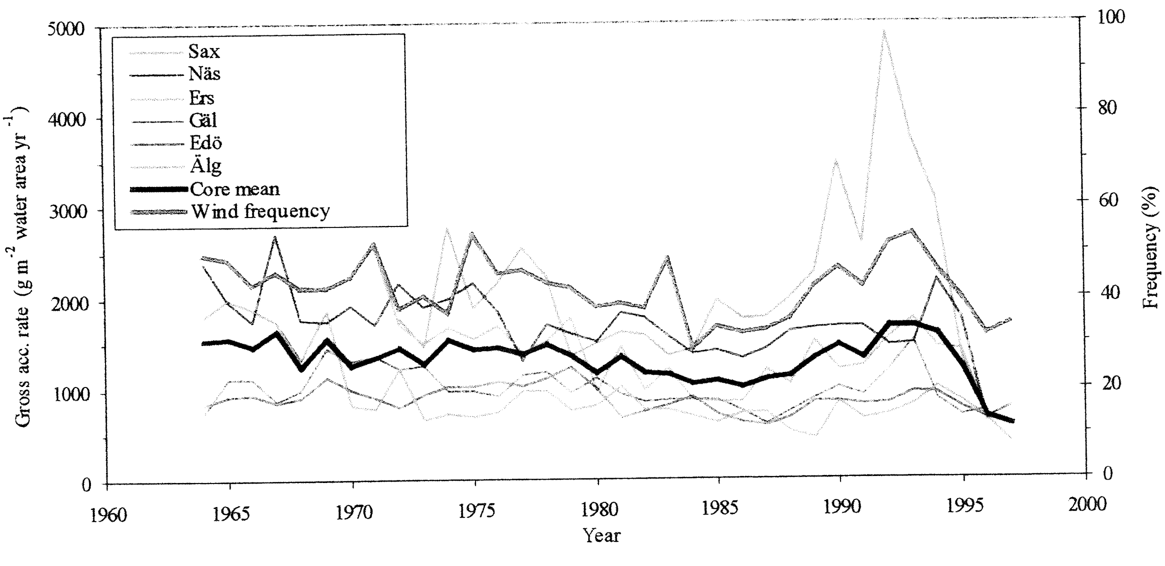


Figure 5.9: Illustrating the similarities in time trends of annual core mean (n=17) of gross accumulation rate and wind frequency ≥ 7m/s.

6 Concluding remarks

The aim of the study was to investigate how wind circumstances can affect sediment dynamics and thereby gross accumulation rates. Six bays situated in the archipelago of the NW Baltic proper made up the main investigation area. One core from a marine area in the NW Baltic proper was also analysed. The methods used were well-known analyses of sediment key parameters and analysis of wind data from the SMHI weather station at Gotska sandön. Possible correlation between deposition rates and wind frequencies were analysed by plotting linear regressions for these parameters.

A good correlation was found in the archipelago area, where gross accumulation rates seemed to be most influenced by wind speeds ≥ 7 –9 m/s. Time trends were studied more in detail for ≥ 7 m/s. It showed that similarities were found with time trends in gross deposition rates. No gross deposition rates could be calculated for the offshore area, as dating of the sediment could not be performed in a satisfactory way.

Former investigation of St. Anna archipelago found that gross deposition rates were influenced mostly by wind frequencies ≥ 14 m/s. In this study sediment dynamics in the archipelago areas showed to be affected also by lower wind speeds (≥ 7-9 m/s). The dissimilarities could partly be explained by the differences in morphology of the areas. Since great similarities were found between the inner and outer Stockholm archipelago and the archipelago of Södermanland it is indicated that the results are valid for a major part of the NW Baltic Proper archipelago area, provided that the predictions are based on a sufficient number of bays and cores.

The main conclusion from this study is that gross accumulation rates in general reach higher values during years with high wind speeds. The higher deposition rates are suggested to be a result from larger input of eroded and resuspended material. If this is the case, and if input from river and primary production is not affected by wind speeds, one interesting subject for future studies would be to investigate the amount of carbon in calm and windy years, respectively. As eroded and resuspended material does not hold newly produced material, the relative carbon composition would theoretically vary with changes in erosion/resuspension activity.

Another factor that was mentioned in the theoretical background is water level changes. If water level changes are high, the wave base and thereby the critical depth of erosion are affected. That is, high water levels create new areas for erosion and low water levels lower the critical depth and with that expose larger areas of the seafloor to erosion and resuspension. These processes could also affect the composition of the deposited material. The possible effect of water level changes on sediment dynamics is also an interesting topic for future studies.

Hopefully, the new knowledge on sediment dynamics in archipelago areas received from this study can be of some use when performing sediment-environmental studies in the future. The dynamics and redistribution of sediment are an important question concerning environmental issues. These investigated relations between time trends in sediment gross accumulation rates and wind forces are one way of describing sediment conditions in the archipelago of the NW Baltic proper.

