Final Report for Publication

H-SENSE

Harbours – Silting and Environmental Sedimentology

Contract No. WA-97-SC.2050

Status: P

Project Coordinator: Rodney Stevens, Department of Earth Sciences, Göteborg University, Göteborg, Sweden. Tel: +46-31-7732807, fax: +46-31-7732849, e-mail: stevens@geo.gu.se.

Partners:

Göteborg University, Sweden (GU)

University of Bergen, Norway (UiB)

Technical Univ. at Delft, The Netherlands (TUD)

Nottingham Trent University, UK (NTU)

Swedish Geotechnical Institute, Sweden (SGI)

State Geol ogical Survey of Latvia (SGSL)

H S F-College, Sogndal, Norway (HSF)

Port of Göteborg AB, Sweden (GHAB)

University of Latvia (UL)

Date: 001128

PROJECT FUNDED BY THE EUROPEAN COMMISSION UNDER THE TRANSPORT RTD PROGRAMME OF THE
4th FRAMEWORK PROGRAMME

H-SENSE
Final Report for Publication

Harbours – Silting and Environmental Sedimentology

TABLE OF CONTENTS

1. Partnership information

Göteborg University (GU), Department of Earth Sciences, Göteborg University, Göteborg, Sweden. Project Co-ordinator: Assoc. Prof. Rodney Stevens, Tel: +46-31-7732807, Fax: +46-31-7732849, e-mail: stevens@geo.gu.se.

University of Bergen (UiB), Geological Institute, University of Bergen, Allégaten 41, N-5007 Bergen, Norway. Principal Investigator: Prof. Dr. Hans Schrader, Tel: +47-55-584719, Fax: +47-55-588108, e-mail: hans.schrader@geol.uib.no.

Technical Univ. at Delft (TUD), Engineering Geology Group, Delft University of Technology, P.O. Box 5028, 2600 GA Delft, The Netherlands. Principal Investigator: Dr. Pieter Maurenbrecher, Tel: +31-15-2785192; Fax: +31-15-2784891, e-mail: p.m.maurenbrecher@mp.tudelft.nl.

The Nottingham Trent University (NTU), Department of Civil & Structural Engineering, The Nottingham Trent University, Newton Building, Burton Street, Nottingham NG1 4BU, England. Principal Investigator: Prof. Michael Rosenbaum, Tel: +44 (0)115 941 8418 (Switchboard), Fax: +44 (0)115 948 6450, e-mail: mike.rosenbaum@ntu.ac.uk.

Swedish Geotechnical Institute (SGI), Swedish Geotechnical Institute, Nya Tingstadsgatan 1, 422 44 Göteborg, Sweden. Principal Investigator: M.Sc., Chem. Eng. Lennart B. Larsson, Tel: +46-31-656575, Fax: +46-31-656577, e-mail: lenlar@geotek.se.

State Geological Survey of Latvia (SGSL) 5, Eksporta Street, LV-1010 Riga, Latvia. Principal Investigator: Chief Geologist Victor Ulst, Tel: +371-7320015, Fax: +371-7333218, e-mail: gas@parks.lv.

HSF-College, Sogndal (HSF), The Faculty of Science, HSF-College, P.O. Box 133, N-5801 Sogndal, Norway. Principal Investigator: Dr. Matthias Paetzel, Tel: +47-57-676238, Fax: +47-57-676201, e-mail: matthias.paetzel@anf.hisf.no.

Port of Göteborg AB (GHAB), Division of Quality and Environment, Port of Göteborg AB, S-403 38 Göteborg, Sweden. Principal Investigator: Bo Jonasson, Tel: +46-31-7312220, Fax: +46-7312342.

2. Executive summary

This report presents the results of the H-SENSE project carried out between January 1998 and the end of February 2000. The aim of the project was to take a scientific approach to the practical problems of harbour silting. Rather than trying to make improvements directly upon the most common methods for harbour site surveys and siltation management, we have utilised our diverse experience from separate but related fields of sediment investigation to identify new procedures and strategies. These suggestions aim to complement traditional methods, and improve, as we see it, both the pragmatic and scientific value of survey and management work that is involved in the harbour management of siltation problems. The project results and recommendations range from specific methods of documentation and data management, to evaluation procedures, including both process interpretations and stochastic (statistical) predictions of parameter associations in models of harbour sediment conditions. Furthermore, we urge the continued integration of scientific and pragmatic perspectives through further network activities dealing with harbour siltation.

Three work packages (Fig. 1) have dealt with 1) Influences on Silting; 2) Environmental Geochemistry and 3) Modelling and Applications.

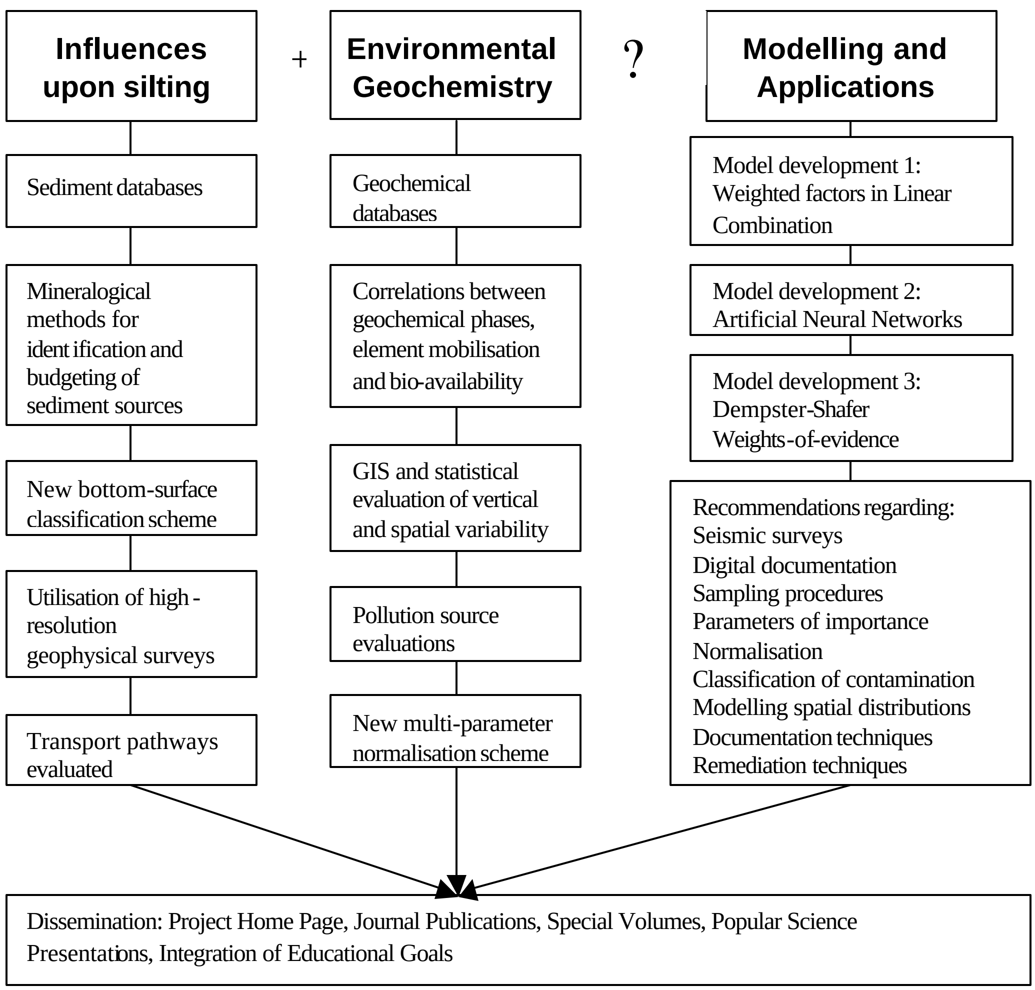


Fig. 1. *Selected achievements within each Workpackage.*

Using largely a ”sediment-perspective” (Fig. 2) to combine with and to show the net effects of hydrologic fluxes, we have evaluated the natural and anthropogenic sediment sources, transport pathways, and diagenetic changes that involve pollutants. Low-tidal estuaries are often effective sedimentation traps, and their soft-bottom floors are particular vulnerable to new turbulence. These natural sediment traps have had a cleansing function on river and coastal areas. The accumulated sediments help remove contaminants from aquatic these environments, but the storage is only temporary since maintenance dredging is eventually necessary for harbour use.

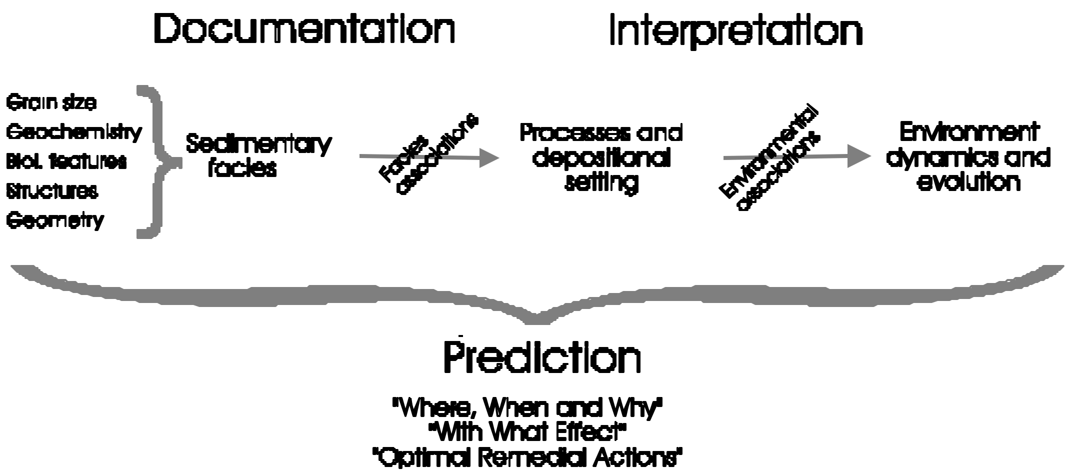


Fig. 2. *The sedimentologic and scientific perspective with the the H-SENSE project.*

Pollutant mobility is linked both to sediment fluxes themselves and to the geochemical conditions that develop within the bottom sediments due to organic degradation and oxidant depletion. The dangers of both catastrophic and diffuse spillage of pollutants are well recognised. Less obvious, but very important is the release of pollutants that have previously accumulated in the sediments. Also, both negative and positive effects can be anticipated in connection with the exchange across the water-sediment interface and with the precipitation and dissolution of solid phases. Consideration for the sedimentologic character of each setting has provided a framework for optimised management of both silting and pollution problems. The results of the sedimentological and geochemical work that was carried out in Work Packages 1 and 2 during the first year are summarised below (and in Deliverable D3).

It has been the aim of the H-SENSE (Harbours - Silting and Environmental Sedimentology) project to develop predictive, sedimentological models for the management of harbour activities with regard to silting and the evaluation of environmental pollution applicable to estuaries and coastal settings which have limited tidal influence. The applications of this modelling, especially for dredging procedures and traffic management, will have importance for both the industrial potential and the overall environmental health of the harbour waters and adjacent regions. The alternatives for modelling, their strengths and weaknesses, have been presented in Deliverables D4 and D5. Recommendations to harbour management strategies formulated as a result of the work carried out in H-SENSE are summarised in Deliverable D6. The concept behind H-SENSE is that low tidal ranges enable comparisons between sediment accumulations at relatively undisturbed sites (as baseline control) with disturbed regions, and evaluate the natural changes expected through time. The intention has been to use Göteborg Harbour (Sweden) to develop generic models and Bergen Harbour (Norway), and Ventspils Harbour (Latvia), to develop case based reasoning.

Coastal environments, fjords, inlets and estuaries are resources that can be made unusable or unattractive for the urban society, but which also have a certain capacity for renewal that can be aided by proper management and active remedial measures. This project has dealt with the impact of harbour activities upon silting and environmental pollution.

Achievements

The H-SENSE project has involved both standard and innovative methods aimed at characterising and modelling harbour silting and sediment pollution. An evaluation of the methods used within H-SENSE is given and will hopefully also provide initiative for methodological developments within harbour site investigations more generally. Considering the largely sedimentological and scientific backgrounds of the H-SENSE partners it was not the objective to duplicate the efforts of numerous practising consultants and planning engineers, but rather to seek new or overlooked possibilities to increase the effectiveness of site investigations and the use of sediment data.

Each harbour has been investigated as a scientific case study involving both geochemical and sedimentological processes and the overall environmental evolution. The applications of the modelling, especially dredging procedures and traffic management, have importance for both the industrial potential and the overall environmental health of such harbour waters and adjacent regions.

Publications and information dissemination

- 6 Deliverables (reports to DG VII).
- 9 completed Postgraduate and Undergraduate Theses at partner institutions.
- More than 15 abstracts and presentations at international conferences.
- 5 papers submitted to international journals, one accepted for publication.
- 6 published papers in conference volume on “Characterisation and Treatment of Sediments”.
- Review paper for special publication Problems of Silt and Siltation (Thomas Telford, Institution of Civil Engineers), in preparation.
- Special Volume for Environmental Geology, 10-12 papers in preparation.
- H-SENSE homepage has over 100 pages which have undergone active development and has been used for conferencing and networking “Chat”.
- Technology transfer: training in use of GIS for harbour applications, short course in scientific writing, student exercises in harbour GIS applications.
- Several seminars and consultations with industrial and government end-users.
- Popular science and newspaper articles published.

Specific goals achieved

- Harbour sediment databases compiled for all three harbours.
- Sampling density schemes reviewed using geostatistics.
- New classification scheme developed for bottom sediments.
- Geochemical normalisation techniques conducted and assessed.
- Demonstrated methodology evaluating sediment sources, transport pathways, and budget calculations based upon grain size and mineralogy.
- Use of expert systems analysed.
- GIS prediction methodologies assessed.
- Artificial neural network (ANN model) predictive capabilities developed.

3. Objectives of the project

1. Identification of the sediment sources, transport pathways and deposition in a harbour setting having limited tidal influence.

2. Evaluation of the geographic and vertical associations between sediment components and the geochemical transfer mechanisms involving pollutants, with particular reference to bottom turbulence.

3. Establishment of a generic model for component and process quantification, and to suggest model scenarios involving dredging and environmental change in harbour settings.

4. Means used to achieve the objectives

The H-SENSE project has used standard evaluation techniques for site survey incorporating geophysics, sedimentology and geochemistry. The project investigators come from a wide range of specialities, providing a good diversity of experience. The approach to harbour sampling has been far more extensive than that required for routine site surveys to allow an evaluation of new techniques and to give suggestions for alternatives aimed at specific harbour problems.

The H-SENSE project has constructed databases for the harbours of Göteborg (Sweden), Bergen (Norway) and Ventspils (Latvia) in order to allow modelling of siltation and related environmental effects. The H-SENSE database development has combined archive data with the results of new analyses conducted during the project, the sequential process being typical of many large site investigations. The first step required the identification of available data, an evaluation of their utility, and organising their storage so that retrieval and assessment of quality can be assured. Secondly, the methods for complementing the database were chosen and sampling was planned. These investigative procedures were themselves important to evaluate and have a general relevance for other harbour site investigations when defining the possibilities and limitations. By examining the necessary steps in “distilling” the essential data for interpretation and modelling, these processes will become less clouded by scientific mysticism.

The first major action in H-SENSE was the completion of geophysical surveys and initial sampling in both the Bergen and Göteborg harbours during two full weeks in February-March. The geophysical work was lead by the TUD team, while UiB, HSF and GU were responsible for co-ordinating the cruise activities on the whole. Due to the unusually warm winter, starting the fieldwork during February-March in these Nordic harbours was earlier than could normally be accomplished. This rapid start was further motivated in Göteborg by the planned dredging in several harbour areas that would have disturbed sampling carried out later.

Approximately 175 km of high-resolution profiles (using CHIRP-sonar echo sounding) were obtained. The geophysical interpretations were needed to give a basic control upon the overall sedimentation situation reflecting the hydrographic processes (**Task 1.1**). The thickness of the upper, loosely consolidated sediments was interpreted and plotted along the profiles within both harbours. These maps were then supplied to the partners in Bergen and Göteborg.

In addition to cores taken to provide “ground-truth” for the geophysical work, systematic sediment sampling began for the sedimentological and geochemical documentation in both Bergen and Göteborg harbours. In Bergen, two additional cruises were completed using the University of Bergen research vessel “Hans Brattstrøm” (despite poor weather along the Norwegian west coast in the first half of 1998). The second cruise (2 days) carried out further bathymetric surveying of the Bergen harbour area to complement the previous maps and compare those with Norwegian maps made in 1956. The third cruise (2 weeks) made detailed survey of sediments in the Bergen harbour with collection of high quality surface sediment samples and short cores at over 100 stations. The sediment samples were processed for geochemical analysis in Canada and in Bergen.

In Göteborg, the initial cruise in March 1998 resulted in short cores and box cores being obtained from 33 sites. Short, 1-2 day cruises were later carried out and timed to allow use of MS Saxkran between its assignments as the principal work boat for the Port of Göteborg (GHAB). In June, a 2-day cruise was possible through co-operation and use of the Swedish Coast Guard vessel KBV 051. In total, 18 stations were sampled using a box corer (50 cm) and a piston corer (3 m). The Swedish Coast Guard also assisted with the sampling of 17 additional sites in April, 1999.

For the cores from both harbours, detailed documentation of the features within different sediment units (facies) was made to identify both vertical and geographic variability. The correlation between units defined from the geophysical profiles and the facies defined from the cored sediments (**Task 1.2**) were necessary steps in the modelling of **WP 3**. Smear slides were selectively used to make initial, microscopic examination, and these also provided a valuable archive of the harbour sediment.

The aim of the sampling schemes was to provide an extensive geographic coverage and a good (geo)statistical basis for modelling. At the start of the project the main effort was to analyse the sedimentology and geochemistry (including environmentally sensitive elements such as Pb, Hg, Cd, Zn and others) since these features constitute core data for **Tasks 1.2, 1.3, 1.4, 2.1** and **2.2**.

In order to make comparisons with an extensive sediment sampling and geochemical analysis program carried out in 1996 by GHAB in Göteborg harbour, SGI has, assisted by GHAB within the H-SENSE programme, re-sampled and analysed nine of the previous sites and four new sites. Both surface layer and lower, sub-surface samples have been analysed. Since no dredging has been performed between the two sampling times, the comparisons have given us a valuable insight to the geochemical changes that are time-dependent. Emphasis was placed upon the organic contaminants, specifically the various congenes within PCB pollutants. This study was included as parts of **Tasks 2.3** and **2.4**. The only specific difficulty in carrying out our workplan has been caused by a surprising lack of hydrographic data regarding the recent harbour currents and water salinity in the harbour office archives. It had been planned that this data would have been used for initial modelling (**Task 1.1**) using the estuary-modelling package called ECoS, an estuarine simulation shell developed by the Plymouth Marine Laboratory in the UK. Hydrographic modelling has been simplified and limited to the data available.

The harbour sampling in Bergen and Göteborg was done largely during the first half of 1998, with a few selected sites sampled after this time to complement the spatial coverage and to control specific features. In Ventspils, the sampling campaign began first during September 1998. However, initial results indicated that the Ventspils setting was sufficiently different from the other two harbours that it essentially represented a third variation in the types of harbour settings that were compared. This means that it lost some of its value as a test site for modelling, but gained value as an additional variety.

Elemental composition of the sediments was determined for the total samples and for selective chemical leaches that attempted to reflect the different phases with which metals are associated. These components were also of particular importance for the evaluation of contaminant mobility and the changes that can be expected with time and burial or mixing of the sediment deposits. The normalisation of geochemical results was considered using a new, multi-parameter approach where the weighted factors for this normalisation were determined through factor analysis for each element and sediment component (see Engström & Stevens, 1999). In Bergen, smear-slides were used to estimate the particle size, and this approach was evaluated as a method to be used within harbour site investigations where time and economy do not allow particle-size determinations on all samples.

A sediment surface classification scheme was developed within the Göteborg Harbour area so that areas with similar visual characteristics could be readily recognised as their distribution is often of basic importance for the sedimentological interpretations. The scheme also took advantage of the advances in digital photographic documentation and the flexibility of box-core sampling during harbour-site investigations. The classification and other initial recommendations for sediment-oriented documentation method are taken up in Stevens *et al.* (1999).

The compiled databases were different in many ways, just as the harbours and the teams involved in the harbour site surveys were also varied. This posed certain limitations, but also offered opportunities for contrasting both the methodology and the environmental characteristics. Both the problems and advantages were necessary for development of models that were more than just applications of earlier approaches.

During the final year of the project, and particularly within the last 6-8 months, the project activities were increasingly focussed upon modelling objectives. To assist the evaluation of data collected from harbours for component and process quantification, new modelling techniques were developed following three different types of modelling approach.

1. Weighted factors in Linear Combination
2. Artificial Neural Networks
3. Dempster-Shafer Weights-of-Evidence

The harbour studies at Göteborg were used to develop generic models based on statistical reasoning. Similar investigations were conducted on the harbour studies at Bergen in Norway and Ventspils in Latvia and were used as the basis for case-based reasoning.

The generic model construction was developed using a net effect approach analysed through the application of GIS. The physical and geochemical characteristics of the sediments were outlined in WP 1 & 2, forming the basis for selection of hypotheses concerning the associations of such characteristics with the relevant sedimentological processes.

Collecting data from the site surveys, literature, baseline information and general information plans required roughly the planned input anticipated in original project proposal stage, but the reduction in grant award meant that a much greater proportion of time had to be spent compiling information into a usable form than had been originally hoped. This was overcome by identifying key hypotheses and developing the generic model in a manner which demonstrated the techniques as opposed to attempting to produce an all-encompassing system. Limitations of data from some of the case studies were thereby taken into account by concentrating on those sites where sufficient data could be made available within the timeframe required to allow development of the models.

Having established the scientific methodology appropriate to the low tidal harbour environment on the basis of hypotheses constructed from expert knowledge of the harbour environment, the generic model was then developed to facilitate the integration of the diverse information available, incorporating local knowledge and professional judgement along with the hard analytical data.

The first approach to model development was based on a linear combination of factors, weighted according to their relative importance. The multi-criteria approach permitted the calculation of suitability maps, so enabling decision support. The concept of belief was taken further by incorporating the Dempster-Shafer Weights-of-Evidence procedure, which enabled an evaluation of the degree to which evidence provided definite support for a hypothesis (belief) and the degree to which that evidence did not refute the hypothesis (plausibility). The Artificial Neural Network approach operated using existing knowledge. This established links between the complex interaction between the various factors, comparing results (output) with the (known) field values, with errors removed by iteration. Apart from mapping, the other task of ANN was to identify the relative importance of each factor.

In addition to the project meetings we felt that there was considerable need for alternative means of maintaining communication and moving forward with important issues. One attempt has been to use Internet possibilities for virtual meetings, "Chats". These were initiated by our Webmaster, Hans Schrader, directly after the February project meeting and were held on a weekly basis. We were able to exchange ideas on a broad range of topics, related to the progress and concerns within our H-SENSE program. Dissemination of the project goals was available to interested parties via the H-SENSE homepage, which has over 100 pages of information and has undergone active development throughout the project time period. Partner co-operation was also successfully maintained through regular e-mail exchange and individual visits to partner organisations.

The importance of database and modelling was also reflected by our efforts, parallel to the H-SENSE activities, to spread awareness and increase competence in GIS (Geographical Information Systems). A short course in GIS was organised in Göteborg and included a number of H-SENSE participants. Prof. M. Rosenbaum was guest lecturer for the one-week course, 23 February – 1 March, 1999. We took advantage of the gathering of H-SENSE colleagues and had formal and informal discussion regarding H-SENSE progress and possibilities.

In general, the project has created an increased exchange between partners. Separate, but nevertheless related to our contact network, a "Scientific Writing Workshop" was held in Riga in September, 1999, organised by R. Stevens and with 20 participants. Nine of these participants were also able to come to a postgraduate course in Environmental Sedimentology held in Göteborg, February-March 2000, and which highlighted some of the results from H-SENSE, including modelling exercises lead by Claire Burton (NTU) and GIS exercises based upon the datasets from Göteborg and Ventspils.

5. Scientific and technical description of the project

5.1 Results of Workpackage 1 - Influences on Silting

In order to construct a comprehensive database and gain an understanding of sedimentary processes this Workpackage involved a wide variety of determinations. The large number of techniques employed in the project has resulted in positive recommendations for specialised purposes as well as for cost efficient routine measures. Methodological developments and improvements which may prove va luable to harbour surveys include digital documentation techniques, smear slide analyses, bottom surface classifications and mineralogical techniques for identification and budgeting of sediment sources.

Bergen Harbour, Göteborg Harbour and Ventspils Harbour comprised the study areas for the H-SENSE project and their locations are outlined in the map (Fig. 3) below. More detailed descriptions of the individual locations is given in Appendix 1.

Fig. 3. *Map showing the three harbours investigated in the H-SENSE programme*

Using a sediment perspective to combine with, and to show the net effects of, hydrologic fluxes, enabled evaluation of the natural and anthropogenic sediment sources, transport pathways, and geochemical changes that involve pollutants. Consideration was given to the effects of sediment mixing by harbour traffic. For example the widespread erosional conditions documented in central Göteborg Harbour between 1996 and 1997 were probably induced by such a development. Harbours that utilise low-tidal estuaries and bays are often effective sedimentation traps, and their soft-bottom floors are particular vulnerable to new turbulence. These natural sediment traps can therefore provide a cleansing function for river and coastal environments. By using low-tidal settings, we can compare sediment accumulations from relatively undisturbed sites as a baseline control for the natural changes expected through time.

One means of extending the sediment data is by correlation to seismic survey results. The use of variable frequency pulse signals from a Chirp transducer have allowed the distinction of sediment units on the scale of decimetres in the upper 3-5 m of sediment on the harbour bottoms (see also Degen et al. 1996; Maurenbrecher et al. 1998). Results of geophysical surveys also indicate the harbour environment is very dynamic with rapid sediment oscillations indicating periods of accumulation, followed by erosion, slumping and then renewed deposition. One example (Fig. 4) from the Göteborg area is illustrative. Although these oscillations are most obvious in the deeper, older sequences, the changes reflect upon the sensitive balance between factors influencing sedimentation. These factors, such as water depth, sediment supply, exposure to waves and bottom currents, salinity stratification and climate, are variable even today. The uppermost meter of recent sediment sediments represents the last 100 years when accumulation has again predominated within the area. But since this period was preceded by a nearly 1000 year period of erosion. We need to be cautious in concluding that these sediments are stable.