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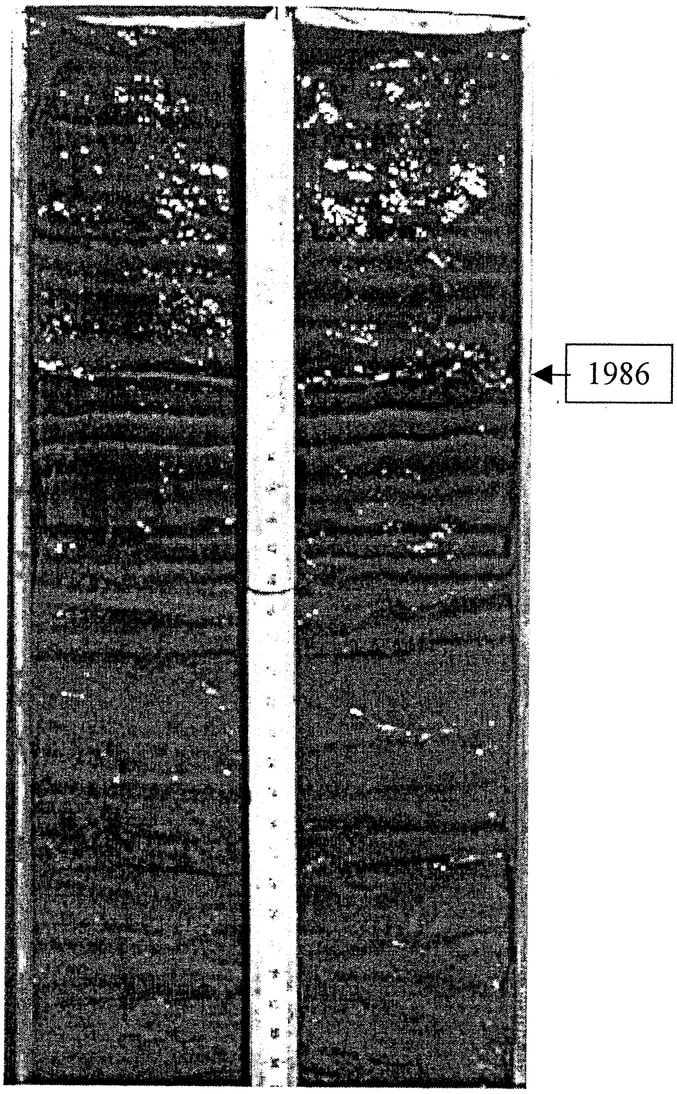
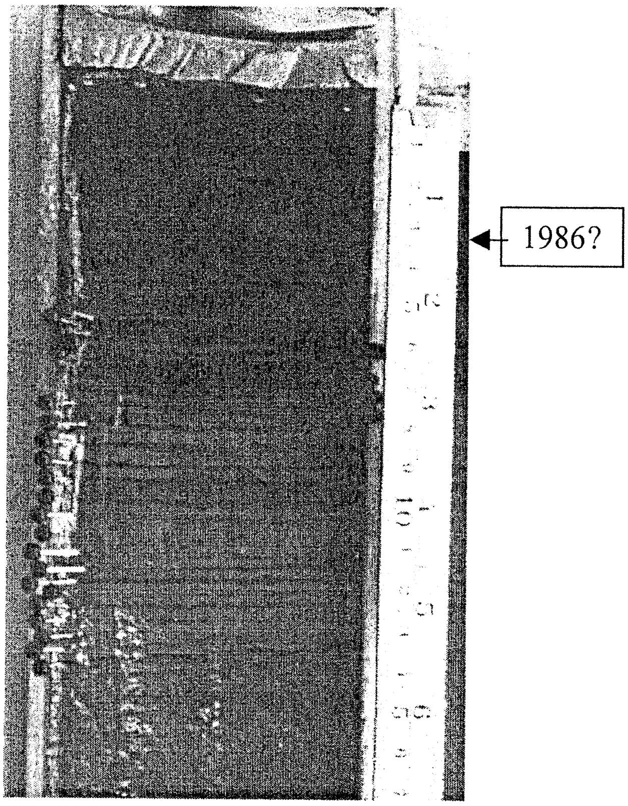
Appendix 1. Photographs



A1.1: Archipelago area
Bay Gälnan, core B, depth 22 m.



A1.2: Offshore area
Laxen 1, core C, depth 197 m.

Appendix 2. Core sampling positions

A2.1: The archipelago area

Area	Inlet	Core	Year	Depth (m)	Position: Long	Lat	Reference*
Stockholm inner archipelago	Erstaviken	B	1996	57	E 18°22,55	N 59°14,11	EUCON
	"	C	"	56	E 18°23,43	N 59°14,03	"
	"	D	"	67,5	E 18°23,37	N 59°13,52	"
	"	E	"	71,5	E18°24,06'	N59°13,17'	"
	Ö Saxarfjärden	A	1996	67	E 18°32,797'	N 59°25,001'	EUCON
	"	B	"	64	E 18°31,79'	N 59°25,643'	"
	Älgöfjärden	B	1997	27,5	E 18°40,993'	N 59°19,109'	Ö-sjö97
	"	E	"	35	E 18°39,441'	N 59°20,658'	"
Stockholm outer archipelago	Gälnan	B	1996	20	E 18°45,52'	N 59°30,49'	EUCON
	"	C	"	23	E 18°45,42'	N 59°30,95'	"
	"	D	"	24,5	E 18°45,35'	N 59°31,30'	"
	Edöfjärden	B	1997	26,5	E 18°40,399'	N 59°27,584'	Ö-sjö97
	"	G	"	37	E 18°37,126'	N 59°26,302'	"
Södermanland archipelago	Näslandsfjärden	A	1996	39	E 17°40,862'	N 59°04,031'	EUCON
	"	B	"	35,5	E 17°41,035'	N 59°03,789'	"
	"	C	"	27	E 17°40,641'	N 59°04,947'	"
	"	D	"	19,5	E 17°39,427'	N 59°05,130'	"

* Refererring to projects where primary data was collected.

A2.2: The offshore area

Area	Site	Core*	Year	Depth (m)	Position: Long	Lat
NW Baltic proper	Laxen 1	A	1999	194	E 17° 56,433'	N 58° 02,272'
		C	"	197	E 17° 55,846'	N 58° 00,893'
		D	"	203	E 17° 57,241'	N 58° 01,004'

* Note that calculation of dry substance deposition has been performed only on core C