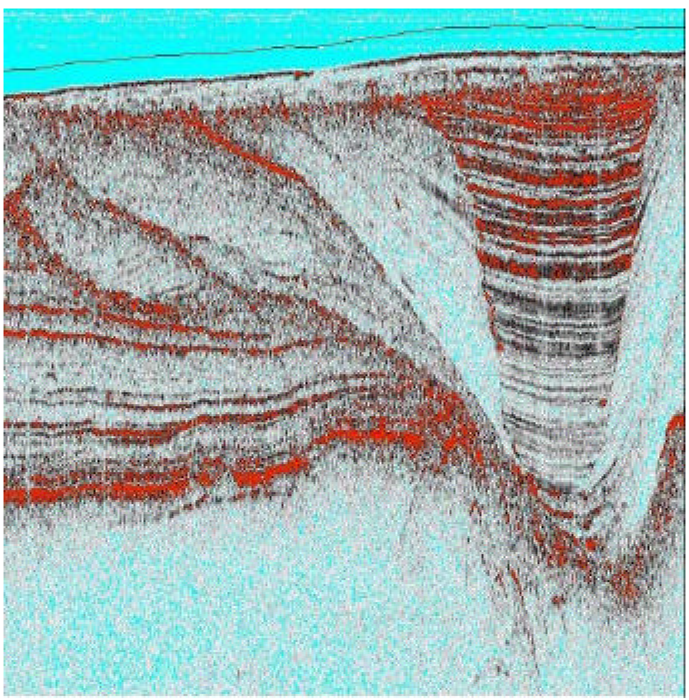


Fig.4. *Part of a geophysical chart taken outside of Göteborg Harbour.*

Sampling of 50-150 sites has been carried out in each harbour, aiming to allow the resolution of processes operating on the scale of tens of metres in areas of special interest. Sedimentological documentation for facies classification has selectively included (a) visual and colour description, photography and videotaping of open cores, (b) X-ray photography of closed and open cores, c) transmitted and polarised light microscopy of sediment smear slides, (d) determination of microfossil foraminifera and diatom changes, (e) particle-size analysis, (f) density/porosity variations within lithological units, and (g) measurement of magnetic susceptibility. Sediment "facies" (deposits with similar features) are defined upon these parameters, and with consideration for their interpretative possibilities regarding transport and deposition expected in an estuary/harbour environment. The distribution of these units is ideally mapped using both the seismic data and the variability documented from sampled sites (Brack & Stevens, 1999) and by mutually modelling these data within a GIS structure.

Sediment particle-size data also have the advantage of being closely correlated with organic matter and heavy metal contents. Although mapping particle size is in itself much less costly than most other types of sediment transport studies, the correlation with proxies such as magnetic properties (Lepland & Stevens 1996) or quartz/illite ratios (Lepland et al. 1999) can be utilised to enhance both the interpretative basis and the cost-efficiency of routine analyses.

Göteborg Harbour

Göteborg Harbour is an example of a non-tidal salt wedge estuary. The harbour requires regular dredging as sediment in-filling is an evident problem, with clay sediments brought in through the Göta älv River. Within Göteborg Harbour a detailed sediment archive is utilised to identify sediment facies, evaluate sediment variability and propose a bottom surface classification integrating the sedimentological, geochemical and biological features. This integration is considered essential towards developing future classification concepts/schemes for contaminated sediment – a task which we feel our results can contribute to. CHIRP profiling has indicated that the record of siltation is very dynamic and the estuary is not only a zone of accumulation. Short-term (1996-1997) sediment accumulation and erosion rates have been also been calculated with high spatial resolution. The sedimentological conditions of Göteborg Harbour have been compiled as text, numeric determinations, photographic and digital images. The value of documentation has been addressed and has resulted in a detailed archive including primary data in the form of samples, which will be accessible to future harbour investigations. The Göteborg dataset has had particular value for the stochastic modelling, e.g. Artificial Neural Network (ANN) models.

Facies characterisation and historical control

The sediment samples from Göteborg Harbour were collected using a piston corer and a box corer. The samples from the harbour and the adjacent, inner archipelago were classed into units (facies) on the basis of their visual properties of lithology, colour, consolidation and structure. Relatively homogenous, grey-brown, slightly silty clays with variations mainly in organic matter content, colour, and consolidation are predominant. Soft, organic-matter rich and therefore dark clay (omC) usually overlies hard, light coloured clay (gC and dC). The upper part of the soft layer is often represented by silty clay (siC), sandy clay (saC) or sand (S) on the surface, especially in the harbour area. The soft sediment layer has a mean thickness of about 0.4 m, varying between 0 and 1.5 m. Both the physical and chemical sediment analyses (grain size, geochemistry, and dating) support the differentiation of the visual units.

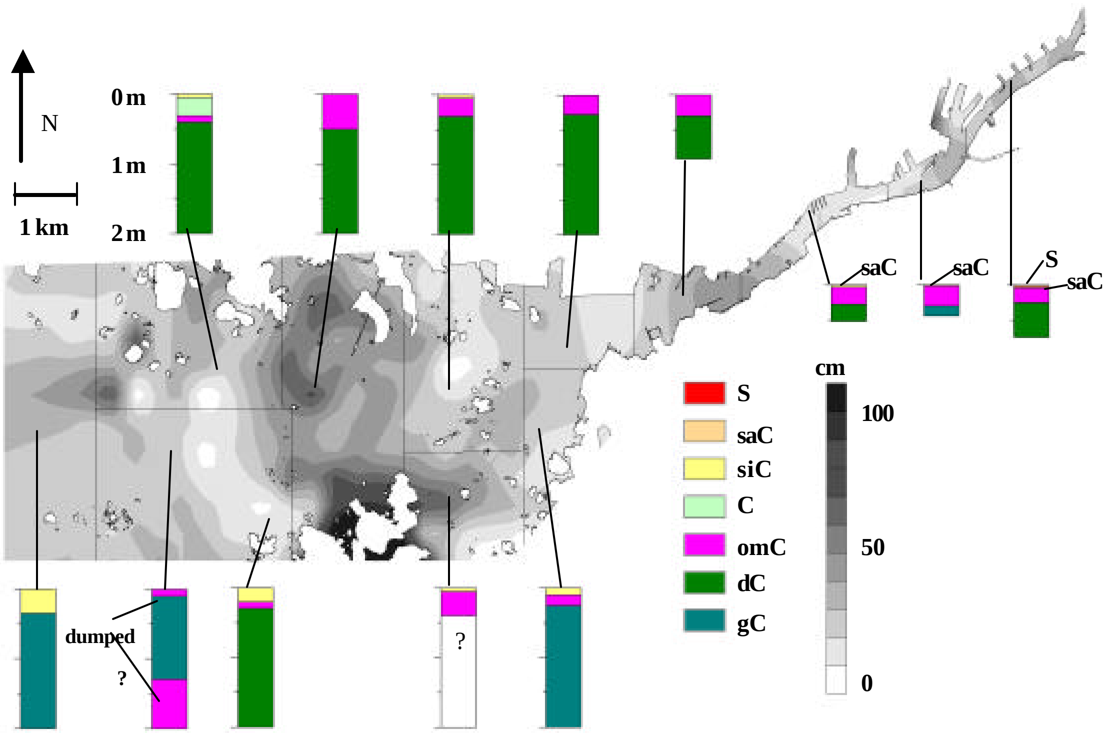


Fig. 5. *Lithostratigraphy in the Göteborg harbour and archipelago. The thickness of recent sediment (cm) as interpreted from seismic lines is shown as a contour-map, and synthetic core profiles of different areas are shown in colour. S = sand, saC = sandy clay, siC= silty clay, C = slightly silty, light coloured clay, omC = organic matter rich silty clay, dC = consolidated clay (4000-1000 BP) and gC= consolidated clay (> 10,200 BP).*

Dating by the ^{14}C-method and Pollen analysis revealed that the hard clay gC is older than 10200 years BP (9700 BC) in four stations. This clay is interpreted as dumped dredging material from the harbour in two of these stations. It seems that the natural sequence involves the other consolidated clay facies dC as an intermediate layer, which has been dated to an age between 4000 and 1000 years BP (2500 to 950 BC). The bottom of the soft sediment layer has been dated to being younger than 100 years at three sites where it is found above the dC, suggesting a gap (hiatus) of around 850 years in between those layers. This could either be caused by erosion or by non-deposition, followed by a new onset of sedimentation about 100 years ago. The origin of the main facies has been interpreted from lithology, geochemistry, dating and diatom analysis. The oldest clay, facies gC, is a distal glaciomarine sediment, while the younger consolidated clay, facies gC, was deposited in a more estuarine setting. Erosion or non-deposition between 1000 BP and 100 yrs before now is attributed to the shallowing of the area caused by isostatic land uplift of the area. The onset of deposition ca. 100 years ago can be both due to climatic changes and human activity such as river regulation.

Differences between sediment facies

A good connection between visual and geochemical parameters has been shown by statistical analysis. It was found that the variability inside a sediment facies is less pronounced than the difference between the main sediment facies silty clay (siC), organic-matter rich silty clay (omC), sand (S) and consolidated clay (gC and dC). The non-parametric Kruskall-Wallis Test (Ebdon 1977) combined with Dunn's multiple comparison test (Dunn 1964) show that the soft, recent clays siC and omC differ significantly from the consolidated clay in all parameters except the clay content. Most interesting for environmental applications of the facies characterisation is the fact that the recent sediments differ from the consolidated clay in their heavy metal concentrations, due to contamination. The medians of the water content and the organic matter content of Facies gC and dC are significantly different, reflecting a difference in age and resulting consolidation and a difference in the depositional environment.

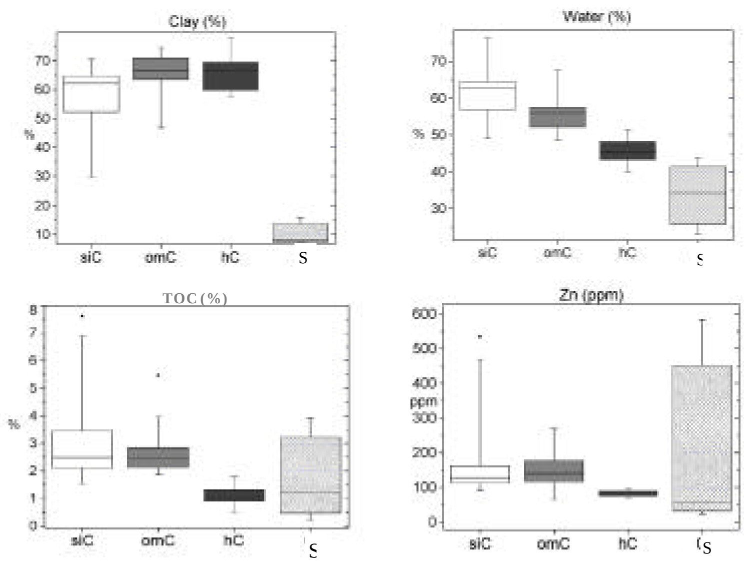


Fig. 6. *Box and whisker plot for contents of clay, water, total organic and Zn in the different sediment units.*

Bottom surface classification

A bottom surface classification has been proposed, based upon the written and digital documentation of the box core samples. The classification combines both sedimentological and biological features distinguishing seven different classes. The initial interpretation of their environmental associations is included in Fig. 7. The river samples often have a coarse-grained, smooth surface, while the more estuarine samples are dominantly fine-grained reflecting the increasing distance from the major energy and sediment source, the Göta älv River. Filter feeding fauna is present in large parts of the estuary and imply a certain supply of detrital organic particles and aerobic conditions. The distribution of the "worm tube" class reflects the area with saline bottom water. Other biological indicators, e.g. molluscs, are present at the sewage outlet suggesting a favourable supply of nutrients and suspended particles. The classification of different surface characteristics is a promising and rapid technique to interpret the environmental conditions in the harbour.

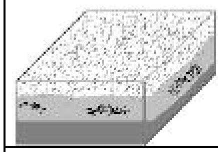
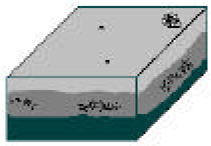
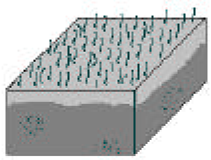
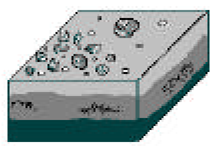
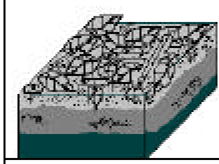
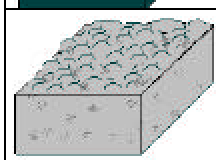
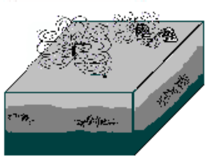
Illustration	Characterisation	Area of Occurrence	Possible associations
	Coarse-grained (sand), smooth.	Mainly in the river and inner harbour area, occasionally in the outer harbour at shallow, near shore sites.	Deposition under a relatively high-energy regime, bottom fauna limited by sedimentation conditions.
	Fine-grained, smooth with occasional empty shells.	Mainly in the inner and middle harbour, returns at the seaward sites in the outer harbour.	Deposition under calm conditions, bottom fauna limited by sedimentation conditions.
	Worm tubes on smooth surface, particle size varies.	Dominant in the middle and outer harbour, occur in the inner harbour at a few sites.	Nutrient and food supply is sufficient. The environment is probably not too turbid. Oxygenated bottom water, commonly marine influenced.
	Clasts on fine-grained, relatively smooth surface, usually silty clay.	At a few sites in the river and middle harbour, which are near the riverside or a quay.	Dumped material or ice transported.
	Leaves and reed on fine-grained surface.	At a few sites in the inner and middle harbour, near the harbour sides.	Wind or river, local transport. Influences sediment-water exchange and erosion resistance. Sheltered sites.
	Stiff lumpy clay.	At a few sites spread throughout the river and harbour areas, often in the main channel area.	Non-deposition, erosion bottom or dredged area. Turbid environment. Disturbed recently reworked deposits.
	Living molluscs (e.g. sea mussel colonies) on smooth surface.	At a few sites in the outer harbour, especially outside the wastewater treatment plant.	Favourable supply of nutrients and suspended particles for bottom fauna.

Fig. 7. *Classification of bottom-sediment surfaces.*

Sediment accumulation

The sediment accumulation rates and dispersal patterns in the harbour area vary due to several factors. Dredging is regularly carried out every 4^{th} to 5^{th} year along the harbour sides of the inner and middle parts and about every 10^{th} year in the outer parts of the harbour. Each or every other year dredging is done in a few areas with particularly high sediment accumulation. Detailed dredging information, including time, location and amount of sediment removed, is available only for the past three years. As the harbour is situated in an estuary, the salt wedge position is an important factor regarding the enhancement of sedimentation. Only limited information of the salt wedge position and fluctuation is presently available. The river and harbour geometry is also believed to be important in influencing the sedimentation pattern, by the effect on bottom currents. Also knowledge of the historical geometrical changes of the harbour is valuable for predicting sedimentation patterns. Göteborg Harbour is a very densely trafficked area with about 12000 ships/year, including traffic passing through. Mapping the distribution of the traffic within the harbour, both amount and type, would give a valuable perspective to the discussion of possible disturbances to sedimentation.

The accumulation and erosion rates between 1996 and 1997 were calculated using high-resolution (? *c*. 5 cm) bathymetric maps obtained in May 1996 and in September 1997. The area under investigation measures 1,149,009 m^2, and is dominated by erosional processes. Erosion exceeds accumulation in 56% of the total area. Rates of accumulation vary from –1 m to +1 m, but most values in the study area are predominantly in the range of –0.1 and 0.1 m/year. Erosion generally occurs in the deeper parts of the harbour, essentially restricted to the sailing channel and close to quays where large vessels turn and dock. Erosion outside the sailing channel is more likely related to water turbulence stirred up by the ships rather than the salt-water streaming along the bottom, since the velocities are low. The area outside Stenpiren is the only part of the sailing channel where accumulation occurred during the time period examined. Accumulation is generally more apparent at shallow water depths, especially in the meanders outside Eriksberg and Stenpiren and in the quays in Frihamnen. The net erosion, in the study area during this period is 5 cm/yr, and the net sediment volume eroded over the total time interval is 57,000 m^3.

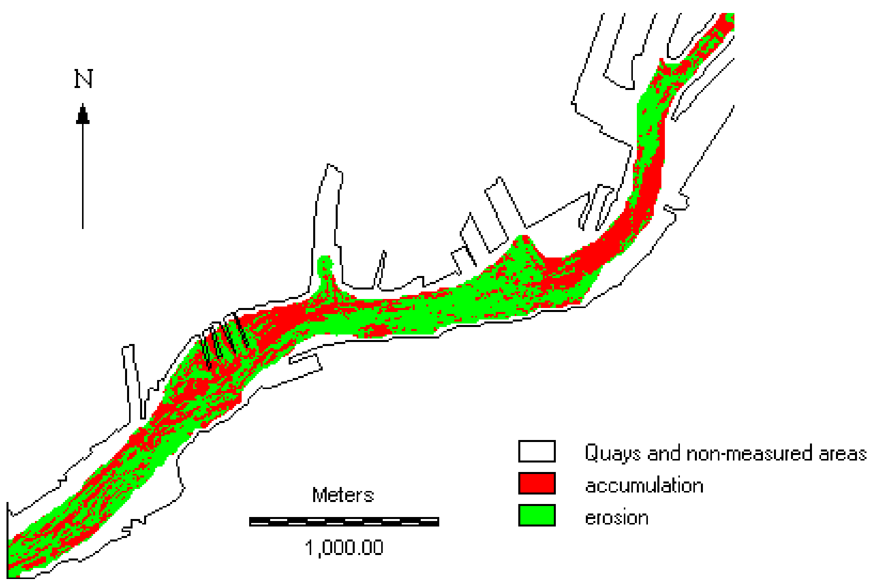


Fig. 8. *Map of Erosion and Accumulation in Göteborg Harbour between 1996 and 1997.*

The erosion/accumulation trends between 1996 and 1997 are consistent with those areas know to commonly require dredging, including the quays of Frihamnen, Sannegårdshamnen and Stenpiren (Wallroth, 1996; Lars Dahlin pers.comm.). The location of the tip of the salt wedge in this part of the harbour (Selmer & Rydberg 1993) also stimulates sedimentation due to flocculation in this area. The rates of accumulation and erosion within Göteborg Harbour can be attributed to both the dynamic, estuarine processes of a salt-wedge estuary and the effects of anthropogenic activity such as vessel traffic. In particular, the dominance of erosion is notable, and probably related to increased ship turbulence, e.g. the introduction of the water-jet ferries.

This study (details in Ekermo, 2000) illustrates the potential of the high-resolution geophysical techniques now available. In addition to bathymetric changes, the bottom-surface variability and to some extent, the large surface structures were also possible to evaluate.

Bergen Harbour

> *Bergen Harbour is an example of a highly polluted, low tidal, fjord system with no river input and highly variable bottom sediment conditions. Within Bergen Harbour a detailed sediment archive has been collected including a sediment facies classification and an evaluation of sediment variability. An evaluation of smear-slide analyses was conducted and Bergen has produced a smear-slide archive that is accessible to the public at the H-SENSE website (*http://hjs.geol.uib.no/hsense/*) and will be available for future harbour studies. An assessment of sediment sources has been conducted along with a sediment quality assessment using benthic microfossils. The result of long-term dumping of raw sewage and excavation material directly into the harbour was the main focus of the study with recommendations produced regarding remediation options and problems related to indiscriminant dumping of dredged material. The Bergen case studies have been of particular value for illustrating the sediment response to environmental change, both over time and geographically in these highly variable settings.*

Sediment facies distributions

Six main different surface sediment facies could be recovered and defined in the Bergen harbour area. These include the deeper hemipelagic facies (lilac) present in the Byfjord below 50 meters water depth, the sandy, pebbly, eroded channel facies (blue) caused by mass movement from the shallow inner fjord parts to the deep, the sandy, carbonate-fragment rich sediments (yellow) covering the slightly shallower sill areas, the organic-matter and pollutant rich rim (green), and the facies of the deeper inner basins that are very organic-matter rich and heavily contaminated (red).

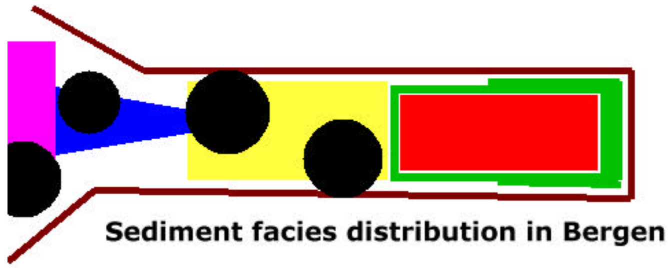


Fig. 9. *The main facies in the Bergen harbour with the deep fjord hemipelagic facies (lilac), the coarse grained eroded channel facies (blue), the sandy coarser grained sill facies (yellow), the inner basin facies with water and organic-matter-rich sediments (red) and the ring of shallower, organic-matter-rich, agglutinated, coarse sediments.*

All these sediments occur in blankets that are from 0.5 to 1.5 meters thick, excluding the several-meters-thick hemipelagic, deep fjord facies. Allochthonous facies occur occasionally that contain material foreign to the Bergen harbour and that are derived from dumping of stones from the Bergen area and from dumping of material from ships.

The underlying sediments are thick marine moraine rests that are thickest along the southern shores of the fjords and that are derived from the deglaciation after the Younger Dryas event. These moraines frequently consist of glacial clays that are of light grey colour and contain no contaminants and no organic matter; they also are heavily consolidated and have a very low water content.

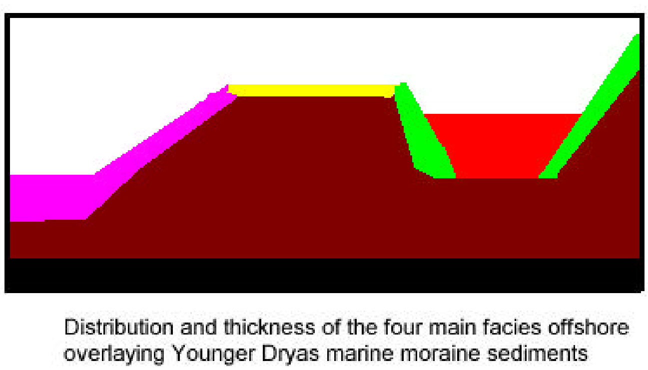


Fig. 10. *Schematic cross section through the four main facies (violet, yellow, green, red and green) overlaying Younger Dryas moraines that rest on top of basement bedrock (black)*

Sediments of the “yellow” sill facies, the “green” basin rim facies and the “red” basin facies are the repositories of pollutants in the Bergen harbour. Cleanup activities require the removal of these sediments to a safe depository. Open water deposition in the deeper parts of the Byfjord would be environmentally unsound and unjustified.

Benthic microfossil sediment quality assessment

Benthic organisms were found to be the best indicators of environmental bottom pollution because they react to and record long-term changes (Johansen 1998). Benthic foraminifera are a diverse protozoan group that produce carbonate shells. The distribution of living, epifaunal and endofaunal species, their diversity and their population densities are excellent quantifiers of environmental stress resulting from the input of abundant organic matter, poor bottom-water circulation and input of pollutants. We have defined for the Bergen area four associations that mirror perfectly the quality of bottom sediment conditions from very bad to relatively good conditions.

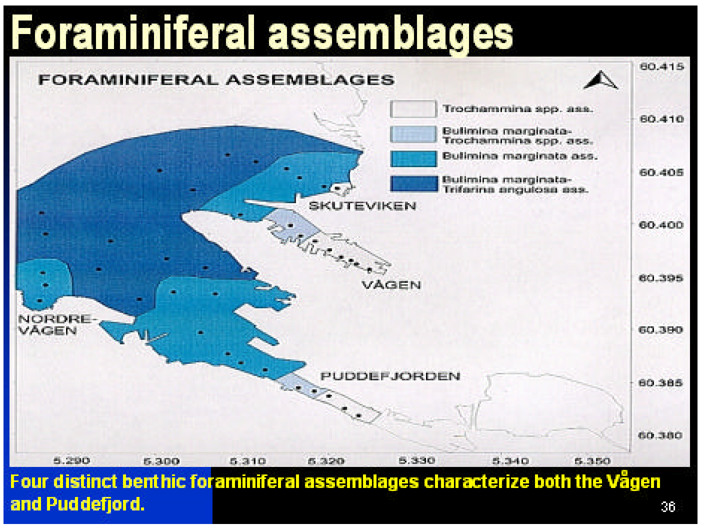


Fig. 11. *Assessment of sediment surface and bottom environmental conditions based on the presence, abundance and diversity of living Benthic foraminifera (carbonate secreting shelled protozoa). Healthy populations occur in the deeper Byfjord (dark blue area) and specialised monospecific and stressed populations indicating low oxygen conditions occur in the inner fjords (light blue to white areas).*

Silting and environmental change

Monitoring of siltation and environmental change must be done within the "red" facies that represents high accumulation of both anthropogenic derived and naturally derived sediment material. Monitoring most recent changes and control of state agency policies must be done here taking utmost care to collect the sediments that have been accumulated during the last 1 to 2 years.

An program for control, detection, and assessment of long-term effects of "allochthonous" (deviating) facies represented by the black spots must follow our area mapping efforts and clearly mark those areas for later subsequent monitoring. These facies were derived from the dumping of foreign material in the harbour and may have included dumping of carbonate material used for cement production, mussel shells derived from canning activities, mid- to large-sized stone dumping derived from tunnel construction and other building excavations.

Regional mapping of sediment parameters

Sediment distribution and their load of pollutants have a complex pattern in the Bergen Harbour system. Six different main facies and their geotechnical and geochemical content were identified and classified. The "allochthonous" facies represents material originating elsewhere and deposited in the Bergen Harbour. The other five facies were influenced in their spatial (=geographic) and temporal (=thickness) distribution by three main factors: bathymetry, surface and bottom water activity, and injection of raw (untreated) sewage.

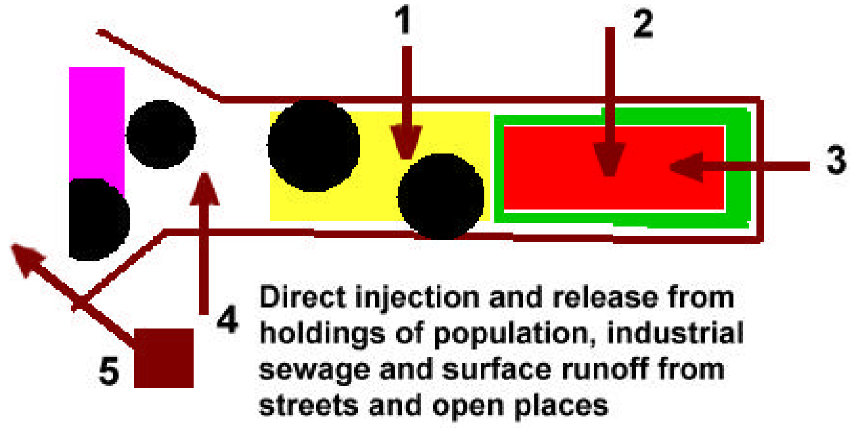


Fig. 12. *Pathways from sources of sediment material outside the harbour basins.*

The facies were characterised by their geotechnical parameters (ranging from semi-fluid, water-rich muds to consolidated and compacted clays), by their sedimentological parameters (with grain size ranging from clay to boulders), by their geochemical parameters (with moderate to high TOC and associated high trace metal concentrations) and by their micro-faunal parameters (indicating healthy or stressed faunal populations related to bottom conditions).

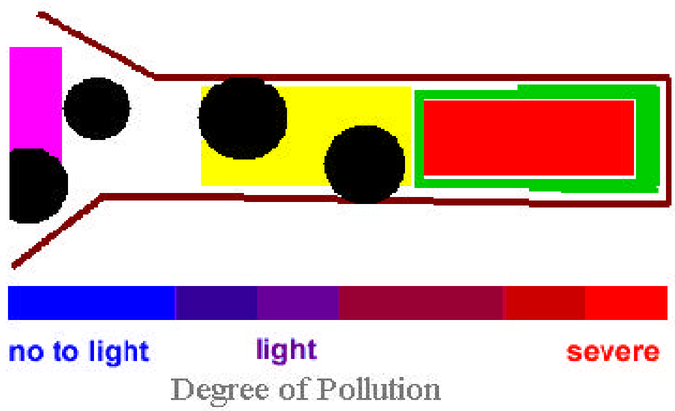


Fig. 13. *Bottom sediment environmental assessment quality, ranging from little or no pollution in the distant parts of the harbour and deeper Byfjord to the heavily and severely polluted, inner, deeper basins and their rims.*

Most recent activities and changes

Several areas in the Bergen harbour are being used as dumping sites for excavation material from tunnel and road construction. One such area is close to the docking pier of RV Hans Brattstrøm and close to the Department of Marine Biology within the general HIB complex. Here huge volumes of soil and rocks are being dumped into the Solheimsviken.

The contractors have followed state SFT regulations and have placed a floating net shielding in order to avoid the spread of suspended heavily polluted material into the wider fjord. Visual inspection over longer periods indicates well that suspension clouds escape through the shielding and spread further. These are the heavily polluted sediments.

Fig. 14. *Digital photo of the HIB complex with the department of marine biology to the right. Large dumping site encircled by floating mats that are intended to trap suspended sediment material during the active dumping process. Trace metals and PCB's heavily pollute the suspended sediments. The trapping effect of the hanging mats is not perfect. Digital photo by Hans Schrader from UiB's RV Hans Brattstrøm February 3rd, 2000.*

Data archives

Our goal in archiving and presenting the Bergen harbour H-SENSE data was to avoid loss of public accessibility if such were to be included in a few "Reports" of rather limited distribution. We took advantage of the possibilities to archive, organise and display complex data on an Internet web based format with world public accessibility and served from a reliable and well-maintained server.

The Bergen harbour H-SENSE generated data are available from the following archives:

-*The Sonar CHIRP archive* (Fig. 1 5) with all raw data generated during the seismic survey conducted during the early phase of the program. Track lines can be "hot" clicked and the associated sequence of seismic frames can be retrieved. The image quality is high enough to print out seismic sections on any high-resolution laser printer.

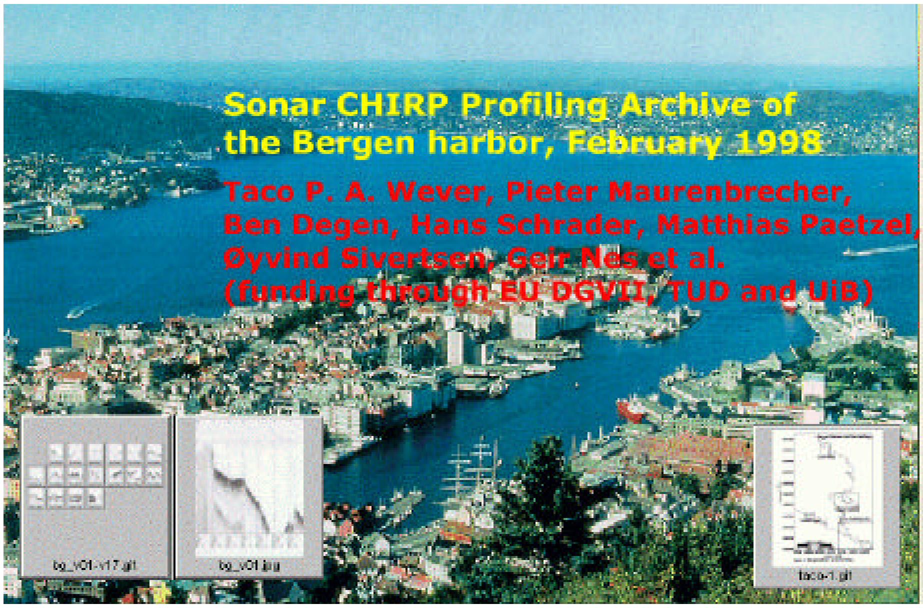


Fig. 1 5: *The Bergen harbour H-SENSE sonic CHIRP seismic profiling archive. All profiles are contained in this archive that were conducted during the first H-Sense cruise in February 1998 in the Bergen harbour area. The archive is located at this URL=http://hjs.geol.uib.no/hsense/publications/public/bergen/chirp-archive/.*

-The Bergen harbour H-SENSE coring archive (Fig. 1 6) contains x-radiographs of all cores (Niemestoe and gravity cores) collected during the H-SENSE program. These x-radiographs represent facies distributions and contain the raw positive print of the x-radiograph films, an interpreted facies distribution and in some instances some blow ups of some special structures. Core locations are “hot” clickable and will retrieve from the archive complete core information.

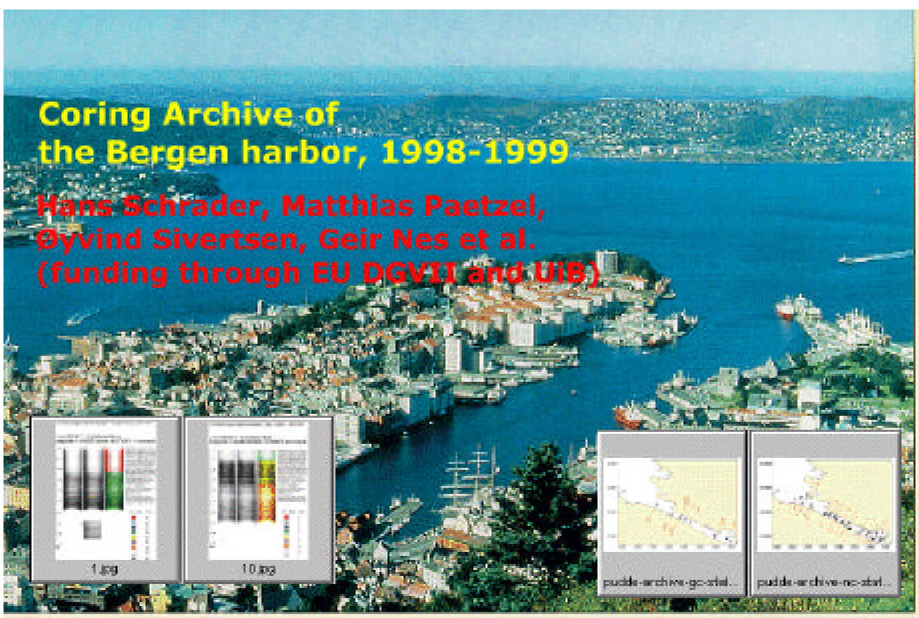


Fig. 1 6: *The Bergen harbour H-SENSE sediment coring archive. This archive houses digital scanned images of original 1:1 (positive) x-radiographs of all Niemestoe and OSU-type gravity cores combined with a down core facies interpretation. The archive is located at this URL=http://hjs.geol.uib.no/hsense/publications/public/bergen/coring-archive/.*

-The H-SENSE Bergen harbour smear-slide archive (Fig. 1 7) represents a photo micrographic catalogue and archive of the different sediment particles encountered during the course of the sedimentological assessment routines. In addition we have included here the smear slide based criteria to determine component percentages. A detailed discussion of the smear slide technique together with instructions on how to make smear slides is included with the H-SENSE home page.

Fig. 1 7: *The Bergen harbor H-SENSE sediment smear slide reference archive. Displaying and defining the major sediment components, their grain size distribution and the resulting compositional definitions. The archive is located at this URL=****http://hjs.geol.uib.no/hsense/ publications/public/bergen/smear-slides/***.

-The H-SENSE Bergen harbour geotechnical, sedimentological and geochemical data archive (Fig. 1 8) contains tables of all data that we generated during the course of the H-SENSE program duration. These data sets include sample co-ordinates, geotechnical data with water content, wet bulk density, dry bulk density, porosity, shear strength (on some cores), sediment color, structure, smear slide determination of sediment components, pipette grain size determinations (some), XRAL geo-chemical data, CHNS data, carbonate, organic carbon, and any other data.

***Fig. 18**: The Bergen harbour H-SENSE geo-chemical, geo-technical, geo-micro faunal data archive. URL=http://hjs.geol.uib.no/hsense/publications/public/bergen/geo-data-archive/.*

Ventspils Harbour

Ventspils Harbour is an example of a micro-tidal, highly stratified salt-wedge estuary that is also strongly influenced by long-shore currents flowing northward. An expansion in international trade with increasingly larger vessels has resulted in an urgent need for deepening the port channel and thus an understanding of sedimentation processes is required. Within Ventspils Harbour a detailed sediment archive has been collected, including sediment facies and water-column nutrient and trace-metal chemistry. A detailed history of the siltation pattern and sediment volume within Ventspils Harbour has been reconstructed for the last century using historical data. Sources identification, sediment-budget calculations and the interpretation of transport pathways illustrate the potential of mineralogical and textural data combined with the trends documented in sediment geochemistry. The Ventspils case study is an application of the "sediment perspective" toward central problems for harbour management.

Mineral composition of sediments

The sediments of the coastal zone of the SE part of the Baltic Sea are predominantly the products of glacial discharge. Their mineral composition is relatively uniform over the entire area. The changes in the content (%) of different accessory minerals are associated with the mineralogical differentiation that occurs during sedimentation.

In order to characterise the mineralogical composition of sediment in the area of the Ventspils port, 13 samples have been used, out of which 2 samples have been taken from the underwater shore slope near the port gate, 6 in the outer harbour, 5 in the mouth area of the Venta River. The samples to be analysed were taken in the intervals 0-2 and 10-15 cm from the bottom surface.

Based on the results of the studies of the mineralogical composition of the 0.1-0.05 mm fraction, it was found that the following accessory minerals prevail: amphiboles (30-60%), ores (6-25%), pyroxene, zircon and epidote (up to 10-13.6%). The content of other minerals (leucoxene, rutile, tourmaline etc.) is insignificant. As regards the light fraction, the following minerals prevail: quartz (77-87%), feldspar (7.5-20%) and carbonates (3.2-9.7%). The content of glauconite (0.2-2%) and mica (<1%) is insignificant.

The mineralogical composition is within the above-mentioned limits in the sediments of the Venta River, the outer harbour and outside the jetties. Glauconite, however, is absent in the sediments of the Venta River. In the 2 samples taken from the underwater shore slope near the port gate the glauconite content is 0.5 and 2%, and in the outer harbour sediments varies from 0.2 to 1%. Thus, the distribution of glauconite, as well as that of different grain-size fractions, reflects the moment of the influx of marine sediments in the outer harbour.

Siltation in Ventspils Harbour

After the construction of the harbour (1900-05), the jetty heads extended seaward and reached a depth of ca. 7 m, almost completely crossing the longshore sediment current. That is why, as early as 1908, sand accumulation was observed on the outer side of the southern jetty, where the shoreline moved 120 m seaward. Altogether, during the 40-year period, the coastline has moved ca 600 m. The impact of the southern jetty upon the coastal processes can be observed as much as 4.5 km to the south, where an accumulation coast with a sandy beach and a foredune has formed. Sand has accumulated on the underwater slope, adjacent to the southern jetty. The map of depth measurements of 1932 shows that the 6 m depth line (i.e. the outer edge of the wave- breaking zone) was already located outside the jetty heads (Fig. 19). The interrupted longshore sediment transport that is associated with this zone was able to bypass the jetties and start anew. The shore protuberance at the southern jetty side decreased considerably. During 1932-42, the shore moved in the sea direction for 30-50 m.

Since storm waves are directed obliquely against the coastline, a protected zone is situated behind the northern jetty. After the restoration of the sediment transit, sand accumulation started there, and the coastline near the jetty moved forward for 200-250 m during the 40-year period. In the 1930s, the length of the accumulation shore comprised 1.5 km, the velocity of its advance decreased, and, during 1932-42, the shore moved seaward for 30-40 m, like that at the southern jetty. In the vicinity of the harbour the underwater coastal slope predominantly contains fine sand and silt with some areas of gravels and boulders. In the harbour basin itself a layer of silt and fine sand covers underlying glacial clays.

Further north, a long eroded shore is located due to the diminished sand supply from the south. The maximum erosion is observed 3-6 km from the northern jetty, and it displays a tendency to move further from the harbour.

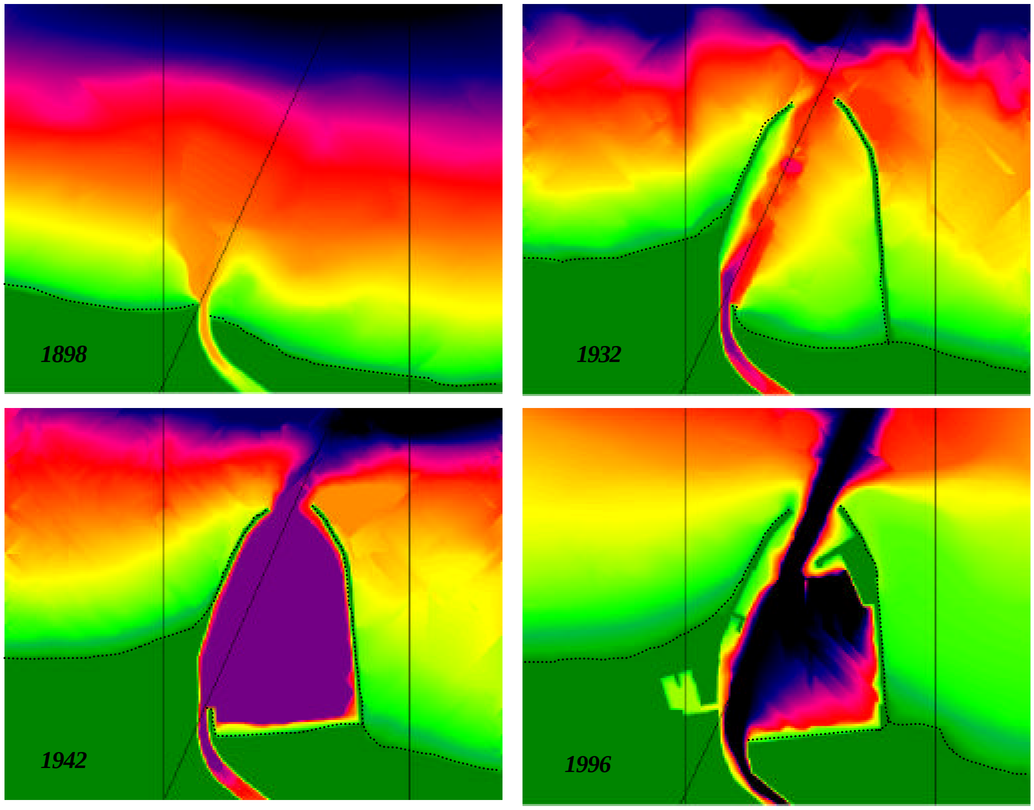


Fig. 19. *Digitised maps showing Ventspils River and coastal changes in connection with harbour construction, using data from Ulsts (1998).*

In the protected zone of the northern jetty, sand accumulation has continued, and from 1942 to 1967, the 5 m depth line has moved 500-730 m. A comparison of the large-scale depth measurement maps of 1967, 1995 and 1996 shows that, between the northern jetty and the nearest soil dump (its western edge is located at a distance of ca 3 km from the northern jetty), sea bottom erosion occurs, as during this time period the 6-9 m depth lines have moved towards the shore from a few tens of metres to 200-300 m. The seismic profiling results have demonstrated that the bottom erosion occurs even at the depth of 10-12 m at both banks of the entrance channel. The port entrance channels are the main reason for the sea bottom erosion. Their depth is up to 15.7 m and they almost completely interrupt the sediment flow.

The maximum silting was observed within the first 800 m from the port gate in the main entrance channel. Based on the studies of LENMORNNIPROYEKT (St. Petersburg), 275,000-550,000 m^3/year of sand deposit there, while, in the channel – 300,000 and 850,000 m^3/year, depending on the sea storm force. About 1/3 of the sand, volume depositing in the channel, enters the outer harbour.

During years with weak storms prevailing, the accumulation of sediments in the channel in the zone 800 m from the port gate is, on the average, 275,000 m^3/year and 300,000 m^3/year in the whole channel area. During years with strong storms prevailing it is estimated to increase to 550,000 and 850,000 m^3/year respectively. In the outer harbour area sediment accumulation is in the order of 130,000 m^3/year and in the mouth of the Venta (including the channel) it is 70,000-80,000 to 80,000-100,000 m^3/year.

Source Budget Calculations

There are two major sources of sediment in Ventspils Harbour: the Venta River and the long-shore coastal currents. Three different, mineralogical calculations were made of the same grain-size interval (500-0.2 mm), using the mineral ratios Quartz/$Feldspar_{tot}$, Quartz/Mafic Minerals, and Quartz/Carbonate Minerals. All three indicate that the Venta River is the major sediment source, accounting for approximately 77% of the sediment deposited (Fig. 20).

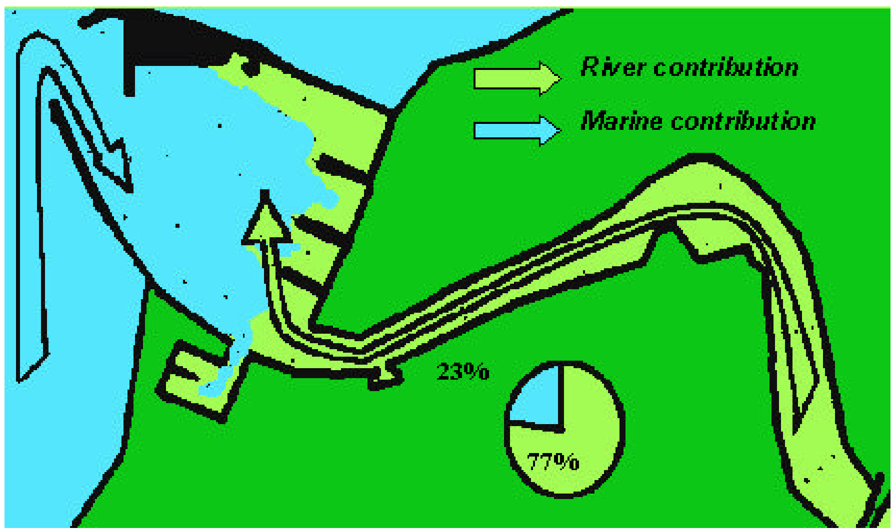


Fig. 20. *Source contributions into Ventspils Harbour, mean result based on calculations of three different mineral ratios.*

Most of the sandy material was found to accumulate in the deep harbour entrance-channel. The quartz concentration was higher in the sandy sediments originating from the longshore drift than it was in the fine-grained river sediment. The supply of fine material (silt and clay) is predominated by the river suspension transport, but sources of fine material may also be found within the harbour where deep dredging may have cut into the underlying clay (Ulsts, 1998). Siltation of finer material occurs on the northern side of the outer harbour, near the berths, and in the fishing harbour where the water is shallow and less turbulent.

Transport Dynamics

Fine materials (clay and fine silt) tend to be transported in suspension, which is reflected by the mode of transport (Fig. 21). Coarse material (sand) is associated with bottom transport where the water turbulence tends to be higher, whereas fine silt and clay particles are predominately carried by suspension transport. Plotting the cumulative frequency of grain sizes from each total sample on a probability scale gives information about sediment-transport characteristics for each site (Fig. 21a, b, c).

Sediment interpreted to have been transported in saltation (one type of bottom transport) dominates in the sea samples and at the vessel turning point in the outer harbour. Saltation is also important in the fishing harbour and in one river sample. Suspension is the dominating transport process in the inner harbour basin and at most sites in the river.

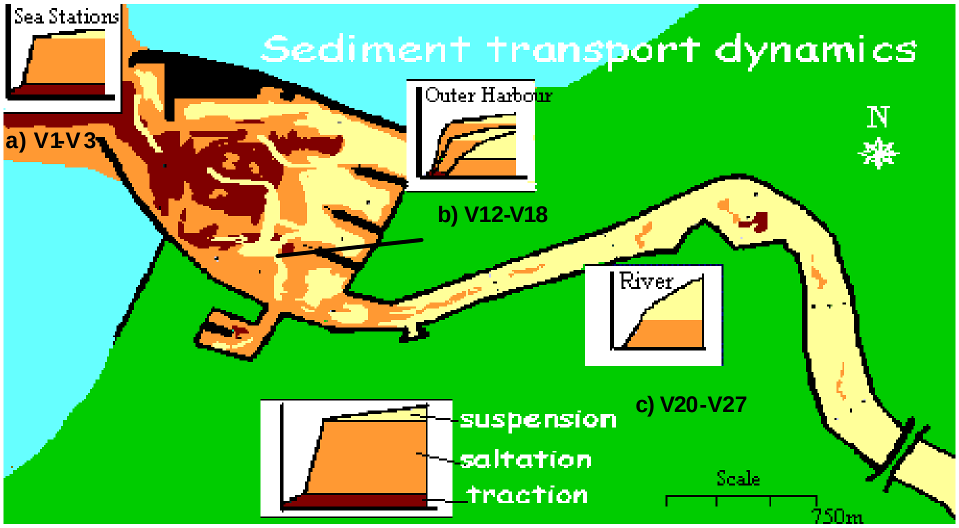


Fig. 21. *Transport mode interpreted from cumulative probability plots. A) Station V1-3, b) Station V12-V18, c) Station V20-V27.*

Resulting vectors were drawn from the trend matrix, to indicate possible sediment transport paths (Fig. 22). The resulting vectors show possible outward transport trends of fine material from the river. This might be feasible, due to the transport dynamics, since most fine-grained material is transported in suspension and the selective deposition takes place in tranquil areas. Coarse material is suggested to be transported inward along the bottom by saltation and traction, through the port entrance channel into the outer harbour.

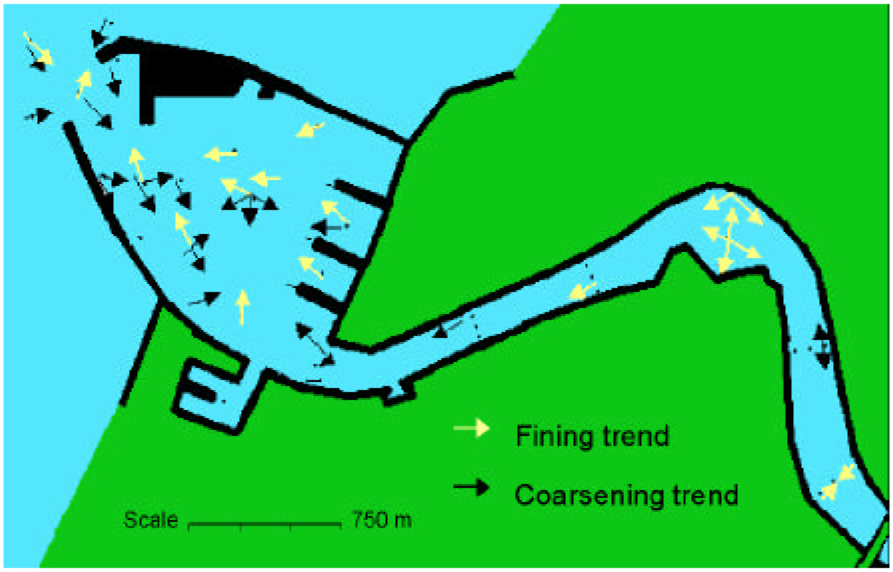


Fig. 22. *Transport patterns in the Ventspils Harbour, interpreted from the McLaren method*

The results from the source budget calculation were consistent with the transport vector analysis. The source budget calculation indicated a major sea sediment influence in the outer harbour with the river being the main source of sediment in the river-mouth area. At the vessel turning points, mixing of sediments occurs and the sediment appears to spread out into the surrounding areas. Interpretations based on transport dynamics, mineralogy and budget calculations indicate that when the finer riverine material reaches the outer port, the sediment transport continues to the north. Most of the coarser, marine-derived sediment occurs in the depths of the outer harbour channels, presumably trapped due to the sheltering .

Hydrographic Processes

Ventspils Harbour displays far-reaching intrusions of saline waters (Fig. 23). The uppermost part of the river in the area studied shows freshwater in the upper 5 m layer and then gradual increase of salinity and turbidity towards the bottom. Stations in the inner harbour neighbouring the marine area confirm a large seawater influx along the bottom occupying a layer up to the 4 m from the water surface. Minimum turbidity corresponding to the seawater values occurs just below the river outflow. Near the bottom a resuspension effect of the seawater flow is noticeable.

Nutrient distribution over the study area is mainly governed by dilution with seawater. As a result, in general, maximum nutrient values are measured in freshwater and lowest in the seawater influx. Nutrient concentrations entering the harbour from upstream should be considered relevant for eutrophication of the recipient marine area. Phosphate in the upper layer of stations V34 – V36 was 1.24 – 1.36 µmol/l and total phosphorus 2.17 – 2.33 µmol/l.

Simultaneously, nitrate varies from 0.27 to 0.31 µmol/l and ammonia from 0.3 to 1.0 µmol/l both testifying to low rates or certain completeness of nitrification. Phosphorus and nitrogen concentrations relative to particulate substance (%) decreased with depth reflecting a reduced presence of living components.

Nutrient concentrations in the waters leaving the harbour seawards decrease compared to the initial values, due to dilution seawater. The nutrient removal by mass exchange between the fresh- and saline water layers is proportional to the salinity increase. In parallel, enrichment of the surface layer with ammonia is evident.

The upper layer in the water column (in the range of 0 – 4-5 m) generally accommodates the outflow of the Venta River to the Baltic Sea. The underlying water masses probably originate from the Baltic Sea. Gradients between the layers depend on the site investigated and salinity distributions show individual patterns for each station, influenced by the mixing conditions. In the outer harbour, the salinity profiles display homogeneity in the deep seawater layer. Turbidity, in turn, reflects mixing due to regular harbour traffic. In the inner harbour, salinity boundaries between the layers are smoothed. Probably, the more dynamic vertical exchange induced by navigation has provoked a relatively complicated turbidity profile at this part of a harbour. Salinity values in the upstream river station indicate homogeneity of the inflowing waters. Resuspension in the deep layer takes place due to both turbulence caused by interchange of the moving layers and active contact of the saline water influx with the bottom sediments.

Particulate phosphorus content versus salinity displays an inverse relationship in concentrations over the range 0.25 – 5.80 PSU with frequent excess of phosphorus at greater salinity values. The phosphorus elevation in the higher salinity region is also clearly discernible for total phosphorus concentrations. The increased phosphate values could be due to either phosphate release from the bottom during resuspension or tiny phosphate rich sediment particles passing 0.45 µm filter pores, mixed up by turbulence.

In contrast to phosphate, the nitrate data shows a well-defined linear relationship with salinity over the entire range. This confirms that resuspension of the bottom sediments can not be considered as an important source of nitrate and dissolved phosphate for the nutrient pool of the water column. Like phosphorus, particulate and total nitrogen reveals an inclination of concentrations from conservative behaviour at high salinity. Additionally, for both parameters the rise is of similar magnitude.

Phosphorus and nitrogen concentrations relative to the weight of suspended material decrease with depth indicating an addition of particulate substance of lower nutrient content in the deep layer. The N/P ratio also decreases with depth, however, if there is an overall decrease of phytoplankton in particulate matter towards the bottom the N/P ratio would be expected to increase. This indicates that other living constituents, such as bacteria and microzooplankton which contribute to the N/P ratio, were not considered. A solely geochemical interpretation of the apparent contradiction could be to propose the enrichment of non-living particles in phosphorus during their residence in the water layer because of resuspension. At the water surface, a large increase in the N/P ratio is noted from the harbour to the marine area that coincides with diminution of the algal part in the particulate substance.

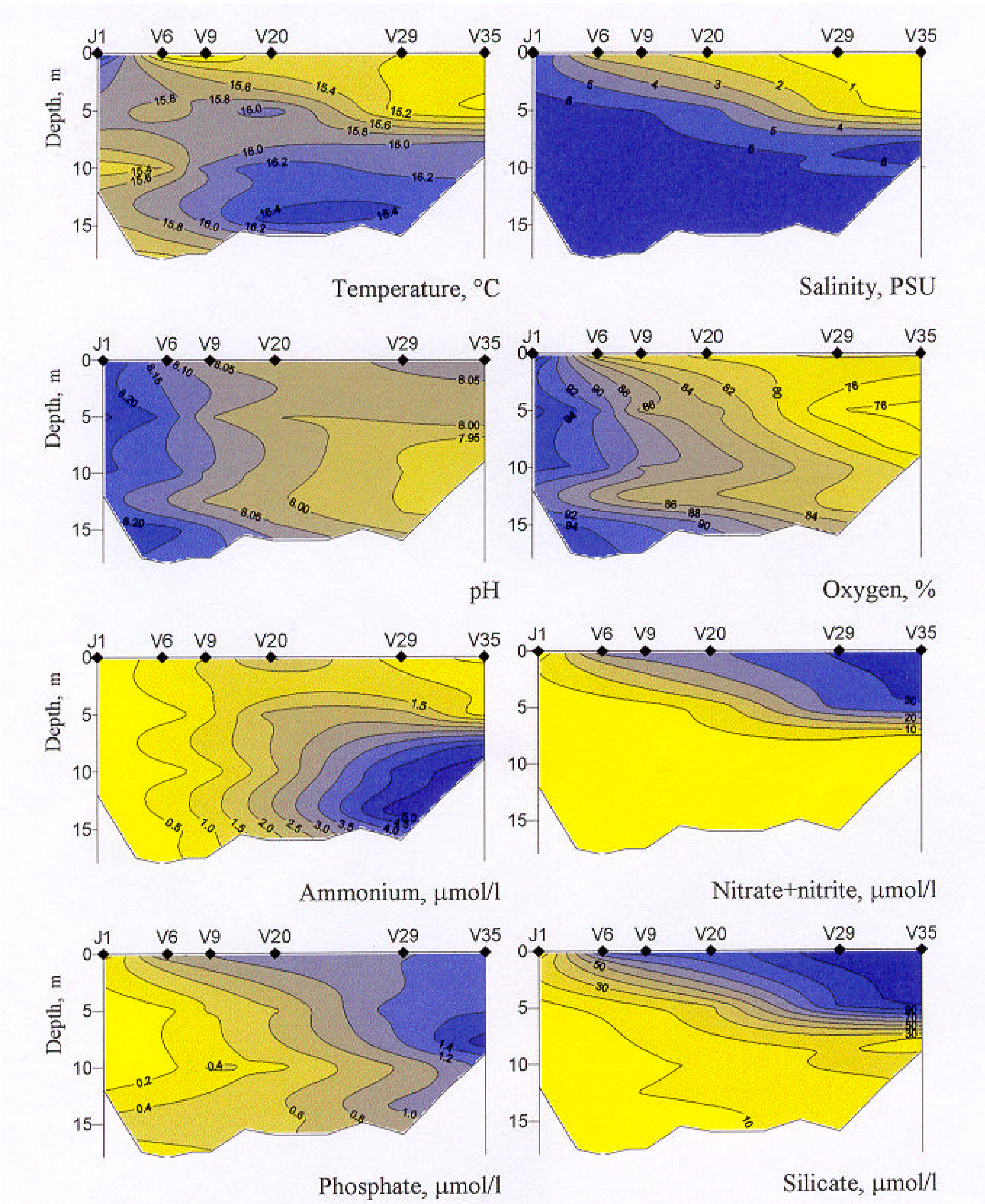


Fig. 23. *Hydrographic parameters and dissolved nutrients in the Ventspils Harbour.*

5.2 Results of Workpackage 2: Environmental Geochemistry

The objective of workpackage 2 was to establish a geochemical database within the three harbours ensuring quality control and suitable parameters for modelling. Furthermore, it was the aim of the H-SENSE study to gain an understanding of vertical as well as spatial trends since dredging and ship turbulence affects more than just the uppermost surface sediments and which could result in the remobilisation of old contaminants into the water column. Several tasks have been conducted which have dealt with process interpretations. There is a need to understand the processes causing changes that occur after deposition. Changes in depth have been shown to reflect sedimentation and environmental changes as well as the pollution history. There is a need to compare sites and this was addressed by considering different means of normalising the data, resulting in the recommendation of the multi-parameter method related to sedimentary characteristics for each setting. Current contaminant classifications used by most harbour authorities are not sensitive to mobility and toxicity of elements in different phases. The identification and evaluation of phase- specific metals is an important result from this study.

Göteborg Harbour

External to the harbour the main source of contamination is the Göta älv River. Although the Göta älv River is considered less polluted by toxicants than many other European rivers, its sediments are a continuing source of elevated concentrations of organic pollutants and heavy metals. The geochemical archive produced for the harbour and the archipelago illustrates our approach to the interpretation of vertical and spatial trends, the need for normalisation and the advantage of integrating interpretations from several parameters. Geochemical relationships were investigated using multi-parameter normalisation. Significant time-dependent changes in the geochemical properties of the harbour sediments were also documented over a two-year period, highlighting the need for routine geochemical surveys to be conducted immediately prior to dredging operations.

Variability of the sediment heavy metal content

The variation of heavy metal concentrations within the recent sediment layer has been studied in the archipelago. The relative standard deviation values for all heavy metals are higher between samples from different parts of the archipelago than between samples from one profile in the recent sediment layer. This is mostly due to the spatial variation of grain size and organic carbon, which is greater than the variation with depth. The contents of silt, clay, water and TOC vary more spatially than in the recent sediment layer of one profile (Table 1). The difference between spatial variation and variation with depth is most pronounced for Cu, and decreases for other tested metals in the order Zn-Pb-Hg. This could be due to a difference in the importance of local sources for these metals. The relative standard deviation of Cu, Zn and Pb are of the same order of magnitude, while Hg has about twice the value, suggesting different sources and/or transport or sedimentation processes. The greater variation of Hg is most pronounced in the profiles, suggesting separate influences upon the accumulation of Hg and the other heavy metals.

Table 1. *Vertical and spatial variation in heavy metals and sediment characteristics. Vertical variation (? = standard deviation and rsd = relative standard deviation) is calculated from different samples at different sediment depth from the same site (5 cores), and spatial variation from the same sediment depth at 35 different sites.* rsd_d/rsd_s *indicates the difference between vertical and spatial variation.*

Vertical	Cu (ppm)	Zn (ppm)	Pb (ppm)	Hg (ppb)	Sand (%)	Silt (%)	Clay (%)	Water (%)	TOC (%)
$mean_v$	59.06	235.75	68.80	1505.92	7.07	30.45	62.48	52.93	2.70
?$_v$	16.16	68.24	21.08	1235.56	2.77	3.17	3.83	2.84	0.48
Rsd_v	0.27	0.29	0.31	0.82	0.39	0.10	0.06	0.05	0.18

Spatial	Cu (ppm)	Zn (ppm)	Pb (ppm)	Hg (ppb)	Sand (%)	Silt (%)	Clay (%)	Water (%)	TOC (%)
$mean_s$	45.42	177.99	50.80	965.60	11.75	26.02	62.03	56.83	2.61
?$_s$	26.03	97.34	20.69	857.44	12.98	6.21	11.23	7.40	0.89
Rsd_s	0.57	0.55	0.41	0.89	1.11	0.24	0.17	0.13	0.33

Difference	Cu (ppm)	Zn (ppm)	Pb (ppm)	Hg (ppb)	Sand (%)	Silt (%)	Clay (%)	Water (%)	TOC (%)
Rsd_d/rsd_s	0.48	0.53	0.75	0.92	0.35	0.44	0.36	0.42	0.54

In addition to the samples from three levels (0-2, 10-12 and 15-17 cm) that were analysed at each station, the vertical geochemical changes in five 30-70 cm long cores were studied in more detail. They were interpreted in connection with ^{210}Pb- and ^{137}Cs-datings done in three of them. The recent, soft sediment layer contains varying levels of heavy metals, with high concentrations most often below 10 cm sediment depth, independent of grain size trends. In two of the three longer cores the maximal concentrations were found as deep as 25 cm. The interval of enrichment is usually wider for Hg than for the other heavy metals, and it is attributed to the period of high Hg discharges from chlor alkali industry, paper industry and sewage in the 1950's to late 1970's. In a core from the middle of the archipelago, a sharp peak with very high concentrations at 12 cm depth probably represents an episodic influx of contaminated terrestrial material. Also in some other cores, sharp peaks at sediment depth corresponding to the early 1990's were found (Fig. 24). This suggests a trend of decreasing pollution overlain by local events of contaminant influx.

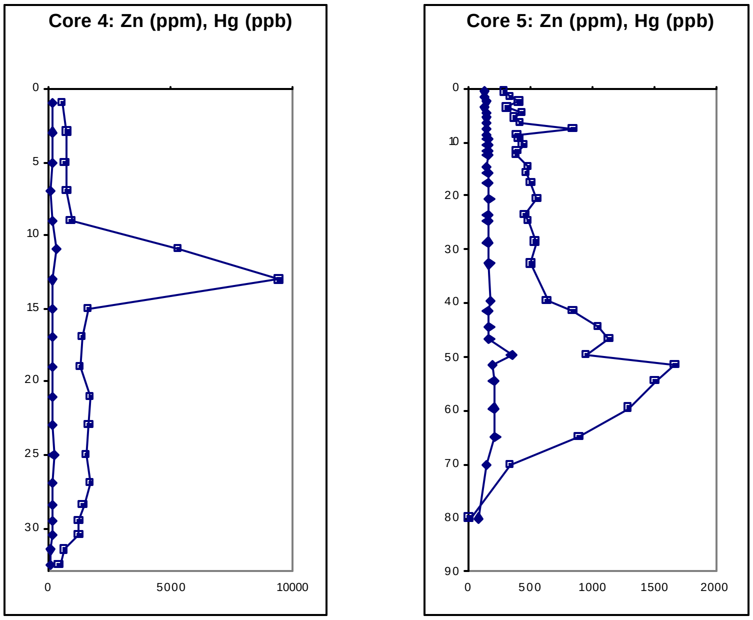


Fig. 24. *Zn, and Hg in two cores from the archipelago a sharp peak at 12 cm (core 4) and an interval with elevated concentrations in the lower part of the core (core 5).*

Geochemical mapping

Earlier investigations of the geochemistry of the Göteborg harbour sediments have been performed by the port authorities (GHAB) prior to dredging campaigns in order to determine if the material to be dredged is contaminated or not. Two levels from each short core are normally investigated (0-2 cm and 40-45 cm). Threshold values are applied to define if sediments are contaminated in respect to Hg, Cd, and PCB. Contaminated sediment has to be taken to an isolated bay for disposal. Data from these investigations are available from 1984 until today. These investigations do not include important parameters, such as organic content and grain size characteristics, and they do not account for vertical variability in heavy metal contents.

Organic matter content of surface sediment

The total organic carbon in the surface sediment varies from a mean of 1.5 % in sandy clays and 2.1 % in silty clays in the harbour to 2.6 % in silty clays in the archipelago (Fig. 25). Some areas show concentrations up to 5 %, and just outside the outlet of the sewage treatment plant, 7.5 % have been measured. There is generally an increase towards the outer harbour, which is both related to decreasing grain sizes and the position of the sewage treatment plant. There is also an indication that the tributary in the northeastern part has a local influence on the organic content. C/N ratios suggest that the material is a mixture of marine and terrestric organic matter, with an increase of the marine component outwards, toward the archipelago.

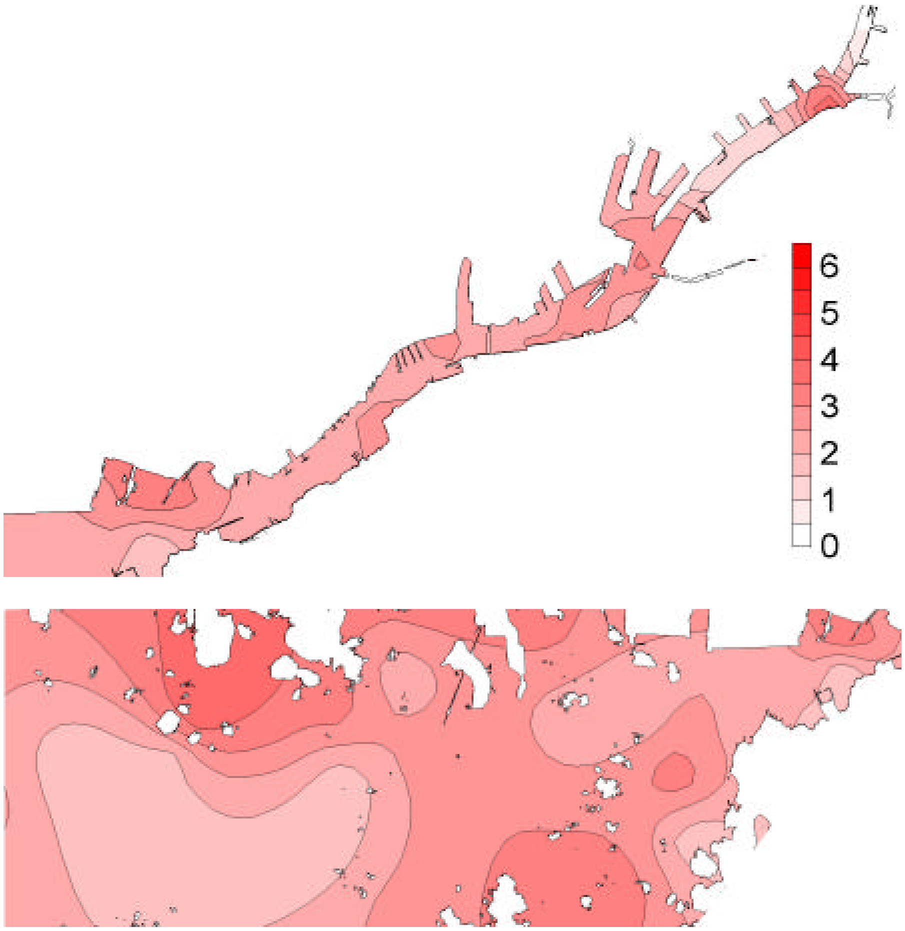


Fig. 25. *Total organic carbon concentrations (%) in recent sediment (0-2 cm) in Göteborg Harbour (above) and in the archipelago west of the Göta älv estuary (below).*

Copper (Cu)

Total Cu varies from background concentrations (15 ppm) to 100 ppm in most of the recent sediment from Göteborg Harbour, with extreme values reaching up to 900 ppm (Fig. 26). Most of the sediment has concentrations below 200 ppm, which is the Probable Effect Level for Cu in fresh water sediment and estuarine sediment (Smith et al., 1996). The highest concentrations are found at the mouth of the tributary Säveån and in the middle harbour, close to the dock of a large passenger ferry. In some areas, that is at the mouth of the tributary, in Frihamnen, at the ferry terminal, at the old quay Nya Varvet and downstream the sewage treatment plant, the sediments are contaminated with respect to all heavy metals. Approximately 5% of the water from the waste treatment plant is discharged untreated into the harbour and some metals may be added to the harbour in this way. The distribution of Cu indicates the influence of additional local point sources. Since high concentrations often occur close to docks and since it is known that anti-fouling paints contain copper, these sources are probably significant.

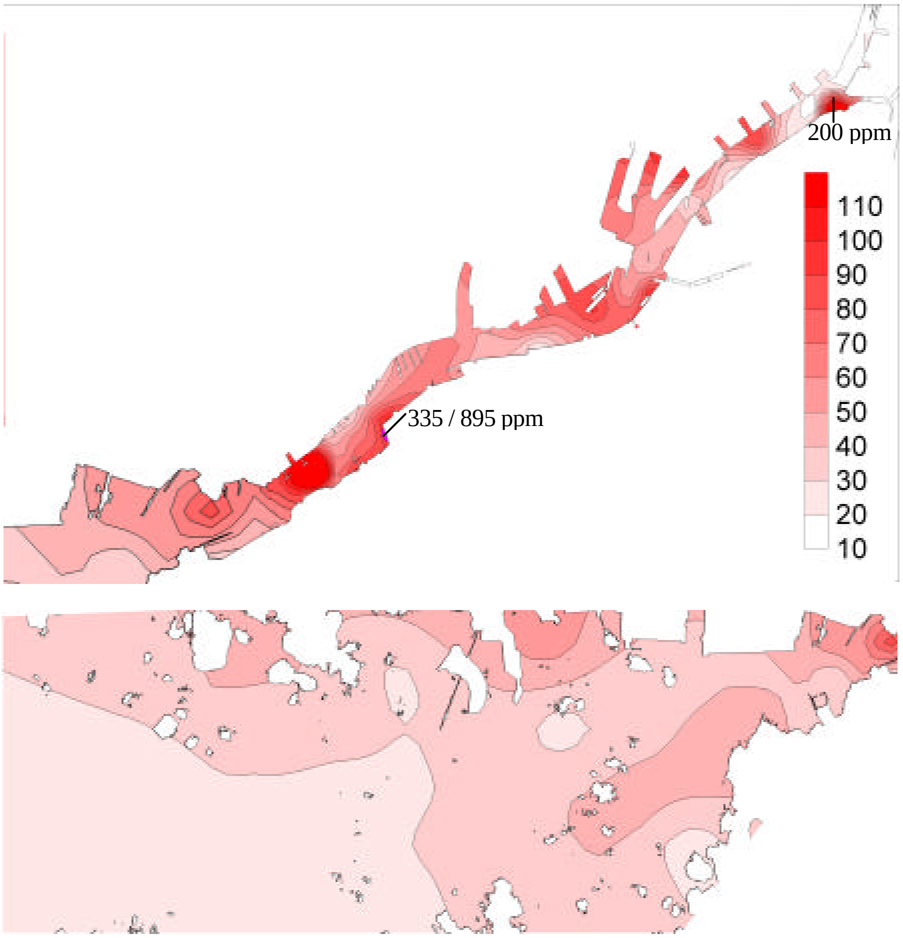


Fig. 26. *Total Cu concentrations (ppm) in recent sediment (0-2 cm) in the Göteborg Harbour (above) and in the archipelago west of the Göta älv estuary (below). Concentrations >200 ppm can give adverse biological effects.*

Downstream of the outlet of the sewage treatment plant he highest concentrations of the outer area are found. In the archipelago, total Cu varies from background levels (15 ppm) to 150 ppm in recent sediment, with a mean of about 40 ppm. As for all heavy metals, the concentrations decrease outwards, and they are relatively high in the northern archipelago. This is probably both connected to sediment characteristics (high organic matter content and fine grain sizes) and transport of contaminated suspension load with the river outflow along the northern coast.

Lead (Pb)

Total Pb concentrations in recent sediment from Göteborg Harbour vary from background (15 ppm) to 100 ppm, with extreme values of up to 4600 ppm (Fig. 27). Most of the sediment has concentrations below the Probable Effect Level for Pb (100 ppm, Smith et al., 1996). High Pb concentrations are found in the generally polluted areas mentioned above, and in the middle harbour along the southern shore. Extremely high concentrations were found close to two, separate, ferry terminals. In the archipelago, there is a general decreasing trend seawards.

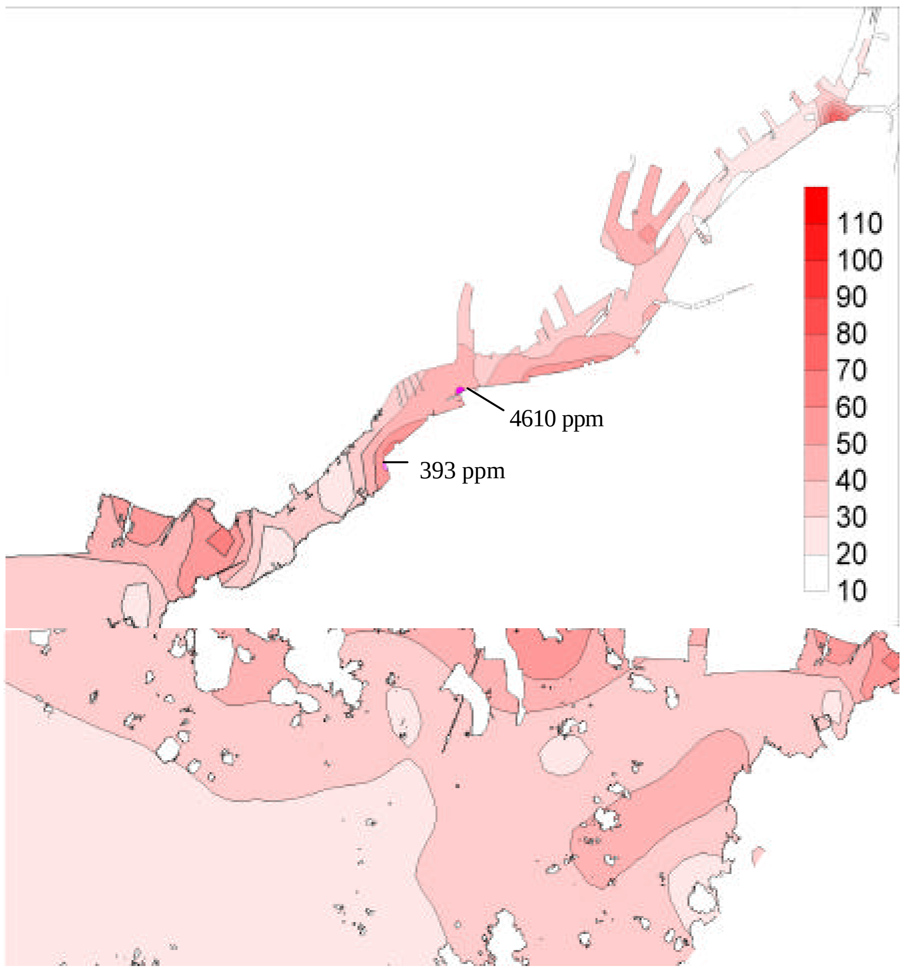


Fig. 27. *Total Pb concentrations (ppm) in recent sediment (0-2 cm) in the Göteborg Harbour (above) and in the archipelago west of the Göta älv estuary (below). Concentrations >90 ppm can give adverse biological effects. The two extreme values (specified in the harbour) have not been mapped.*

Zinc (Zn)

Total zinc varies from background levels (83 ppm) to 300 ppm in most of the recent sediments from Göteborg Harbour (Fig. 28). The Probable Effect Level for Zn is 300 ppm (Smith et al., 1996). Extreme values of up to 1000 ppm were found in the mouth of the tributary Säveån and at two quays. The distribution of Zn is generally similar to that of Cu and Pb. This is also the case in the archipelago.

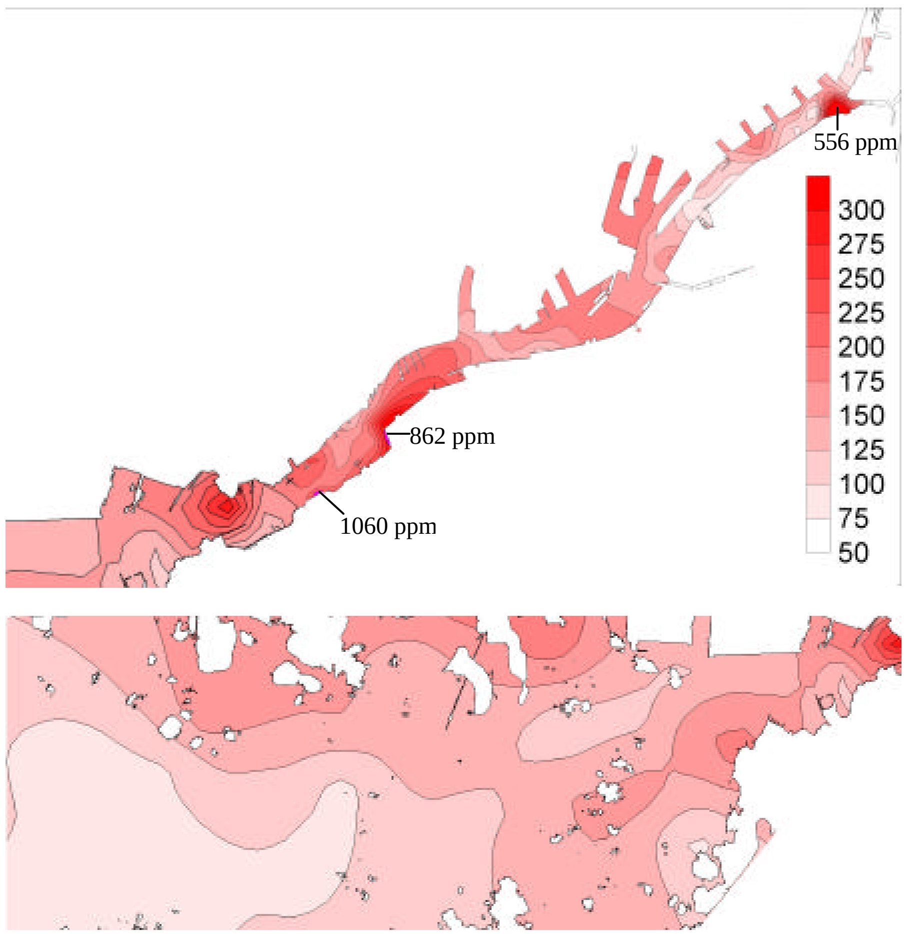


Fig. 28. *Total Zn concentrations (ppm) in recent sediment (0-2 cm) in the Göteborg Harbour (above) and in the archipelago west of the Göta älv estuary (below). Concentrations >315 ppm can give adverse biological effects. The two extreme values (specified in the harbour) have not been mapped.*

Mercury (Hg)

Total mercury varies from background concentrations (20 ppb) to 800 in most of the recent sediment from Göteborg Harbour, with extreme values of up to 2320 ppb (Fig. 29). Near the tributary, in some parts of the middle harbour and downstream from the waste- water treatment plant and in the northern archipelago the sediments have concentrations above the

Probable Effect Level for Hg (486 ppb: Smith et al., 1996). The main Hg-sources are industries located upstream from the harbour.

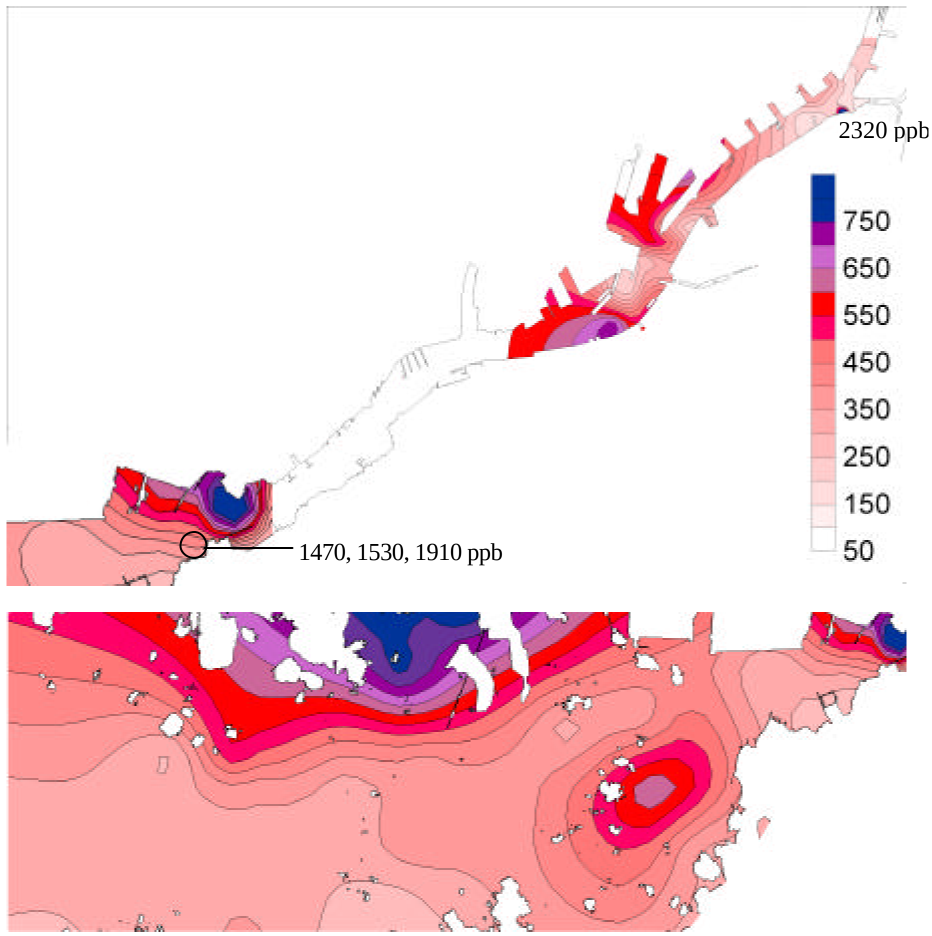


Fig. 29. *Total Hg concentrations (ppb) in recent sediment (0-2 cm) in the Göteborg Harbour (above) and in the archipelago west of the Göta älv estuary (below). Concentrations >486 ppb can give adverse biological effects. The extreme values (specified in the harbour) have not been mapped.*

Geochemical Relationships

Within Göteborg Harbour, correlation statistics indicate that there are few strong correlations between any two parameters. The distribution of the sediments and geochemical elements are therefore dependent on more than one parameter. Identifying contaminant sources requires that the inherited, natural, geochemical variation be accounted for, and normalisation techniques based upon several different combinations of parameters were tested on the Göteborg Harbour database.

Particle size and organic content varies widely in the surface sediments analysed in the Göta älv estuary, preventing the use of single-parameter normalisation. A total of 88% of the geochemical variation in the surface sediments are explainable by association with (1) fine-grained particles (<16 ?m), (2) organic material or oxidisable sulphides, (3) anthropogenic contributions, (4) carbonate material (mainly shells), and (5) Fe and Mn oxides. Factors 1, 2, and 4 are considered to be natural components and are included in the multi-parameter normalisation. The large variation in both particle size and organic content (0.02-3.75%) in sediments from Göteborg Harbour and the lack of strong correlation between individual normalising parameters and the geochemical data made it impractical to use just one such parameter for normalisation.

The spatial distribution of non-normalised, total element content in the surface sediments divides the elements into four different groups. A) Al, Ba, Cu, Ca, Fe, K, La, Mg, Mn, Ni, Sc, Na, Sr, V, and Zn which have low to moderate concentrations in the river and inner harbour sediments and moderate to high concentrations in the middle and outer harbour. This spatial distribution corresponds well to that of particle size and TOC, and many of these elements are associated with clay minerals (Buckley & Cranston 1991). B) The distribution of total Pb is different from that of all the other elements. Pb has a generally moderate content throughout the harbour. The distribution of Pb is not related to that of particle size or TOC, and seems more likely to be related to anthropogenic contributions. C) Spatial distribution patterns of Cr and Y display a contrasting pattern, with high concentrations throughout the estuary and low concentrations at a few stations mainly in the river and inner harbour. The overall high levels are in part due to the association of Cr with aluminosilicates (Prohic & Kniewald 1987), but could also be related to a high discharge of Cr from several harbour activities (Brian *et al.* 1982). D) The content of Co, P, Ti, and Zr in the surface sediment is low in the river and inner harbour, and in parts of the middle and outer harbour. The concentrations are however, high in the middle and outer harbour and near the tributary Säveån River. The pattern of these elements is largely consistent with that of particle size and TOC.

The factor analysis indicates that there are several sediment parameters of importance for the variation in geochemical elements in the surface sediments from the Göteborg harbour. The use of a single parameter for normalisation is therefore not suitable in this area. A formula for normalisation in the Göteborg harbour, incorporating the three natural factors identified, can be expressed in this form:

$$E^* = E\frac{1}{w \; ? \; [<16 \; ?m\%] + x \; ? \; [org/ox. \; sulph.\%] + y \; ? \; [carb\%]}$$

where w, x, and y are element specific constants used to weight the normalisation effect of the three natural factors, as determined within each setting by the factor loadings associated with each element.

This approach was tested on the two metals Ni and Pb. The content of non-normalised Ni increases outwards in the estuary (Fig. 30a), while extremely high concentrations of Pb are not systematically distributed (Fig. 30b). A reversed trend is observed for Ni after multi-parameter normalisation with higher relative values in the river and inner harbour (Fig. 30c). The same trend could be observed for Pb, but with a larger spread of the data (Fig. 30d). The relative standard deviation after normalisation is smaller for Ni than Pb with 32% and 67%, respectively. The different effect of the normalisation for Ni and Pb is partly due to their association with separate sediment components. Ni is tightly bound in the mineral lattices or in strong organic complexes, while Pb is mainly associated with more mobile components.

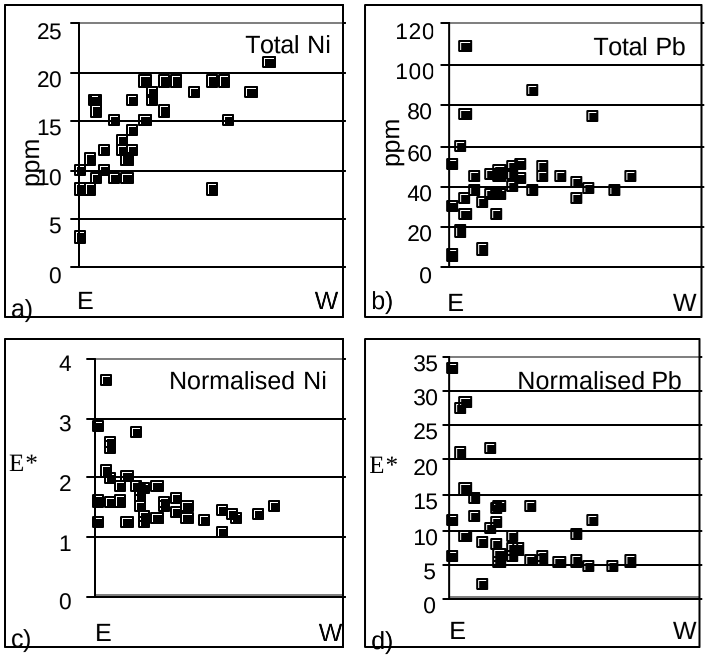


Fig. 30. *Non-normalised content of (a) Ni and (b) Pb in the surface sediments and (c) Ni and (d) Pb values after multi-parameter normalisation.*

Time-dependent changes in PCB and Hg

The disposal alternatives for dredged sediments are normally decided on with regard to the content and concentration of environmentally hazardous substances. As geochemical testing of harbour sediments is carried out some time prior to scheduling dredging operations, the possibility of time-dependent changes between testing and dredging is an important concern. Therefore, time-dependent changes within PCB's and Hg were investigated over a two-year period.

During March 1998, nine cores were taken from sites (Fig. 31) that had been previously sampled and analysed by the same methodology as in 1996. No dredging was carried in the vicinity of these sample sites over this time period. The concentration of Hg, each PCB congene and total 7PCB at a depth of 0-5 cm has been compared and evaluated for all nine sites.

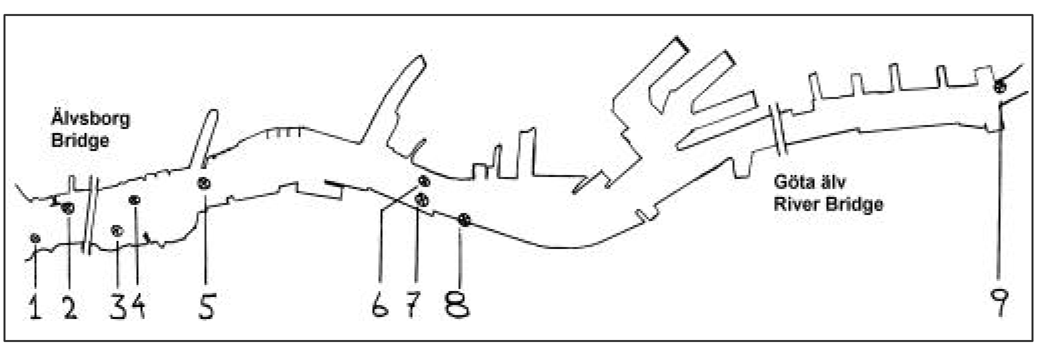


Fig. 31. *Sites sampled in 1996 and re-sampled in 1998 in the central portion of Göteborg Harbour.*

A reduction in Hg concentration between 1996-1998 is found to exist near the channel centre (Fig. 32), but with increasing distance from the centre there is a strong tendency for Hg concentrations to increase (except for site 8). An increase in the Hg concentration is found to correlate to an increase in the TOC present. However, a reduction in the total 7PCB (sum of the selected seven PCB congenes) concentration is noted between 1996-1998 (Fig. 33). The highest detected concentration of 7PCB in the nine sites is 3.4 µmole/kg (site 5) in 1996 and 0.77 µmole/kg (site 3) in 1998. Unlike Hg, the concentration of 7PCB is not clearly correlated to TOC. This is also in contrast to most observations where hydrophobic contaminants such as PCB tend to be bonded to or associated with organic components (e.g. Harkness et al., 1993).

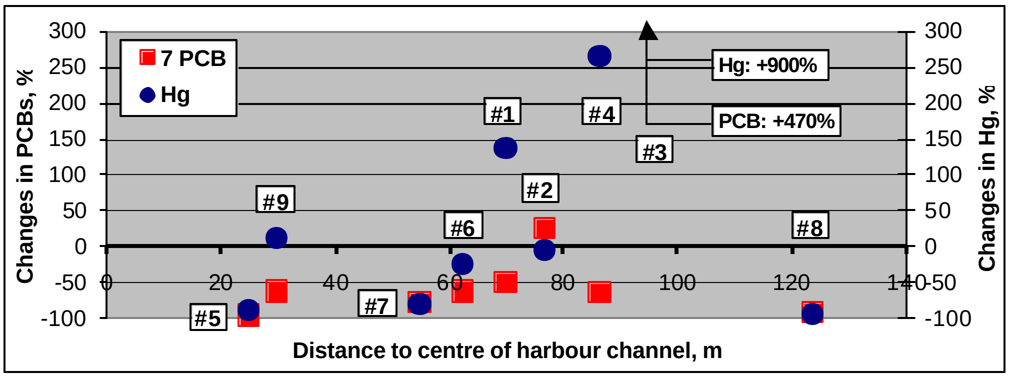


Fig. 32. *Changes in % of Hg and 7PCB between 1996-1998 at 0 -5 cm, relative to the distance from the centre of harbour channel. Each number (#) corresponds to the site in Fig. 31.*

The heavy PCB congenes dominate both in 1996 and in 1998 (Fig. 33). However, in 1996 site 9 only contained low chlorinated PCBs (0.1 µmole/kg). In 1998 no low chlorinated PCBs are detected at this site, but instead only a small amount of some highly chlorinated PCBs are documented (just above detection limit). In all other samples, the majority of the highly chlorinated PCBs occur in higher concentrations than for any of the low chlorinated PCBs. Generally, PCB138 is the most abounded congene in both 1996 and 1998, among the seven congenes analysed (except site 9).

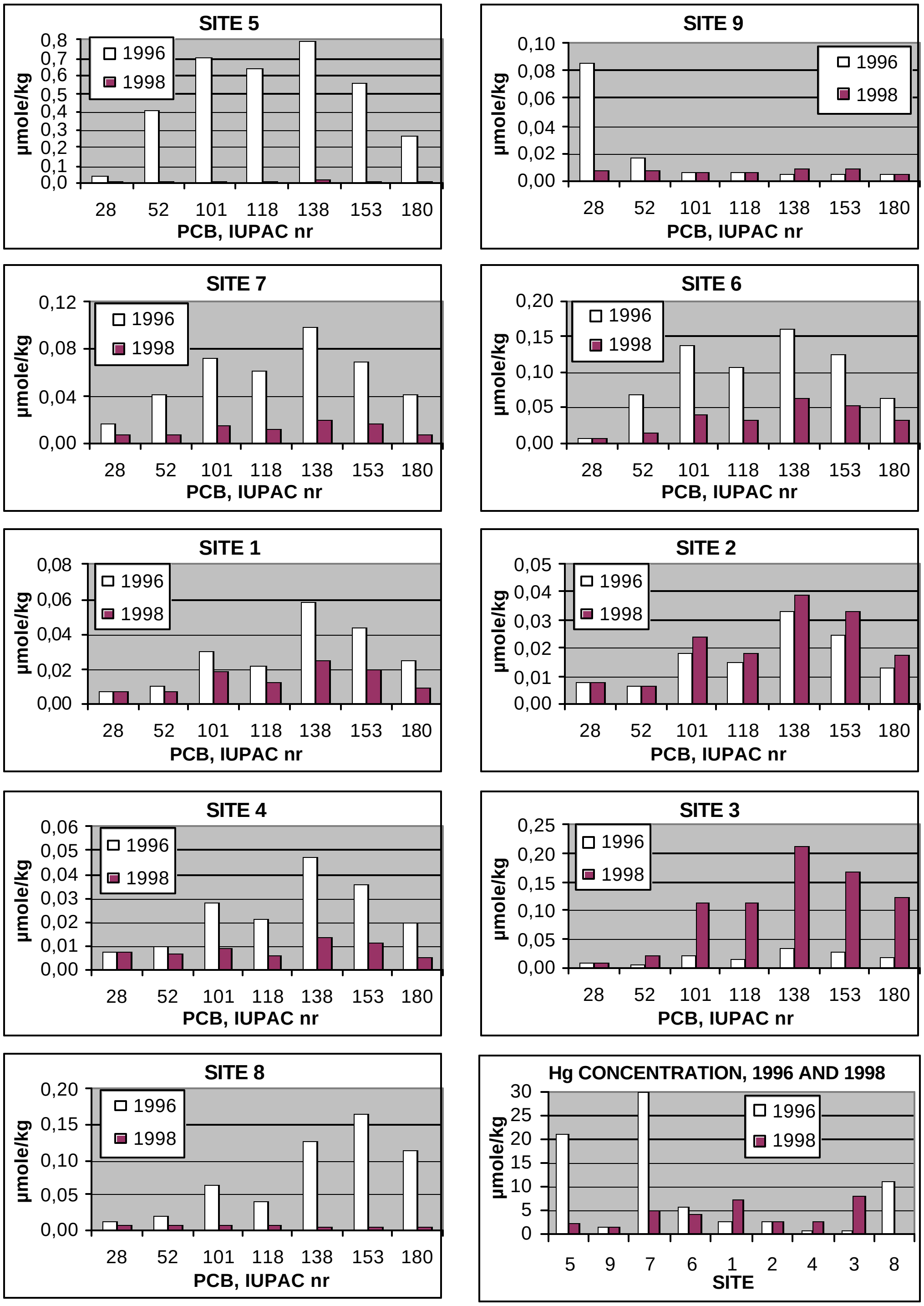


Fig. 33. *Concentration of each PCB congene at 0-5 cm in sites 1-9, from 1996 and 1998. The figures are presented in order from the site nearest the centre of the channel (site 5) to the most distal site (site 8). <u>Bottom right figure:</u> Hg concentration in 1996 and 1998 at 0-5 cm. The sites are in order from the nearest the centre of the channel (site 5) to the most distal site (site 8).*

There is a weak tendency for the concentration of 7PCB and Hg in the surface layer to decrease near to the centre of the harbour channel from 1996-1998, and increase away from the channel centre. This tendency is more pronounced for the low-chlorinated PCB congenes.

Time-dependent changes in concentration of Hg and PCB in Göteborg Harbour may largely be explained by physical transport of the sediment that carries these contaminants. Both the turbulence of ship traffic and natural currents within the estuary have presumably influenced sedimentation.

Significant changes in the concentration of environmental hazardous substances are found to occur in the harbour sediments during the two-year study. The possibility of significant changes, even in much shorter time span should not be excluded, and could present even larger problems. The timing of geochemical analyses and subsequent dredging activities is therefore an important concern as previously non-contaminated sediment may have become contaminated, resulting in deposition of contaminated masses in areas reserved for non-contaminated masses. Further, non-contaminated masses may unnecessarily increase the burden in disposal areas for contaminated sediment.

Discussion

Geochemical analyses, including heavy-metal measurements of total contents and "speciation" contents (associated with specific sediment components), have been carried out in the whole harbour and in the adjacent archipelago. Both geographical distribution and vertical trends of contaminants in the sediments were documented. Three areas in the estuary and the archipelago were investigated in detail. The Frihamnen-Göta Verken area has been used as a shipyard since the 1920s. The distribution of total Cu and Pb reflect higher concentrations inside the Frihamnen and downstream from the shipyard area (Göta Verken). The concentrations of Cu, Zn and Pb are as high as 10 times background values. Since there is no younger pre-industrial sediment preserved, background concentrations were taken from the consolidated clay. Hg concentrations show 25 times background values on average, with a rather uniform distribution in this area. Speciation of Cu and Pb reveal that more than 50% is bound in the non-residual and more mobile phases (mainly to Fe and Mn oxides or to the organic/sulphidic phase). This suggests that anthropogenic sources are larger than natural mineralogical ones. In the river mouth and outer estuary, heavy metal concentrations are highest at the outlet of a sewage plant and in the northern archipelago. Also here the highest values are the ones for Hg (28 times background), which are of the same average order as in the shipyard area in the middle harbour. Zn, Cu and Pb show 2-3 times background concentrations on average in the archipelago.

Bergen Harbour

Bergen Harbour is highly polluted and until 1999 received untreated sewage from more than 100,000 householdings and from industry. Within Bergen a detailed geochemical archive has been produced for the harbour with vertical and spatial trends investigated. There is a strong correlation between organic matter content and metal concentrations, but of even greater importance is the history of pollution discharge and how it has governed accumulation. The study in this harbour has provided recommendation policies for the treatment of contaminated *sediments. The deposits in parts of the harbour represent potential contaminant sources, which may become increasingly significant with further change in the harbour geometry and use.*

Organic matter content of surface sediments

Organic matter in marine sediments is derived from two main sources, namely from biological activity and from sewage input. The majority of the organic matter in the Bergen harbour sediments is sewage derived and is most concentrated close to the former outlets of untreated sewage from the Bergen population (Fig. 34).

These high organic matter (=carbon) masses lead also to extremely low dissolved oxygen concentrations of the bottoms of the inner basins that are only occasionally ventilated when strong storms mix these deeper waters. Near-surface sediments have a strong H_2S smell. The black sediment colour is due to FeS precipitation, also related to the bacterial production of H_2S during the degradation of organic matter.

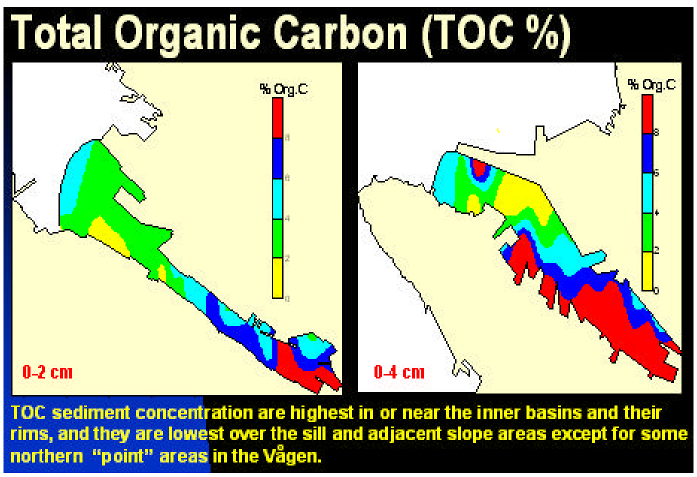


Fig. 34. *Organic matter concentrations determined by the CHNS Analyser are highest in or near the inner harbour basins where up until last year untreated raw sewage was discharged. Since 1999 sewage is collected and sent to centralised sewage treatment (mechanical and chemical) plants.*

Mercury (Hg) content of surface sediments

Very high mercury concentrations occur in the Vågen and slightly lower values are present in the surface sediments of the Puddefjord (Fig. 35). These high Hg values are presumably related to the dramatic increase in the use and release of dental amalgam that started in the late 1950's. Today the use of dental amalgam has decreased drastically and dentists must filter drilled and replaced amalgam from dental fillings and not directly discharge these into the sewer system. We have not, however, detected a noticeable decrease of mercury in the most recent and youngest sediments.

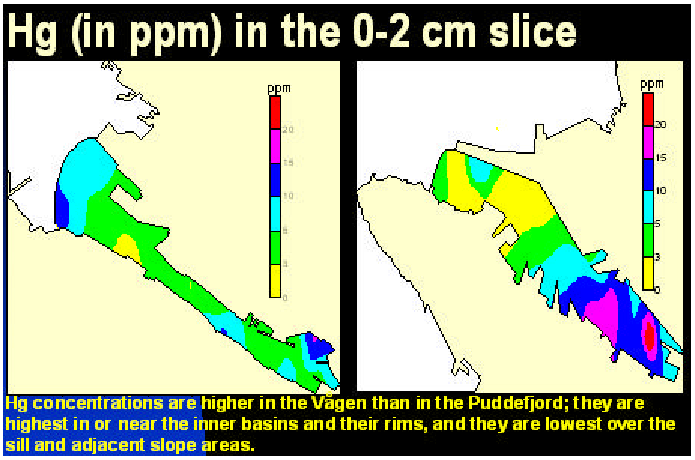


Fig. 35. *Mercury concentrations are greatest in the inner basins, especially in the inner Vågen (right). Discharge related to dental activities in the late 1950's may have been a major source.*

Lead (Pb) content of surface sediments

Lead sediment surface concentrations are greatest in or close to the inner basins where the largest volume of untreated sewage was discharged until the middle of 1999 (Fig. 36). These Pb concentrations are derived from different sources, including metal industry, gasoline stations, automobile exhaust, runoff from the streets, and battery maintenance, recycling and exchanging services.

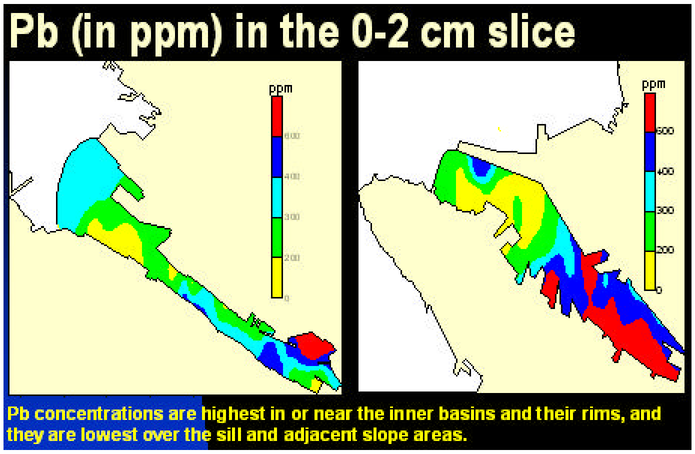


Fig. 36. *Lead concentrations are highest in the inner harbour basins, presumably related to untreated runoff from gasoline stations and roads as well as from small-scale industrial activities.*

Zinc (Zn) concentrations in surface sediments

Zinc concentrations are close to point sources in the Bergen harbour and are related to metal industry and ship yard activities (Fig. 37).

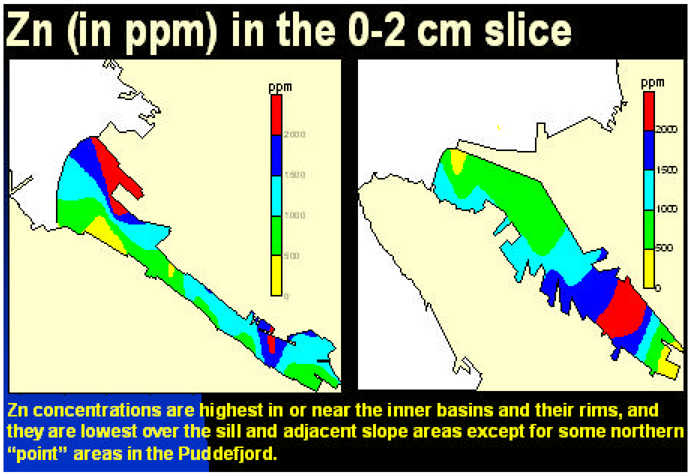


Fig. 37. *Zinc surface sediment concentrations are highest in or near the inner basins and to some industrial point sources in the northern Puddefjord.*

Ventspils Harbour

Metal concentrations within Ventspils Harbour are generally low but require documentation since this harbour is undergoing a major phase of expansion, raising concerns for future pollution problems. A detailed geochemical archive has been produced for sediments in both the vertical and spatial context. Both total metal contents and mobility were examined using sequential extraction techniques. Geochemical relationships were also investigated using multi-parameter normalisation. The Venta River sediments are believed to be the main source of contaminants. It is therefore of considerable importance to determine the transport pathways and mixing of this material with the coarser, sandy sediments supplied from the coast.

Metal and organic matter distribution at the surface layer (0 - 2 cm)

Upstream from the harbour area, intermediate to high metal concentrations were noted as compared to the other stations sampled (Fig. 38). Within the inner harbour, sediment metal contents are generally lower adjacent to the river banks than in the deeper shipping channel in the centre of the Venta River. Metal concentrations (with the exception of cobalt) tend to increase from the ship turning point (V29), through the industrial area of the inner harbour towards the Venta River mouth. Highest metal and organic matter contents are found immediately downstream from the Venta River mouth at stations V14 and V18. An area of high metal concentrations also stretches along the eastern and northern edge of the harbour basin where concentrations are similar to the industrial area of the inner harbour. From the south-western edge of the harbour basin concentration levels decrease towards the sea and concentrations at the marine station V1 are distinctly lower than in the inner harbour and at the upstream station V35 for all parameters investigated. The lowest concentrations are generally observed at station V7 close to the south-western breakwater. Also at station V13 in the centre of the outer harbour observed metal and organic matter contents are generally low.

Concentrations normalised to Al show the same trends along the cross section as the raw data. However, differences between the individual stations are less pronounced for the normalised data and the concentration decrease towards the sea is also smoothed. This is especially obvious for Ca, Cr, Fe, and organic matter (C_{tot}, N_{tot}). Normalisation also smoothes the concentration increase from the river to the industrial harbour area. For Pb normalised concentrations at the sea (V1) and the upstream station V35 are roughly equal whereas all other parameters showed lower normalised concentrations at the sea than at the upstream station. Normalisation was found to remove part of the variance noted in the raw data and decreased concentration differences, but the relative differences between the stations are still preserved. Therefore, factors in addition to grain size seem to be responsible for the observed patterns. Sediments at stations V10 and V11 may also be specifically contaminated by point sources.

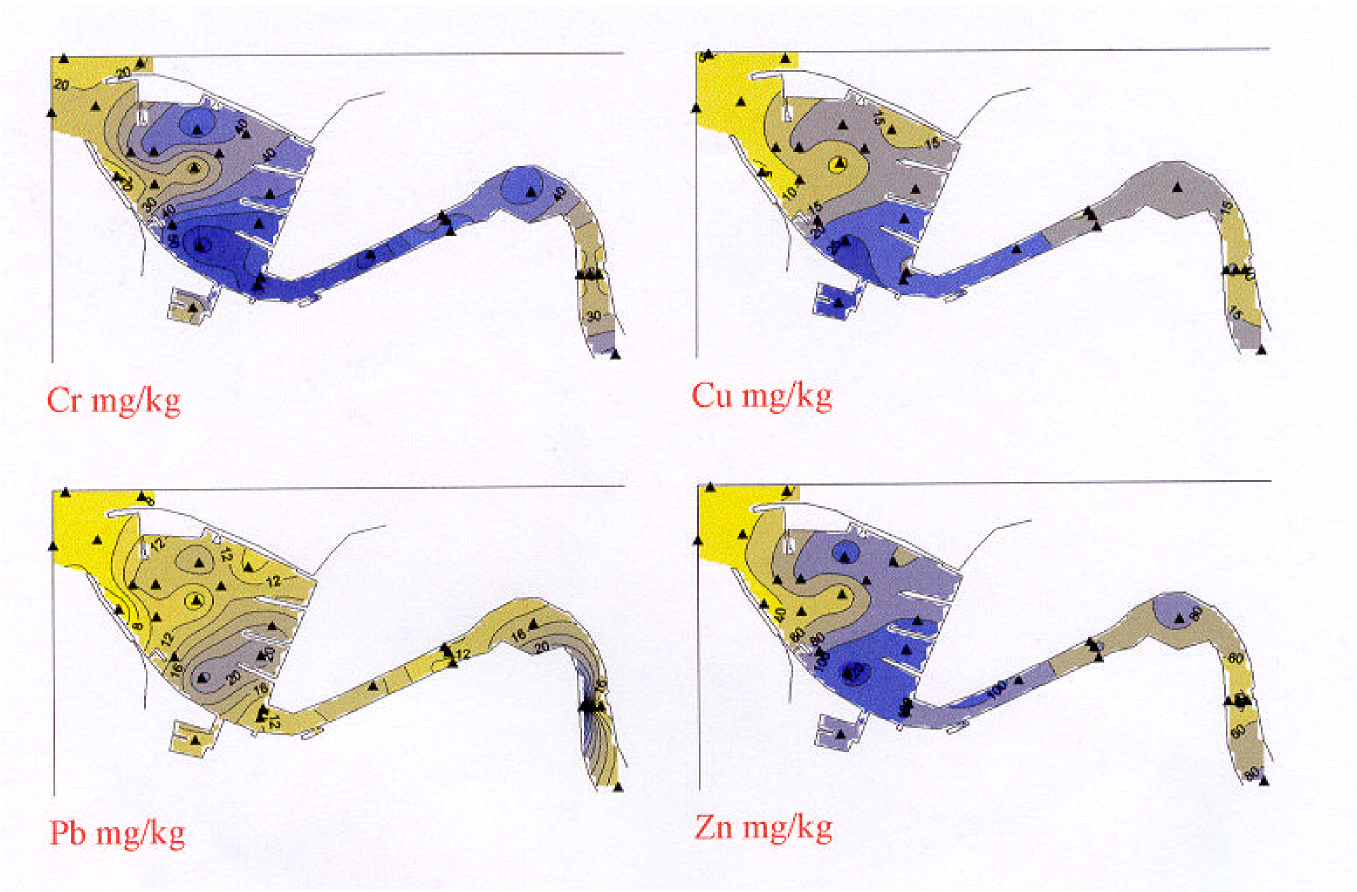


Fig. 38. *Selected trace metal concentrations in the surface layer (0-2cm).*

Metal and organic matter distribution at 10 - 12 cm

Within the limited data set for 10-12cm (12 stations) metal concentrations usually reached their maximum at station V15 at the south-western breakwater, i.e. at the data point closest to the opening of the Venta into the outer harbour (Fig. 39). Concentrations generally decrease towards the sea, but the trend is not as pronounced as that observed in the surface layer. Unlike the surface sediments the lowest concentrations are observed at station V8 rather than at the station closest to the harbour gates (V6). Within the inner harbour parameter concentrations are similar to the neighbouring outer harbour stations. Contrary to the surface layer no pronounced concentration maximum is found in the central shipping channel for the upstream cross-section V31 – V33, but parameter distributions there were almost uniform except for Cr, Cu and Pb that showed increased values at the left river bank (station V33) and Mn at the right river bank (station V31). Distinctly lowered concentration values are observed further downstream at station V22 along the right river bank for Cr, Cu, Fe, Mn, Ni, Pb, Zn, C_{tot} and N_{tot}.

Metal/Al ratios show variable distribution patterns within the outer harbour where differences between normalised parameter values are generally low. Within the inner harbour the high Cr and Cu values along the left river bank (station V33) are considerably smoothed in the normalised distribution.

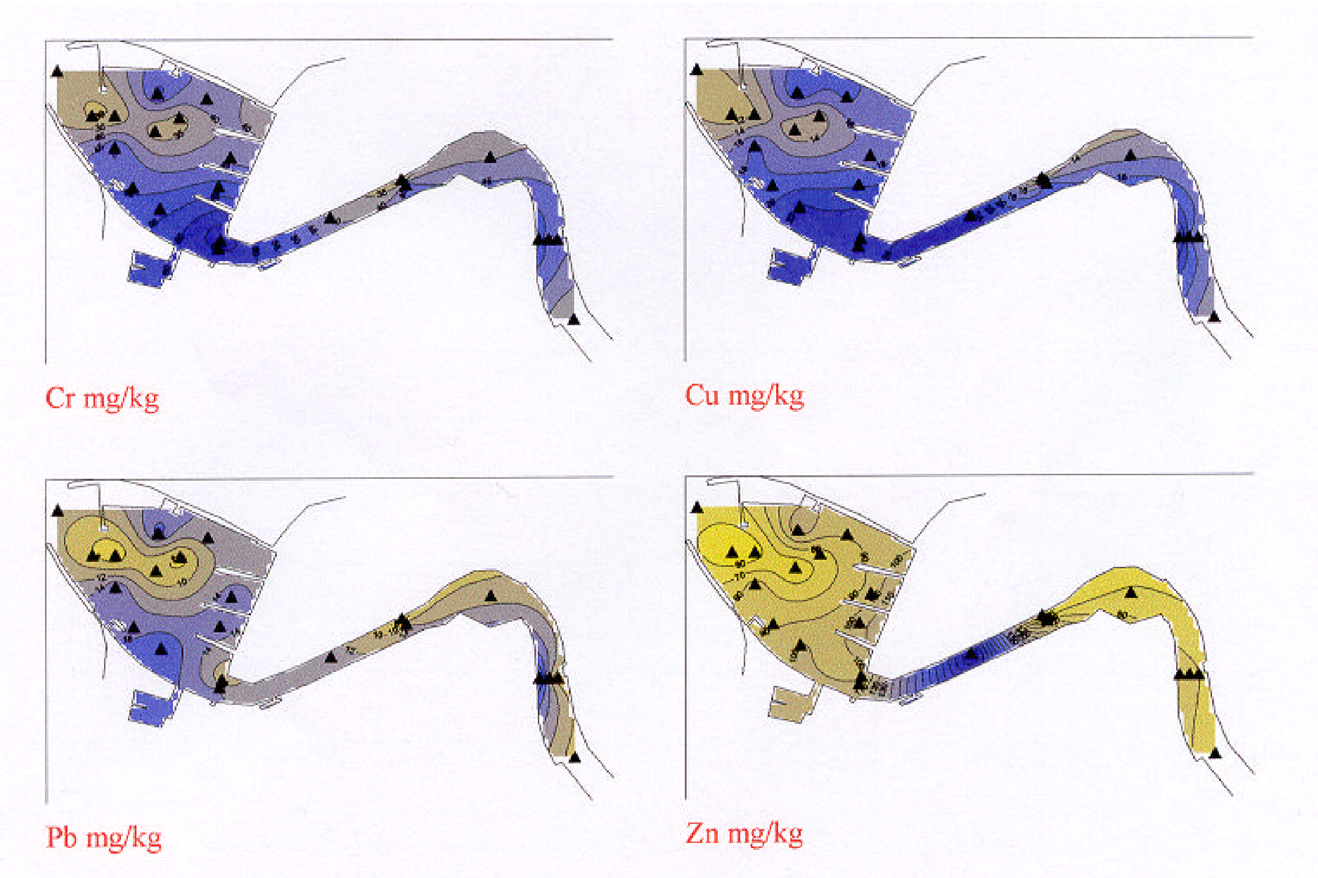


Fig. 39. *Selected trace metal concentrations at a depth of 10-12cm.*

Vertical distribution of metals and organic matter in the sediments

To illustrate the variation in metal and nutrient distribution with depth seven stations were studied in detail. Stations V6 and V9 were chosen since they were characteristic of sediment properties in the seaward part of the outer harbour. V12 and V13 represent the central part of the outer harbour and V14 and V15 were taken near the river mouth (V14 corresponds to the surface concentration maximum and station V15 to the peak concentrations at 10 – 12 cm depth). Station V32 was also studied as it characterised conditions in the upstream part of the inner harbour.

Closest to the sea, stations V6 and V9 show low parameter concentration at the surface and increasing values with depth with the exception of Ni where concentrations remain low. Similar depth profiles are obtained also at station V13, however, organic matter (N_{tot} and C_{tot}) was found to decrease in concentration with depth and Pb levels are similar between the sediment surface and at 2 – 10 cm depth. At station V12 concentrations for most parameters are similar to those noted within the deeper layer of station V9 and generally minimum values were noted at 2 –10 cm. The discontinuous depth profile suggests that sediment properties and sediment genesis are highly variable in the central part of the outer harbour. In station V15 minimum concentrations also occur at 2 –10 cm but overall concentration levels are slightly higher than at station V12. Maximum concentrations at this station are found at 10 – 12 cm for Al, Fe, Mn, Co, Cu, Cr, Ni, and Pb.

V14 is located between station V15 and the mouth of the Venta river and contains the highest metal concentrations at the surface of all the stations. At this site metal concentrations generally decrease slightly with depth except for Co where a slight increase was observed. However, even though station V14 has the highest surface concentrations of all the stations, overall the values are no greater than concentrations noted at 10-12cm depth in stations V9 and V15. When compared to other station regardless of depth high concentrations at V14 were only noted for Cu, Pb, and Zn. Station V32 represents the upstream conditions in the Venta river and the sediments seem to be well mixed with little change noted with depth.

Normalised data was found to again exhibit a lower variability than that in the raw data. The low surface concentrations at stations V6 and V9 appear considerably increased in the normalised data, thus suggesting that the specific metal contamination at the stations close to the harbour gates is similar to that of other sites. For Mn, N_{tot}, Ni, and Pb the smoothing effect of normalisation is rather small, indicating that grain size has only minor effects on the distribution of both metals.

Interrelations between individual parameters

To understand the interrelationships between individual parameters in the Ventspils harbour sediments, the parameters were grouped according to their correlation with aluminium. Aluminium was chosen as a key variable because it is often used as a grain-size indicator. Correlation coefficients with respect to Al that are larger or equal 0.90 were found for Be, Mg, K, Sc, Ti, V, Cr, Fe, Co, Ni, Y, and La. These parameters seem to be highly associated with alumosilicate minerals and grain size possibly has a large influence on their distribution. Na, P, Ca, Mn, Cu, Zn, Sr, Zr, Ba, N_{tot} and C_{tot} on the other hand do not correlate well with Al. Within this group, Sr is highly correlated with Ca (r=0.91), which points to their environmental similarity (van der Loeff and Boudreau, 1997). Highest correlations for Mn are found with respect to Mg (r=0.85). N_{tot} and C_{tot} correlate relatively well with each other (r=0.81) and with P (r=0.76, r=0.78 for N and C respectively). This is in accordance with the composition of natural organic matter that contains C, N and P simultaneously. The correlation with organic matter suggests that a significant portion of P in the Ventspils sediments might be bound to organic matter. Within the heavy metals correlating poorly with Al, highest correlations for Cu are found with Be, V, Cr, Fe and Ni (r=0.80-0.81). Zn distributions are related closest to Mg, Fe, and Cu (r=0.75-0.76). Within this group, Pb has the weakest correlation to other parameters, and the correlation coefficient is larger than 0.75 (r=0.77) only with Cu. The heavy metals that have the weakest association with Al correlate at least partially with each other, suggesting similarities in their occurrence.

pH and redox potential in the Ventspils Harbour sediments

pH values in the Ventspils harbour sediments are neutral ranging from 6.62 to 7.71. Redox potentials in the sediments spanned from –409 to +88 mV. In the majority of samples the redox potential suggested reducing environments. However, the electrode readings were found to fluctuate and thus all measurements could only be taken as approximations.

General Discussion

During 1996 – 1998 the Ventspils harbour area was intensively dredged. However, only at one sampling station (V21 in the Venta mouth) did the chemical analysis indicate (by high Al content and low metal/Al ratios) that underlying glacial clays had been reached. At all other sampling stations the uppermost 10 cm of the sediment seemed to consist of recent fluvial material. Therefore, contaminant concentrations reported do not reflect background glacial till concentrations, but recent sedimentation and sediment redistribution, possibly under anthropogenic influence.

Sediments were highly disturbed in the harbour environment. Since the harbour basin has a maximum depth of approximately 17 m deep, regular resuspension due to shipping can be expected, resulting in sediment mixing. The characteristic pattern of decreasing metal concentrations with depth, reflecting the historic record of anthropogenic metal use, was therefore not found.

Metal concentrations in the Ventspils harbour were generally low and according to Latvian pollution standards, the sediment was classified as "clean" for many parameters. However, anthropogenic contamination signals were obvious in the metal distribution pattern. Metal concentrations did increase from upstream of the harbour towards the industrial area of the inner harbour. This effect was especially apparent for Cu, Ni, Zn, and Pb. Since the depth of the Venta River also increased in this area, the increased concentration could also be due to sedimentation of fine material. However, concentrations normalised to Al were larger in this area, indicating that the higher concentrations were not only due to settling of fine material but also attributable to specifically higher contamination. For some metals, especially for Pb and Zn high variability was noted in the harbour area, which may be related to local (anthropogenic) influences. Finally, Cu, Pb and Zn were not found to correlate with Al, but did show stronger relationships with each other and also with Mg, Fe and Ni. The interrelations between the heavy metals indicate that their distribution was determined by similar influence factors and was only partially due to grainsize effects.

Even though frequent disturbances in the harbour area were obvious from the sediment data, the metal surface distribution mirrored the sedimentation pattern. Highest surface concentrations were found in the outer harbour adjacent to the Venta mouth. The most striking feature in the metal distribution at the sediment surface however was the concentration decrease visible in the centre and seaward part of the outer harbour. Low concentrations in the surface sediments in this area may have been related to increased volumes of marine derived material in the outer harbour.

Contrary to our initial assumptions a comparison of current H-SENSE data with pre-dredging data from 1996 suggested that metal concentrations in the harbour have not changed dramatically since the older sediments have been removed.

Harbour comparisons of metal contamination

To illustrate the degree of possible contamination within Göteborg, Bergen and Ventspils harbour sediments, the trace metal contents were compared.

Table 2. *Metal concentrations in the three investigated harbours (the mean values for Bergen harbour was not calculated due to the extreme variabiltiy).*

Element	Bergen harbour Maximum	Göteborg harbour Mean	Göteborg harbour Maximum	Ventspils harbour Mean	Ventspils harbour Maximum
Cd (mg/kg)	8	<1	1	< 1	< 2
Cr (mg/kg)	187	162	983	41	71
Cu (mg/kg)	1090	60	895	16.2	28.9
Hg (? g/kg)	38000	793	15800	47	65
Ni (mg/kg)	109	28	51	19.7	35
Pb (mg/kg)	1920	72	4610	12.7	44
Zn (mg/kg)	2900	185	1060	80.1	254

Trace metal concentrations in the Ventspils harbour are of similar magnitude to those in the Gulf of Riga or the Kattetat/Belt Sea area for the elements where data is available, with only values for Cr higher in Ventspils than for the Kattegat/Belt Sea (no value available for the Gulf of Riga). Metal sources were found to be anthropogenic in origin but overall levels were not found to be critically high. This is exemplified by a comparison with Latvian national pollution standards (Latvijas republikas vides aizsardzibas komiteja, 1992), that classifies the Ventspils sediments as "clean" with respect to As, Be, Cd, Co, Cr, Cu, Hg, Mg, Ni, Pb, Sb, V, and Zn. For Ba, Fe and Mn the concentrations exceed the limits for the lowest contaminant class, however, the national pollution standards are not based on total metal contents, hence data obtained in this study might overestimate the relevant metal fraction.

Sediments in the Göteborg harbour are more fine-grained, which may partly explain the consistently higher trace metal concentrations than in Ventspils. The main sources of pollution in Göteborg are industry, e.g. chlor alkali industry, which has discharged considerable amounts of Hg, sewage and harbour activities (wharfs and antifouling paints). The threshold values employed by the Harbour Office are frequently exceeded by Hg, but not by the other heavy metals.

Despite the generally coarser grain size spectrum of the sediments in Bergen harbour, trace metal concentrations are highest there if compared with Ventspils and Göteborg harbour. This is mainly attributed to the discharge of raw sewage into the harbour basin "Vågen" until 1999. Other sources are amalgam fillings (Hg), anti-fouling paints (Cu), traffic (Pb and Zn) and photochemistry (Ag).

5.3 Results of Workpackage 3: Modelling and Applications.

The aim of workpackage 3 is to develop a predictive sedimentological model for the management of harbour activities with regard to silting and the evaluation of environmental pollution. Three modelling approaches have been applied to the spatial prediction of clay distribution, harbour bed conditions, Zn pollution and thickness of the recent sediment layer within a single harbour (Göteborg). The relative strengths and weaknesses of the three modelling alternatives are assessed. The Weighted Factors in Linear Combination and the Dempster-Shafer approaches use heuristic judgement (i.e. expert systems) in the prediction whereas the Artificial Neural Network (ANN) approach makes its prediction without using human bias. These models are a first generation development therefore, further steps are required before these tools can be used as a cost effective and justified methodology. One of the best avenues for further development would require a network of sedimentologists, modellers and practitioners.

Although the physical and geochemical characteristics of the sediments can be evaluated separately, the mutual associations and interpreted processes can be more fully evaluated using GIS or ANN modelling. The results from surveys, laboratory analyses, archive data, and other baseline information were compiled in a desktop GIS. The central importance of GIS for producing environmental scenarios is also favourable for planning and remedial-action discussions with non-academic participants, as well as providing the tools for managing dredging activities and for environmental impact assessment, which are the most important objectives of the H-SENSE project.

The object of the modelling was to permit prediction of harbour sediment conditions beyond those locations for which specific information is available. The research within the H-SENSE project has focussed on assessing the applicability of Geographical Information System (GIS) technology, and artificial intelligence to establish a generic framework which could be applied to the low tidal estuaries encountered in the Baltic and elsewhere.

Important to the estimation of a parameter value over an area of interest is the probability or likelihood of a given condition occurring at that point. Decision making needs to take cognisance of the certainty with which the measurements have been made and the parameters identified, and thus a probabilistic approach is suggested as being more appropriate than a deterministic approach. The approaches are based on the concept of belief in each of a range of possible outcomes, described in terms of fuzzy set membership functions. The degree of certainty that pertains to each possible outcome is deduced from the combination of available data, quantified in terms of relative importance and magnitude. The outcome uses fuzzy logic to evaluate the fuzzy set membership values (i.e. possibilities) of data cells based on the concept of transitional changes in class membership across the study area. In decision support, the probability of the influence on the system of a factor supporting the hypothesis is measured but uniquely to Dempster-Shafer and GIS modelling, the probability of the influence on the system of a factor supporting the null-hypothesis is also measured, therefore contradictory data and uncertainty can be incorporated into the model.

Within the H-SENSE project it was found that existing interpolation techniques are often too limited to adequately predict environmental sedimentological conditions over the harbour area. Three new techniques have therefore been developed to assist meeting the H-SENSE objectives, in particular those concerning decision support. These are: (1) Weighted factors in Linear Combination, (2) Artificial Neural Networks, and (3) Dempster-Shafer Weights-of-

Evidence. More than one modelling approach has been deemed necessary for examining the harbour systems, in particular so that the feasibility of each approach could be evaluated.

Modelling Results

Within Göteborg several questions were examined, as the dataset contained many lines of evidence that could incorporate several linked hypotheses, to see which factor in the system was relatively more important than another. The hypotheses examined are outlined below:

1. Depth of the recent sediment layer is determined by harbour bathymmetry and harbour activities
2. Distribution of 'key' geochemical elements is dependent on point source pollution, harbour bathymetry, sedimentology and harbour activities

Fuzzy set theory and three modelling techniques have been applied to the problem of sediment accumulation and pollution (of which Zn was modelled as an indicator element) and their value as an aid to decision support has been evaluated. To be of value to a harbour manager it is a necessary function of the model to display the results in a manner that can be easily interpreted. In all cases a cartographic image was produced with the prediction of areas exceeding a threshold noted using colour. These models were used to predict where recent sediments exceeded 40 cm thickness or when zinc concentration exceeded 200 ppm.

Fuzzy set theory

The probability of a sediment being contaminated was predicted using fuzzy set theory. Rather than just using the state guidelines for contamination threshold (Table 3) uncertainty caused by measurement error was incorporated using fuzzy sets. As the measurement error for each element was calculated to one standard deviation, these figures were multiplied by three in order that a 99% certainty in the predicted results could be achieved. As it is possible that the true value at a sampled point could be three times higher or lower than the measured value, the fuzzy set theory used the assumption that any value lower than the threshold value minus three times the measurement error was definitely uncontaminated. Conversely, any value higher than the threshold value plus three times the measurement error was considered definitely contaminated. A sigmoidal shaped curve was used to determine the probability that a value in between these two end points was contaminated.

Table 3. *Membership of contaminated sediments at 0-2 cm depth in Göteborg Harbour.*

Element	Range of values found (ppm)	Threshold level (ppm)	Measurement error (%)	Membership class 0	Membership class 1
As	0.0-52.0	100	74	0	322
Cd	0.0-2.0	1	59	0	178
Co	3.0-33.5	150	2	141	159
Cr	13.0-938.0	200	10	140	260
Cu	4.7-895.0	100	5	85	115
Fe	12,000-48,000	400,000	3	364,000	463,000
Hg	0.04-2.32	1	20	0.4	1.6
Ni	8-108.5	150	5	127.5	172.5
Pb	10.0-4610.0	100	14	58	142
Zn	19.9-1060.0	750	6	615	885

In the 110 sampled points, recent sediment thickness ranged from 1 cm to 58 cm and the zinc concentration ranged from 52.2 to 1060 ppm. Fuzzy sets were used to identify points where the threshold value was likely to be crossed, allowing for measurement error, and are given in the following figures. Those points with a dark colour certainly exceed the threshold value, points with a lighter colour are within the measurement error and are thus likely to exceed the threshold.

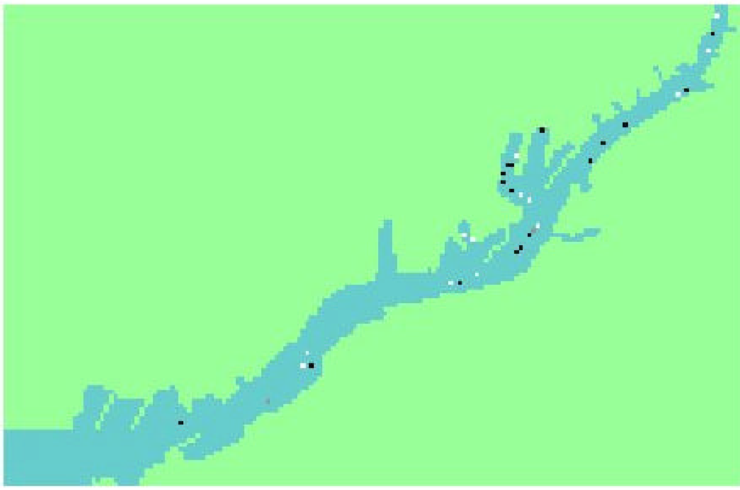


Fig. 40. *Locations in Göteborg Harbour where the recent sediment thickness layer is likely to exceed 40 cm using fuzzy set theory.*

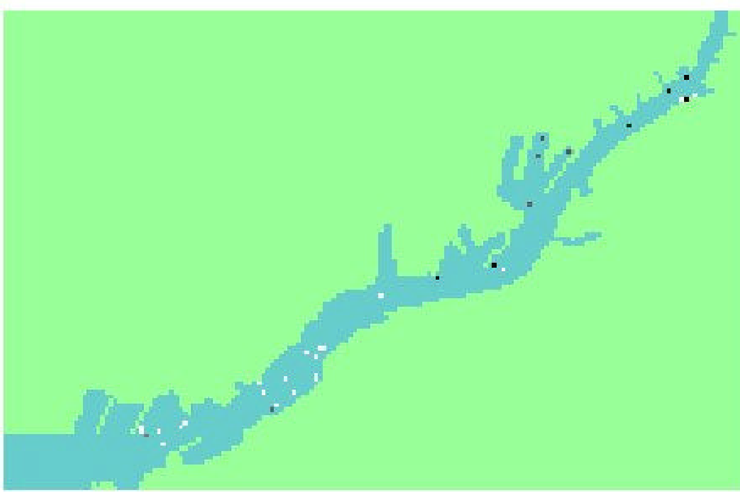


Fig. 41. *Locations in Göteborg Harbour where the zinc concentration is likely to exceed 200 ppm using fuzzy set theory.*

Weighted Factors in Linear Combination

The Weighted Factors in Linear Combination model was the most simple approach used for modelling in H-SENSE. This approach is essentially concerned with integrating the evidence provided by each factor which is believed to indicate a site as having a high sediment thickness layer or a high zinc concentration. These parameters are then combined using a weighting factor based on multi-criteria evaluation. The calculation of the factor weighting coefficients was achieved by group discussion by creating a pairwise comparison matrix (completed examples are given below) in which each factor's importance is evaluated relative to every other factor with respect to determining the likelihood of the threshold value being crossed.

distance from harbour wall	(1/3)	(1/3)	(1/3)	(1/3)	(1/5)	3
3	distance from river	(1/5)	1	(1/3)	(1/5)	1
3	5	distance from shipping lanes	5	3	1	3
3	1	(1/5)	water depth	(1/3)	(1/3)	3
3	3	(1/3)	3	distance from turbidity maxima	(1/3)	3
5	5	1	3	3	harbour activities	5
(1/3)	1	(1/3)	(1/3)	(1/3)	(1/5)	bottom roughness

Pairwise comparison matrix for sediment thickness

distance from harbour wall	(1/5)	(1/3)	1	(1/3)	(1/7)	(1/7)	(1/5)	(1/3)
5	distance from river	1	1	3	(1/5)	(1/3)	(1/3)	(1/3)
3	1	distance from shipping lanes	3	3	(1/7)	(1/5)	(1/3)	(1/3)
1	1	(1/3)	water depth	1	(1/5)	(1/7)	(1/5)	(1/3)
3	(1/3)	(1/3)	1	distance from turbidity maxima	(1/5)	(1/7)	(1/5)	(1/3)
7	5	7	5	5	distance from point source	3	3	1
7	3	5	7	7	(1/3)	clay content	3	5
5	3	3	5	5	(1/3)	(1/3)	TOC content	5
3	3	3	3	3	1	(1/5)	(1/5)	CaCo3 content
1	(1/3)	1	(1/3)	1	(1/5)	(1/3)	(1/5)	1
3	1	1	1	1	(1/7)	(1/7)	(1/5)	(1/3)

Pairwise comparison matrix for Zn concentration

The disadvantage with the weighted factors in linear combination approach is that negative measures of likelihood cannot be incorporated. This approach has given the following map outputs with the darker the colour the increasing likelihood that the threshold will be crossed.

Fig. 42. *Likelihood of sediment thickness layer exceeding 40 cm based on the Weighted Factors in Linear Combination approach.*

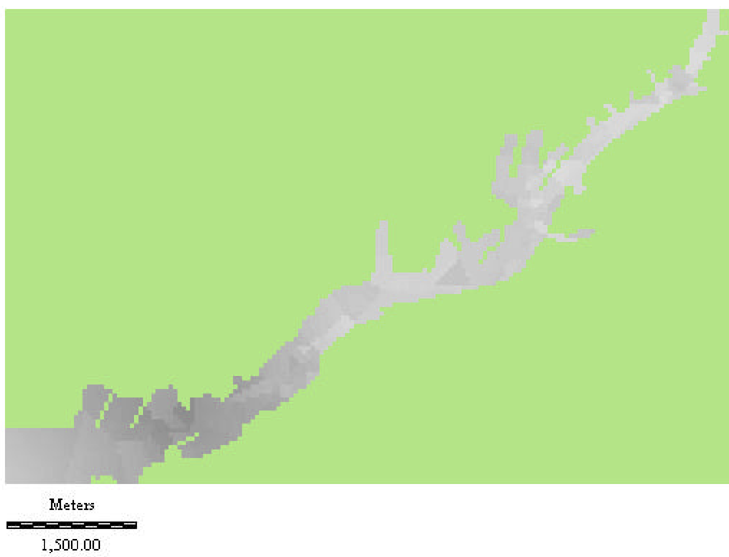


Fig. 43. *Likelihood of zinc concentration exceeding 200 ppm based on the Weighted Factors in Linear Combination approach.*

ANN

In contrast to Weights in Linear Combination, the ANN modelling approach used the actual zinc concentrations and sediment thickness at the sampled locations to formulate the prediction. A variety of ANN training schemes have been tried in order to achieve satisfactory results, which are represented by the convergence to imposed errors in a reasonable training timeframe. This also provides valuable help to the understanding of the influence of different hidden layers, number of nodes in hidden layer(s), imposed error criteria, and training method (either standard and dynamic) on convergence, training time, and prediction results.

With the iterating training, it appears that satisfactory results can be achieved using an ANN model with only one hidden layer for the prediction of Zinc distribution. However, the ANN model for the prediction of sediment thickness had not converged to a reasonable error even though training steps exceeded one million. Thus, a more complex model, with two hidden layers was employed.

Fig. 44. *Areas where there is a high probability of the sediment thickness layer exceeding 40 cm based on the ANN approach.*

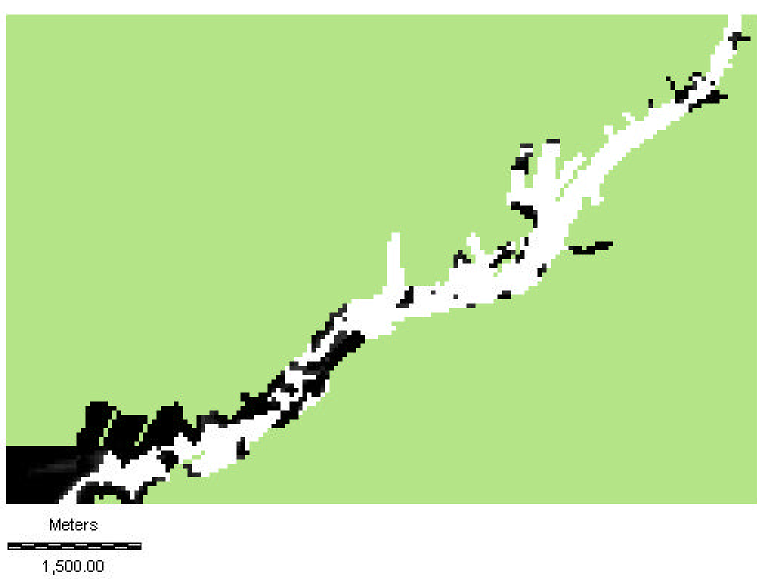


Fig. 45. *Areas where there is a high probability of the zinc concentration exceeding 200ppm based on the ANN approach.*

The ANN model was trained using the most complete training set available but it was recognised that lessening the number of factors required would reduce the costs to harbour management. The impact of such a reduction has been investigated using hierarchical analysis based on the relative strength of effect of input parameters as revealed by the previous ANN modelling results.

In the Zn prediction, it was found that if the factor with the least weight was removed (distance from the most intense harbour activity) there was no significant reduction in the quality of the prediction. This was repeated removing a second factor (distance from the turbidity maxima) and a third (depth of the recent sediment layer) with again no significant reduction in quality. The prediction of sediment thickness was initially based on eight input parameters, however when the factor with the least weight was removed (water depth) the training error failed to converge to a reasonable level. Therefore in this case it was found that all eight factors have to be included for the ANN prediction.

Dempster-Shafer Weights-of-Evidence

In the Dempster-Shafer approach it was necessary to obtain a prediction of sediment thickness and the zinc concentration based on only seven parameters due to the memory limitations of the Idrisi GIS. The following parameters were chosen prior to the model calculation:

Sediment thickness	**Zinc concentration**
Distance from land	Distance from shipping lanes
Distance from shipping lanes	Distance from river source
Distance from turbidity maxima	Distance from point sources
Distance from river source	Distance from intense harbour activity
Water depth	Recent sediment thickness
Clay content	TOC content
Distance from intense harbour activity	$CaCO_3$ content

For each line of evidence entered, Basic Probability Assignment images (in the form of *Real* number *Binary* images with the range 0 to 1) were calculated to indicate the support of each for the selected hypothesis.

However, a Basic Probability Assignment using the full range 0.0 to 1.0 was not considered to be reasonable for the hypotheses as there was no room for ignorance, i.e. a value "0.0" means that all the sediments in the area of interest are certainly below the threshold level, and that a value of "1.0" means that all the sediments in the area of interest are certainly above the threshold level. This placed a very high dependency on the judgement regarding the zinc and sediment distribution dependent on harbour morphology and ship traffic. However, a somewhat less firm indication of zinc and sediment distribution with relation to harbour morphology and ship traffic was found to be more likely to be appropriate. For each parameter fuzzy set memberships were calculated to determine the probability, at different values, of the threshold being exceeded.

None of these pieces of evidence on their own can define the site as having a thick recent sediment layer or a high zinc content. However, where favourable values occur in combination, and where the values are known, they can be used to give stronger support to the hypothesis that the site exceeds the threshold value than when the factors are used individually.

The Dempster-Shafer approach produces three outputs *Belief* image presented deals with the degree of hard evidence, and represents the total support for the hypothesis. This approach is also able to compute the 'plausibility', which indicates the degree to which the conditions appear to be right, and represents the degree to which a hypothesis cannot be disbelieved and the 'belief interval', which represents the degree of uncertainty. Areas with higher Belief Interval are those where new evidence will supply the greatest degree of information.

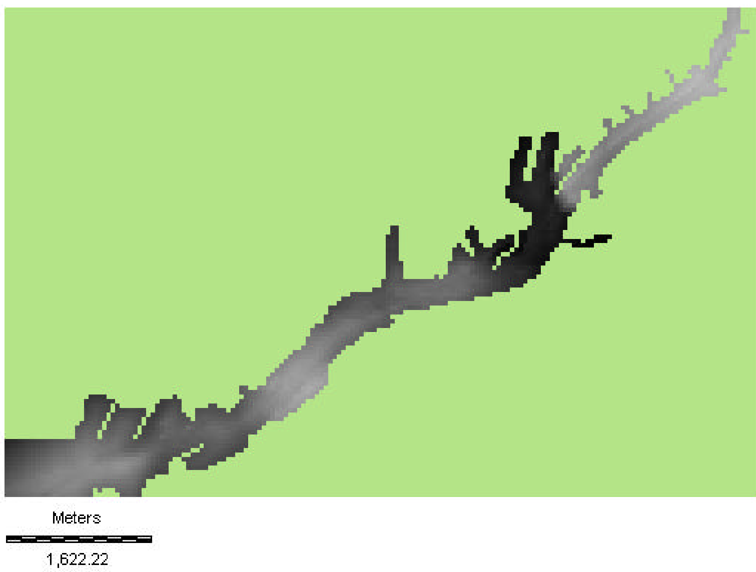


Fig. 46. *Belief Image in support of a high probability that the sediment thickness layer exceeds 40 cm based on the Dempster-Shafer approach.*

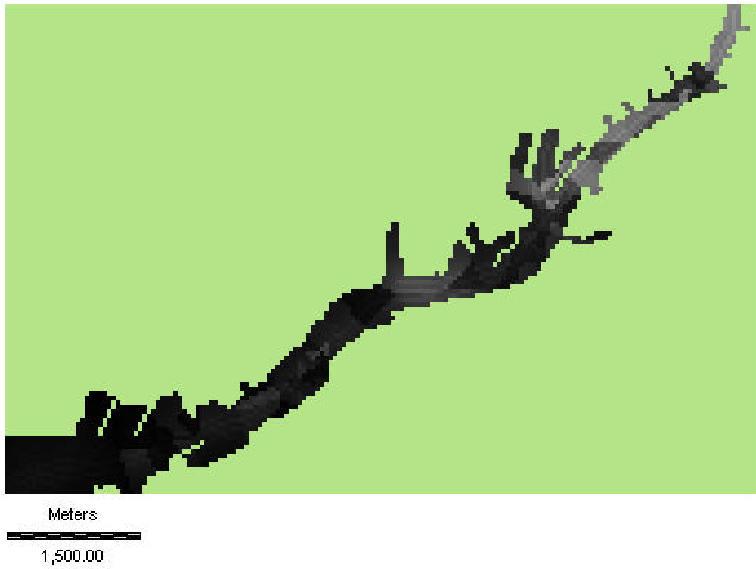


Fig. 47. *A Belief Image in support of a high probability that the zinc concentration exceeds 200 ppm based on the Dempster-Shafer approach.*

Discussion

A comparison of the model predictions with the actual values has noted that none of the model outputs fitted the raw data completely. The Weights in Linear Combination model failed to show any areas where recent sediment thickness has exceeded 40cm. The ANN model prediction was good in most areas, but would be difficult to interpret for decision support. The ANN model did not predict the high sediment thickness that would be expected south of the Frihamnen but in most other areas the prediction was good. In the upper reaches of the river only shallow sediments would be expected, which would also be the case at the harbour widening and in the most widely used part of the shipping lane south of the high sedimentation that would be expected in the Frihamnen area. The map also indicated a high sedimentation area just north of the harbour widening which matched the trends noted in the sampling. The Dempster-Shafer model proved to have the most potential for decision-support as it correctly identified low sedimentation rates in the upper reaches, the high expected in the Frihamnen area followed by the low in the shipping channel. The high sedimentation to the north of the harbour widening also corresponds to the actual patterns noted in the field. The prediction of high sediment rates that would be of use to a harbour manager would be the next step in the modelling process and would require detailed information on dredging volumes and sediment transport dynamics.

The Weights in Linear Combination prediction of zinc concentrations exceeding 200 ppm did identify the Rya Verken area in the south-west of the study area where a waste water treatment plant is located but failed to show any other areas as possibly contaminated. The ANN model prediction was more successful and was generally very good except for a high concentration not identified in the Frihamnen area. The ANN model also showed a trend of higher concentrations along the harbour walls rather than in the centre of the channel which also matched the ground truthing. The ANN model did correctly identify areas where low concentrations would be expected (apart from the Frihamnen) and does have potential as a decision support tool. The Dempster-Shafer model was successful in the northern reaches of the study area and picked up the high concentrations expected in the Frihamnen area not identified by the other models. This model did over exaggerate the extent of the high concentrations in the central and south-west area but has still produced a prediction that would be of value to a harbour manager.

Uncertainty within a prediction regardless of the approach used would be expected, as the complex processes (and process combinations) within a harbour environment are not totally understood. Hence, the model interactions are still quite speculative with refinements needed as our knowledge of the system improves.

All the modelling approaches have used the same database to make the predictions and any further refinements will require either the addition of new parameters that have not yet been considered or a greater understanding of the processes that occur within the harbour environment. In order to apply these techniques outside of the area for which they were developed more information is required from harbours with different environmental controls.

The modelling approaches applied to Göteborg Harbour have provided a step forward in the development of tools to aid decision support. The Göteborg dataset from which a prediction is to be made was found to be complex. However, unlike using standard statistical methods, the Weighted Factors in Linear Combination approach and the Dempster-Shafer approach have the added value of being able to use negative arguments and also inputs that previously were seen as unusable as they are not numerical data (using fuzzy logic). All the models have been able to calculate multi parameter relationships previously not recognised by standard statistical tests. As a result of the H-SENSE project we have been able to improve connections between modelling and sedimentology.

Future developments

The approach envisaged for future development would be the creation of sediment distribution maps, incorporating grain size, mineralogy and geochemical characteristics, which, together with mass transport ratings, would enable calculation of hazard maps. Exposure can be used to develop vulnerability images from which a risk assessment can be developed. Incorporation of errors in data and uncertainties in boundary conditions would enable prioritisation of assessment criteria.

It would be feasible, as a computer software programming exercise, to write a shell incorporating the GIS with the ANN under one environment, but this would require an additional investment in staff time resource beyond the scope of the current programme.

Volume flux calculations would be a new technique to GIS modelling requiring data on sediment source, volume, transport route, deposition and timeframe. For each pixel in the harbour an algorithm would be required to show the input, storage and output of sediment over time. The resultant GIS images could then be run in sequence to demonstrate the volume of sediment transported over the harbour areas and the main areas of storage over the timeframe of interest. This calculation would be of interest to harbour managers especially with regard to determining the best practise of dredging. It was not possible within the time and resource constraints of this project to determine volume flux calculations for a complex natural harbour system.

Although models are powerful tools for harbour management, integrating various components such as site characteristics and exposure assessment, they are nevertheless abstract representations of complex systems and, of necessity, are based on numerous assumptions and approximations. In any case, the quality of prediction which a model enables can be no better than the quality of the data on which it is based.

Models such as the three developed within the H-SENSE project need to be validated and tested in real-world situations, either as part of a risk assessment or within a research project.

The meaning of the absolute values obtained from application of a model is not known, and future research would usefully address this issue by linking with the exposure assessment procedures and field evaluation trials. Field testing and validation of models raises questions concerning the precision and bias of model predictions. Indeed, it is not known whether accurate estimates should be expected from an overall assessment in view of the many uncertainties associated with site characterisation, exposure assessment and the basis for examining the effects of pollutant uptake by humans or organisms. This in turn relates to the issues of risk perception and communication.

The way forward may well lie with the training of those concerned with harbour management (risk assessors and decision makers). Providing a grasp of the scientific basis for system response could provide the key, highlighting the means of establishing influential parameters and identifying the values at which action is required. The end objective is to evolve a defendable decision with recognisable limitations.

6. Applications of project results

End-User, Scientific and Multi-Functional Perspectives

Dealing with siltation and sediment contamination problems can be addressed by extensive monitoring, essentially attempting to measure the parameters involved in each question for each site and occasion. The other extreme is to theoretically predict the effects of the physical and geochemical processes involved. Both approaches are obviously limited by their actual feasibility as well as economic restrictions. The hypothesis below is that an optimal balance between experimental control and site relevance will combine the predictive value of process studies with the necessary confirmation documented by monitoring, i.e. site-specific measurements (Fig. 48). In addition to being cost effective, the use of modelling to combine process evaluation and monitoring is necessary for safeguarding the environment, where a single investigation cannot measure the response of the system to future changes or when threshold conditions are exceeded. A site-specific, engineering approach to river and harbour management would tend to address the individual problems associated with each activity or structure. The danger in this approach is apparent when processes are interrelated and the system response is less predictable than can be expressed by simple relationships.

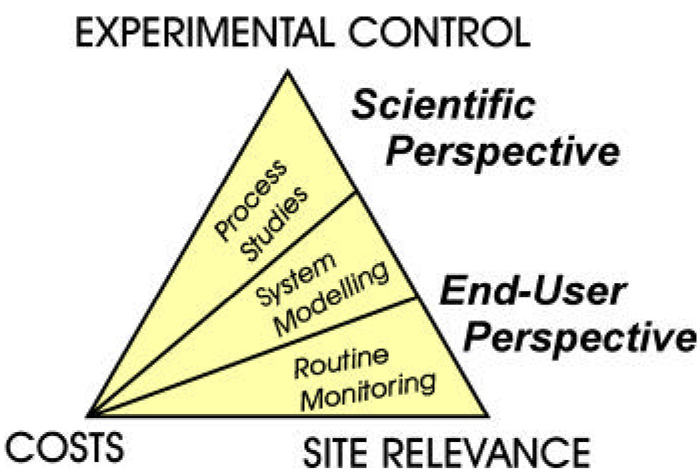


Fig. 48. *The combination of processes studies, modelling, and routine monitoring must be balanced by cost considerations, where none of these individual activities are economically optimal nor environmentally responsible (Newson 1992).*

"Experimental control" refers broadly to all scientific evaluation. In the case of large-scale natural systems this often involves the comparison of the influences and effects of processes recorded in similar environments or changes recorded over time within one setting. In this respect, sediment investigations have a major advantage over many other types of environmental monitoring in that sediment accumulation represents a time-integrated, net effect of environmental processes. Sediment sources, transport pathways and accumulation rates are possible to estimate using water-current measurements, data from sediment traps or tracer studies. However, all of these methods are time-limited and generally become less accurate as the intensity of the processes involved increases, such as during storms or intensive ship traffic, perhaps the most decisive time for their total influence upon the environment. Therefore, a natural filtering of the temporary changes and a record of the summed effects over yearly or longer cycles is a complement to short-term measurements. The value of sedimentological studies is further connected to the strong relationship that normally exists between particle size, organic-matter content and geochemical reactivity, including the level of heavy metals and organic contaminants (Olausson 1975; Salomons et al. 1988). Since natural processes operate at different scales and magnitudes, in both time and space, and interact with man's utilisation of this environment, it is imperative to recognise those factors that can be manipulated and those which can not. The prediction of siltation and the evaluation of pollution risks are essential tasks within harbour sustainability.

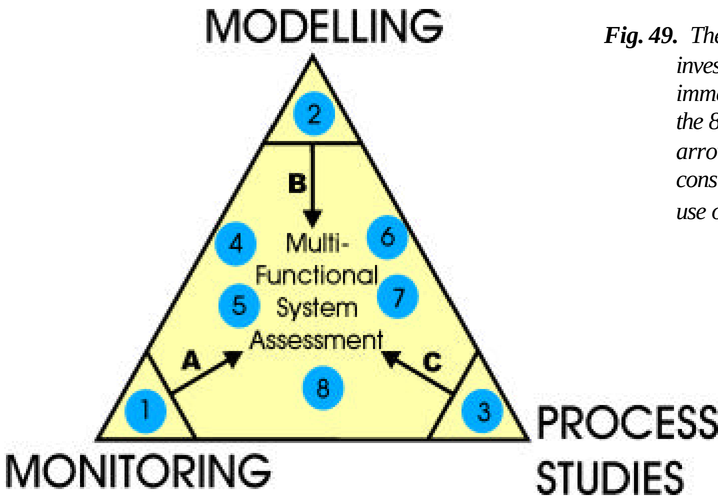


Fig. 49. *The priorities within a harbour investigation are usually related to immediate goals, as illustrated by the 8 examples explained below. The arrows (A-C) indicate motivating considerations for a more balanced use of activities.*

	End-User Objectives (illustrating typical input combinations)
1	Harbour sediment testing prior to dredging.
2	Modelling with archive data or with theoretical principles when no data are available.
3	Sedimentological studies of a siltation or geochemistry at a specific site.
4	Harbour study regarding expansion or other construction changes.
5	Environmental Impact Assessment regarding siltation or pollution conditions.
6	Geological or hydrological evaluation of an environment of sedimentation.
7	Theoretical extension of sedimentation conditions interpreted from selected sites.
8	"Ground-truth" testing of a process interpretation.
	Motivating Criteria for Multi-Functional Assessment
A	Need for greater predictive capacity, both spatially and over time.
B	Need for greater data control and basis in theory.
C	Need for greater applicability with changed conditions.

In Fig. 48, the approach to evaluation termed routine monitoring can also, to a certain extent, be considered to represent the perspectives of end-users, whereas process studies correspond largely to the scientific perspective and approach to environmental analysis. One of the most central premises for the H-SENSE project has been the appreciation that the combination of these perspectives would lead to the most complete evaluation basis and would be most cost effective in long-term harbour and environmental management. The combined perspective will be interdisciplinary and multi-functional if fully developed. At the same time, it is obvious that many investigations are developed with specific, necessary priorities (Fig. 49). To represent end-user perspectives our own experience was augmented by the ideas and responses to direct questions that we could solicit from associates outside of the H-SENSE partnership.

Table 4. *Selected H-SENSE results and recommendations.*

Sediment Parameters	**End-user Perspective**	**Scientific Perspective**	**Multi-Functional Perspective**
Grain size	Generally recognised as important, but still avoided to save costs or assumed to be consistent within environment. Some analyses should always be included.	An essential parameter for sedimentological evaluations. Always required for specific interpretations. Important for normalisation and sample comparisons.	Proxies (e.g. Al, Sc, Li, quartz/feldspar ratios) may be used once relationships are established. Smear-slide estimations possible.
Organic matter content	Similar arguments as grain size, above. Loss on Ignition is only approximate, but OK following site-specific calibration.	Major influence upon redox conditions. Strong correlation with contaminants.	OM is an essential link between biological, sedimentological and geochemical evaluations. See also geochemistry, below.
Component-specific geochemistry	Relatively expensive and requires expertise for evaluation. Metal speciation usually not included in routine surveys.	Metal speciation and organic specification is necessary for evaluating chemical process affecting contaminants.	The specification of chemical components helps interrelate bacterial degradation, contaminant mobility and other sedimentary conditions.
Visual and digital sedimentological documentation	Easily included in routine monitoring, but requires some technical training.	Simple descriptions would have great future value. See also Bottom Sediment Classification, below.	Digital photo documentation is a good complement or replacement for descriptions.
Methods			
Box-coring and digital imagery	Inexpensive. Allows extensive sampling of specific levels. Surface disturbance can limit use.	Records valuable information for future, unknown purposes. See also Bottom Surface Class.	Documentation of multidisciplinary features feasible for non-specialists.
Smear slides and sediment archives	Requires very little space and training. Time-related changes are recorded. Complement lab analyses.	Sediment composition and grain size can later be estimated and evaluated by specialists.	Future techniques may likely increase the value of small sample archives.
Digital particle-size analysis & storage	Costly instrumentation, but increasingly automated routines may increase feasibility in near future.	Complete size distributions will allow data to accommodate theory development.	Greatest flexibility for different users is provided by primary data.
Evaluation Techniques			
Bottom Surface Classification	Comprehensive archive function without strict technical requirements.	Allows scientific evaluation much later than site survey documentation.	Stresses the integration of physical, geochemical and biological factors.
Mineralogical source budgeting	Requires expertise, but sediment archives allow future analyses (see above).	A traditional geological analysis that offers good quantitative potential.	Source budgets seldom feasible with other, less conservative parameters.
Grain-size interpretations of transport	Requires expertise, but provides information of an important net effect.	Good connection between process interpretations and monitoring databases.	Provides a basic description of net transport conditions.
Multi-parameter normalisation	Primary sedimentological data allow later choice of appropriate parameters.	Site-specific associations accounted for, allowing interpretative conclusions.	Combines physical and geochemical and, in some cases, biological observations.
Modelling Approaches			
Weighted factors in linear combination	Inexpensive and not data intensive but requires expertise of the system. Produces a suitability map so enabling decision support.	Heuristic approach. Allows a low measure of likelihood from one factor to be compensated for by high measures of likelihood from other factors, the degree dependent upon the weighting coefficient.	Can identify which parameters are affected by the system, cause change to the system and also their significance. The generic model structures are not limited to the area in which they were developed. Spatial models can be used to identify geological resources, evaluation of hazards, environmental impact, spatial interrelationships and site selection studies.
Artificial Neural Networks	New approach currently under development. Very data intensive but human bias in the evaluation is removed. Produces a suitability map so enabling decision support.	Didactic approach. Can investigate non-linear behaviour. Establishes interactions between parameters and their importance by using weighting coefficients derived.	
Dempster-Schafer Weights-of-evidence	Not data intensive but requires human expertise of the system. Produces a suitability map so enabling decision support. This approach produced the most accurate prediction of the three modelling techniques.	Heuristic approach. Establishes the likelihood of the combined criteria defining a site as suitable or unsuitable together with a measurable degree of plausibility. Can help overcome limitations imposed by uncertain decision rules and by evidence.	

The need for time efficiency, quantitatively specified parameters and total costs and responsibility are perhaps the most important criteria for a harbour manager. To obtain useful data, the methods that are employed in a sedimentological survey have to be adapted to the aims of the assessment, to the harbour setting and to any anticipated future requirements. At each stage of the survey, from planning the sampling scheme, to conducting the sampling procedure, analyses, interpretation through to dissemination, methods should be optimised and standardised as much as possible. The choice of routine procedures needs to be based on detailed surveys that allow the estimation of variability in sediment parameters. Specialised studies will also have the objective to identify processes that are important in the particular environment, e.g. re-suspension at the sediment surface. Based on such reconnaissance studies, a simplified sampling scheme and the use of proxies for sediment characteristics may be justified, and new aspects may be accounted for in the documentation procedure.

In the following, recommendations will be given for bottom and sub-bottom surveys, sediment sampling, sediment sub-sampling, routine analyses, geochemical normalisation procedures, and data dissemination tools, as well as summaries of relevant H-SENSE results. Besides taking up general aspects, the topics will be discussed on the background of the sediment surveys conducted in Bergen, Göteborg and Ventspils during the H-SENSE project. All three harbours are situated in a micro-tidal environment, but differ in other aspects such as hydrology and history. Therefore, the harbour settings are briefly described in Appendix A.

Parameter selection, methods for documentation, database construction and the application goals are first discussed and motivated in terms of their monitoring and immediate value for sediment characterisation. The inclusion of scientific goals is also considered, stressing the possible combination with routine procedures within a necessarily limited, cost framework. The goals of both these perspectives can also be integrated through modelling activities, which can also assist co-operation and understanding between scientific disciplines and between end-users with different goals. Most of our recommendations can be related to the three perspectives discussed above: Scientific, End-User and Multi-Functional. A summary of some of the principle results and recommendations (Table 4) illustrates the advantages gained by simultaneously considering the added value from more than one target group.

Normalisation

The relationship between sedimentary components and geochemistry can be complex in harbour environments (e.g. Göteborg Harbour, Engström and Stevens, 1999; Port of Rotterdam, Krijgsman, 1996). It is important to establish these relationships before choosing one or several parameters for normalisation. Detailed investigations of sediment character including metal speciation in complement to total metal contents are of great importance when establishing relationships between sedimentary components and geochemistry. Once the relationships are established, proxies (e.g. formulas including element specific constants and total contents and grain size and organic content) for metal speciation can be used instead of real values. Total contents, grain size and organic content should be monitored on a routine basis in harbours and are valuable indicators of changes in the environmental conditions. The relationships between sedimentary components and geochemistry are not constant as environmental conditions change with time. To compensate for this, it is advisory to conduct regular, detailed investigations, for example every ten years, to confirm or establish new relationships and routine analysis in the years between.

Classification of contaminated sediment using total contents of contaminants and threshold values is not enough for determining the effect on the environment. The total content should be complemented with investigations of how the metals are bound to the sediment (speciation) and how toxic the sediment is to biota (sediment bioassays).

Normalisation of geochemical data aims to facilitate the comparison between samples with different particle size, organic content or other inherited features. Variations in organic matter, particle size and clay mineralogy can cause the natural sedimentary metal loads to vary by several orders of magnitude (Cauwet 1987; Buckley & Cranston 1991).

The interdependence between sedimentary parameters influences the geochemical variability and might overshadow the trends related to environmental conditions, such as specific anthropogenic sources of contamination. After compensating for the natural geochemical variations anthropogenic contributions to the sediment can be more clearly distinguished and mapped (Loring, 1991).

Particle size, organic content and clay mineralogy are closely related within many environments and one component is commonly chosen for single-parameter normalisation (Loring 1991). Geochemical proxies for clay mineral content (e.g. Al, Fe, Sc, or Li) are especially popular since they are readily determined along within total-sediment element scans. However, Al is associated with both feldspars and clay minerals, limiting its use for normalisation when significant amounts of feldspar occur, e.g. in former glaciated regions (e.g. Boström et al. 1978). Fe and Sc can be involved in diagenetic changes, especially in near-shore areas (Buckley & Cranston 1991). Li is a lattice component of the trace-metal bearing clay minerals that is not associated with feldspars and has proven to be more useful than Al for normalisation in feldspar-rich sediments (Loring 1991). If one of these normalisers has a strong correlation to the metal contents it may be used for normalisation.

Harbours are complex environments where several transport and depositional processes occur simultaneously that may result in irregular compositional relationships that require an evaluation of the interrelations between the elements and other lithological and geochemical features in the sediment in order to select the best normalisation procedure (Boust et al. 1981). Statistical analysis like Pearson correlation and factor analysis can be used to reveal associations between geochemical elements and sedimentary components.

This has been done in Göteborg Harbour and the results revealed that there were several sediment parameters of importance for the variation in geochemical elements in the surface sediments (particle size, organic content and carbonate content; Engström and Stevens, 1999). This implies that more than one parameter should be used for normalisation and a multi-parameter technique has been suggested (Engström and Stevens, 1999). The use of several sedimentary components have been recognised in other harbours as well for example the Port of Rotterdam, where both grain size and organic content are accounted for during standardisation (Krijgsman, 1996).

Once the element-specific constants have been established for an area, total metal values can be used with the established normalisation formula to identify geographic (or vertical) trends in contamination or other sediment-related features. It is of importance however, to also consider the trends in non-normalised as well as normalised data, for example when determining sources. Normalisation can be very useful in producing trends, but if it is used indiscrimanently the trends will not represent actual conditions.

Classification of contaminated sediment

Environmental problems are intimately connected to harbours, where many of society's products are transported, stored and used. The risk for both catastrophic and diffuse discharges of contaminants in harbours is well known. Less well known, but nevertheless very important is the release of contaminants from the sediments, where they previously had been accumulated. Ship traffic, dredging and variations in currents can through turbulence cause a mobilisation and/or a transformation of contaminants in different phases. In particular, metals bound to sulphides can be released (through oxidation) and organic material can be broken down, also resulting in release of metals bound to it. An understanding of how the harbour environment works physically (natural and anthropogenic processes influence transport and depositional conditions for sediment) and chemically (e.g. associations of metals and sedimentary components, toxicity of sediment) is of great importance for the establishing of a classification system that is related to reality and will increase cost-effective handling of contaminated sediments.

The present classification of contaminated sediment in Sweden is done by using the total element content compared to national threshold values recommended by the Swedish EPA (Naturvårdsverket 1985; 1999). These background values do not take into account the site-specific mineralogical character, the particle size, or organic content of the sediment. All these factors are important for the mobility of the elements and the effect on the surrounding biota and environment. Total element contents can never answer questions regarding element mobility within the sediment and water column and then subsequent availability for the biota under different conditions. The relationships between metal concentrations, element speciation and the environmental effect of the sediments (toxicity) are important to include in future classifications of contaminated sediments.

Results from the H-Sense project and also earlier investigations of the sediment from the Göteborg Harbour reveal that several elements such as lead, zinc, copper, and mercury, have values above the national back ground levels. However, the values do not reach the current contaminated sediment threshold of ten times the background value which would require them to be disposed in the contained bay Torsviken, in Göteborg, and the sediment is therefore dumped at sea, without knowing the consequences. The bonding of these contaminants to the sediment may be to the mobile components, which would imply a greater risk for affecting the environment negatively than if the contaminants were bound to the less mobile components (e.g. silicates). Toxicity studies from the Skagerrak show that sampling sites near the Göteborg area are so polluted that harmful effects on the ecosystem probably occur (Magnusson et al. 1996). These results indicate that, although the total sediment values may seem reasonably low, the effect of this sediment upon the biota can still be large.

Similar results have been found in the Port of Rotterdam (VandenHurk et al. 1997), and it is concluded that sediment bioassays are important tools that should be incorporated in decision-making frameworks for the management of dredged material. The present classification system in the port of Rotterdam has been in use since 1994 and it compensates for the content of clay and organic material in the sediment (Krijgsman 1996). According to this classification a high clay and/or organic content allows a higher contamination level since the elements are tightly bound in the sediment and will not be mobilised under normal conditions.

Sediment characterisation using: 1) threshold values, 2) single-component normalisation, 3) multi-parameter normalisation (Engström & Stevens 1999), 4) bioassays, and 5) 3-D sediment classification, all require documentation of environment-specific relationships between parameters before they can reliably be applied within classification schemes. Nevertheless, after establishing the relationships between different sedimentary components and their 3-D variations, the data can be mapped using proxies for the different tests. Threshold values that are most commonly used are not sensitive to variations in sediment conditions and do not take into account how the element is bound in the sediment and which effect the levels have with different sediment conditions. This can cause severe environmental problems due to that contaminated sediment is dumped at sea or that unnecessarily large amounts of sediment are put in expensive sealed off bays. To minimise the amount of material that is deposited in these sealed off bays and at the same time be sure that no contaminated sediment is dumped at sea, it is important to know how much of the contaminants that are tightly bound in the sediment and how much that is bioavailable, i.e. available for living organisms. The classification of contaminated sediment should therefore be related to the variations in sedimentary conditions and the effect on the surrounding environment.

Archive Documentation

An archive can, and should, be used as a resource for harbour management. Prior to new investigations a desk study can be carried out to identify areas of interest and conclusions of past ground investigations. The availability and use of archive data is however, determined by internal company/institution policy surrounding the storage and release of archival information.

It has been the aim of the H-SENSE project that any data obtained should be stored in such a manner that potential future users find the records both easily accessible and easy to understand. To achieve this a standardised approach needs to be followed with regard to data collection and storage. Thus all co-ordinates have to be in a rectangular planer projection (such as UTM) and techniques of data collection and analysis must follow set guidelines.

In an investigation data can be stored in the form of numerical values, plain text and digital images. In order to establish a spatial database, the structure recording the spatial information is very important regarding the possibilities for data management. In H-SENSE all parameters are stored in the form of tables in Microsoft Access format. It is possible within Access to define different keys for their relations and link one table with others. In this way, the sophisticated relations between different data could be retrieved and managed easily. With the aid of a relational database management system (Microsoft Access) relevant information distributed in different tables can be reorganised according to specific needs to enable decision support analysis.

It is neither feasible or economical within a single project to examine all the raw data obtained. In addition to tables with the results of the analyses carried out on sediment cores there should also exist a detailed photographic record as this has a valuable documentation value for potential future investigations.

Data quality is of crucial importance when integrating archival information and in addition to numerical values, detailed documentation files must also be available. Within the documentation file the lineage should be recorded. Errors present within the available data need to be identified, quantitatively if possible. Qualitative terminology should be avoided as data categories termed “usually acceptable” or “poor” can vary extremely from one recorded investigation to another. The quality of historical records can be lowered by unsatisfactory analytical methods, unspecified methodology, and/or limited information regarding the geographical position.

Sedimentological modelling

Any model describing environmental conditions needs to incorporate all the influential mechanisms and each needs to contain all the causative parameters. The initial model input comes from the results of sedimentological process studies, both theoretical and hard data. Refinement of a model comes about by evaluating the output of the model. This evaluation may result in the need for further investigations to improve the model capabilities.

Specific steps in model evaluation include using process study knowledge and monitoring (Fig. 50). The model is initialy constructed using ground truth experience, the modelling results can then be used in the identification of sites for monitoring schemes. The heuristic modelling approach is determined by expert knowledge; if the modelling output disagrees with the ground truth then it is necessary to re-evaluate the hypothesis and the data structure.

Decision support tools

The decision support offered by modelling must be able to reconcile the conflicting goals of a harbour manager. Three modelling alternatives have been used and assessed within the H-SENSE programme. They are described in detail within Deliverable D5.

The development of a decision support system would provide a valuable tool for a harbour manager. Six distinguishing characteristics would have to be met:

1. Be explicitly designed to solve ill structured problems where the objectives of the decision maker and the problem itself can not be fully or precisely defined;
2. Have a user interface that is both powerful and easy to use;
3. Enable the user to combine analytical models and data in a flexible manner;
4. Help the user to explore the solution space (the options available) by using the models in the system to generate a series of feasible alternatives;
5. Support a variety of decision-making styles and are easily adapted to provide new capabilities as the needs of the user evolve; and
6. Allow problem solving to be both interactive and recursive – a process in which decision making proceeds by multiple paths perhaps involving different routes rather than a single linear path.

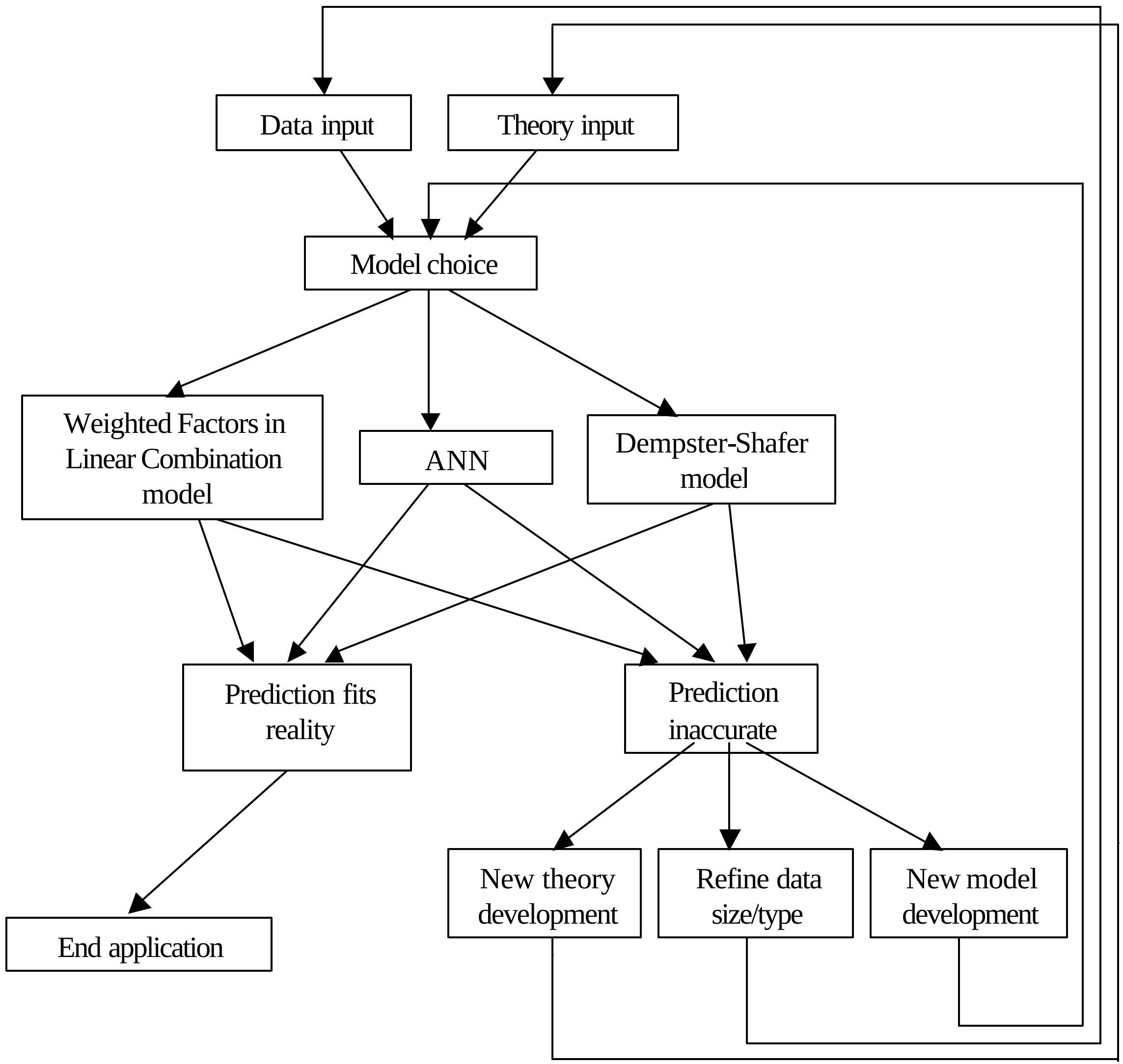


Fig. 50. *Stages of model development*

Work within the H-SENSE project has positively contributed to meeting these six objectives with the following results:

?? A decision support system should be specifically applied to the harbour environment as it is very complex. Standard statistical means have been applied to the data but were limited by the fact that there is no single factor that controls sedimentation/pollution, but a number of criteria where the relationship between each is poorly understood. The ANN model was able to determine relationships between the parameters using non-linear calculations and the multi criteria evaluation approach also examined inter-relationships based on our judgmental knowledge of the system.

?? The multi-criteria approach permits calculation of suitability maps, thereby facilitating decision support. This approach could be combined with cost/value data to derive a methodology for optimum resource allocation.

?? Recent computer developments means that the tools to facilitate a DSS are now available.

?? The GIS (Idrisi) and neural network software provide the basis for a new modelling approach to be assessed. This combination provides a flexible structure allowing new inputs to be added with greater efficiency than hitherto. Modelling alternatives have been discussed in detail within deliverables D4 and D5. The ANN used within the H-SENSE project was developed by a member of the team at NTU, Dr. Y. Yang.

?? The model outputs can be presented either as tables or as a cartographic representation of the harbour, which can be viewed using Idrisi.

Thus far, the tools have been developed but a user interface would still need to be developed before a tool of general utility could be produced. Currently the ANN training is very data intensive. The process of designing and training an ANN can currently only be undertaken by an experienced user. The most appropriate design is only usually found after a long series of trial and error tests for different numbers of hidden layers and for the numbers of nodes in each layer. These may vary as the harbour situation changes. Thus a design developed for one area may not necessarily be applicable to a different harbour where processes do not operate in the same way. The computational time required to train a neural network is also significant using an ordinary PC.

The models developed within the H-SENSE project can be used as the basis for two main approaches in terms of decision support: prescriptive or predictive. Models used for site selection are usually prescriptive, i.e. involve the application of a set of criteria that are set out as good engineering practice, and may result from a blend of scientific, economic and social factors. On the other hand, resource mapping involves the use of predictive models, because the ultimate purpose of determining mineral potential is to discover new deposits. (Bonham-Carter 1994).

Suggested steps forward

Toward Model Implementation

One of the main goals for the H-SENSE project has been the development of predictive models. We have not aimed to provide market-ready software, but demonstrate the suitability of different approaches. Rather, the demonstration of the suitability of different approaches and the capacity for application of such models has been dealt with from our scientific point of view. Furthermore, the hardware and software developments within computerised modelling are rapidly changing the requirements and possibilities that are presented for a harbour manager, who is best served by an understanding of the principles, as we have tried to illustrate.

As we have experienced ourselves, it is likely that one of the major barriers to obtaining working models is the lack of suitable input data. To overcome this, we suggest that prospective harbours review their procedures and strive to construct archives that self-generate the type of data shown to be valuable within the H-SENSE modelling. Routine monitoring in connection with maintenance dredging, as well as specific construction and remediation projects, will, if planned appropriately, provide the basic requirements. Databases (essentially maps) incorporating grain size, sediment composition, geotechnical and geochemical characteristics are desirable, but these do not necessary have to be from the same time or project, in fact the combination of seasonal variations can be utilised in many model approaches. The amount of additional sampling and analysis will be greatly reduced by such procedures. Primary data have, in most cases, the greatest flexibility and should be given high priority in harbour archives (see Deliverable D2 and Stevens et al. 1999).

The models developed within H-SENSE have considered three harbours. It was necessary, furthermore, to restrict the stochastic modelling to Göteborg, where the database and the geographic coverage were most suitable during the period of the project. Case-based reasoning from Bergen and Ventspils, although of importance for the modelling choices, needs to be followed up by modelling similar to that in Göteborg. Additional harbours, with the variations in environmental conditions that are automatically involved, are necessary to more completely evaluate the models. Some harbours may have databases that are essentially ready to use for training within the ANN model, or which can be tested against the experience and judgement of experts familiar with these settings.

The calculation of hazard maps is an obvious step toward dealing with the various types of harbour problems. Exposure can be used to develop vulnerability images from which a risk assessment can be developed. Incorporation of errors in data and uncertainties in boundary conditions would enable prioritisation of assessment criteria. It would be feasible, as a computer software programming exercise, to write a shell incorporating the GIS with the ANN under one environment, but this would require an additional investment in staff time resource beyond the scope of the current programme.

Volume and mass flux calculations are suitable operations using GIS modelling. For each pixel in the harbour database, an algorithm would be required to show the input, storage and output of sediment over time. This can be achieved through deterministic or stochastic approaches (as discussed in Deliverable D5 and in Chapter 6, above). The resultant GIS images can then be run in sequence to demonstrate the volume of sediment transported over the harbour areas and the main areas of storage over the timeframe of interest. This calculation would be of interest to harbour managers especially with regard to determining the best practise of dredging. It was possible within this project to determine tentative volume flux calculations for the natural harbour system in Göteborg (Brack et al. in prep.).

Although models are powerful tools for harbour management, integrating various components such as site characteristics and exposure assessment, they are nevertheless abstract representations of complex systems and, of necessity, may incorporate a number of assumptions and approximations. In any case, the quality of prediction which a model enables can be no better than the quality of the data on which it is based. Therefore, models such as the three developed within the H-SENSE project need to be validated and tested in real-world situations, either as part of a risk assessment or within a research project.

The meaning of the absolute values obtained from application of a model is not clearly known, and future research would usefully address this issue by linking with the exposure assessment procedures and field evaluation trials. Field testing and validation of models raises questions concerning the precision and bias of model predictions. Indeed, it is not known whether accurate estimates should be expected from an overall assessment in view of the many uncertainties associated with site characterisation, exposure assessment and the basis for examining the effects of pollutant uptake by humans or organisms. This in turn relates to the issues of risk perception and communication.

The way forward may well lie with the training of those concerned with harbour management (risk assessors and decision makers). Providing a grasp of the scientific basis for system response could provide the key, highlighting the means of establishing influential parameters and identifying the values at which action is required. The end objective is to evolve a defensible decision with recognisable limitations. A network for harbour siltation and environmental problems is proposed below as a suitable forum for exchange and cooperation.

Connection to Coastal Monitoring

The problems of siltation and pollution in harbour sediments are connected to a geographically larger issue concerning the transfer of sediments and element from land to sea in general. Since harbours are often estuaries, they are centrally involved in the material flux. Coastal monitoring is incomplete without the understanding of harbour system, which combines both natural and anthropogenic processes (see Stevens 1999, Johannesson et al. 2000).

A current application to the European Council programme for Energy, Environment and Sustainable Development deals in with several of the most important aspects related to these connections between harbours and coastal systems. Many of the goals in this project proposal ("Coastal Systems Monitoring" – COSY) are related to, and in part derived from, the H-SENSE project activities. Several H-SENSE partners are involved. Both our results and many of the new goals within the COSY proposal would be optimised by the existence of a network dealing with environmental issues and processes related to the harbour environment.

"Siltation and Harbour Environment" Network

As in most scientific investigations, there are numerous, important questions that have arisen during the course of the H-SENSE project, many of which go beyond the scope of a two-year program. At the same time, the gained experience and published conclusions regarding the original objectives of this project have also brought into focus a number of methods for improving the management of the harbour environment by introducing cost-effective preventive and remedial measures. In particular, the potential for modelling of harbour environments by different approaches has been demonstrated. To deal with both types of project results, the new questions and the application of demonstrated results, we feel that there is an obvious need for continued interaction within the partnership and together with a broad range of colleagues in related industrial, governmental and academic organisations. An optimisation of the H-SENSE results and the results of other relevant programs would be facilitated by the formation of a network for "Siltation and the Harbour Environment".

Possible network activities are:
Workshop and conference meetings to deal with central themes of the network.
Project planning, development and network support.
Training internships, ideally related to spin-off projects.
Traditional and virtual (Internet based) courses dealing with technical concerns.
Homepage discussion board and demonstration programs.
Internet dissemination of member results and other relevant information.

Although the "Siltation and Harbour Environment" Network would ideally involve more than one EC programme area, it would be an ideal platform for several former project groups from both the former "Waterborne Transport" and the on-going "Sustainable Growth" programs.

7. Conclusions

The need to reduce damage to the environment was stressed within the objectives of the Transport Programme in connection with dredging operations and other port activities (Ports, Environment and Safety, Task 6.3.5). The H-SENSE project has addressed both the methods of site surveying and the applications of these studies for dredging management and environmental protection. Detailed sediment characterisation and process interpretations have aimed at identifying the most appropriate sediment treatment and removal techniques.

The problem of polluted sediments was addressed, not just looking at the surface sediments, but down profiles as dredging operations generally remove the top 50 cm layer and must consider re-mobilisation problems of pollution stored within older sediments. The release of pollutants from storage forms a hazard whose effects have to be quantified within the risk analysis, and subsequently managed in a manner appropriate to the ecosystem, feasible regarding operation of the harbour, and consistent with respect to legislation. GIS and geostatistical analyses have also been tested, which would allow the most cost-effective sampling scheme can be suggested, balancing cost of sampling with the potential costs of incorrect disposal if too few samples are collected to detect trends. Different approaches to modelling surface trends were evaluated. Although interpolation can give a visually impressive result, there are problems when considering the statistical description of a chosen variable.

There is no simple solution to the problems created by polluted marine sediments. Such sediments, particularly if fine grained, tend to absorb chemicals including potential contaminants, such as PCBs and PAHs. Contamination may be limited to a "hot spot", but is commonly diffuse, and its distribution strongly influenced by the history of sedimentation and anthropogenic, particularly urban, industrial and agricultural activities in the region. Furthermore, changes upon burial and with time are significant for most elements and depositional settings.

A risk-based approach is advocated to provide for systematic management practice and application of appropriate technologies, and also leading to the consideration of best management practice, regulations, source control and site assessment. Trade-off between resource limitations and remediation efficiency requires a basis for comparison, usually effected by optimisation of cost. This necessitates the risk-based approach. Uncertainties about the nature and significance of chemicals in given concentrations on the ecosystem and/or human health is a major stumbling block, hindering development of such areas. This increases the necessity for quality assurance, demonstrating through an audit trail how a particular management strategy has been developed, and clarifying the basis for the decisions made. The generic modelling developed within Work Package 3 provides a basis for such auditing.

The balance between scientific goals (e.g. process studies) and routine monitoring can often be utilised to benefit both perspectives, and one of the most central instruments for this symbiosis is the harbour sediment database. With proper structure and motivated, complementary documentation, the data archive produced for monitoring purposes will have the necessary flexibility to serve many other users in the future. In particular, the increasingly comprehensive database will allow modelling and statistical evaluations that can save future expenses. Understanding the harbour setting as a system will eventually be the most important result, allowing environmentally sound planning and maximum utilisation of the resources in the coastal zone.

List of publications, conferences, presentations from the project

Deliverables

D1 – 1998: Project Manual, 9 pp, (9 appendixes). H-SENSE Deliverable to EC DG-VII (Transport).

D2 – 1998: Data and Method Priorities regarding sediment investigations of harbour sites. Submitted October 15, 1998. H-SENSE Deliverable to EC DG-VII (Transport).

D3 – 1999: Summary of Harbour Surveys, Sediment analyses and Initial Interpretations in the Bergen, Göteborg and Ventspils Harbours, 52 pp. H-SENSE Deliverable to EC DG-VII (Transport).

D4 – 1999: Modelling Alternatives, 27 pp. H-SENSE Deliverable to EC DG-VII (Transport).

D5 – 2000: The environmental Sedimentology Model: Applications and Limitations, 54 pp. H-SENSE Deliverable to EC DG-VII (Transport).

D6 – 2000: - Characterisation and Evaluation of Harbour Sediments (Recommendations from H-SENSE), 47 pp. H-SENSE Deliverable to EC DG-VII (Transport)

Scientific papers

Brack, K. & Stevens, R.L. 1999: Environmental significance of sediment units and their variability in the Göta älv estuary. Accepted for publication in CATS 4 (Proc. Intern. Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 299-308.

Brack, K. Stevens, R.L. & Paetzel, M. 2000: Holocene environmental change and the accumulation-erosion balance of sheltered river-mouth sediments. Göteborg, SW Sweden. Marine Geology, 170, 347-362.

Brack, K., Johannesson, L.T. & Stevens R.L. in press: Accumulation rates and mass calculations of Zn and Hg in recent sediments, Göta älv estuary, Sweden. Environmental Geology.

Brack, K. & Stevens, R.L. in press: Historical pollution trends in a disturbed, estuarine sedimentary environment, SW Sweden. Environmental Geology.

Burton, C.L., Rosenbaum, M. Stevens, R.L. & Book, S.H. 1999: Creating a harbour sediment database. Accepted for publication in CATS 4 (Proceedings International Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 575-584.

Engström, L. E. & Stevens, R.L. 1999: Multi-parameter normalisation of geochemical data from the Göteborg Harbour. Accepted for publication in CATS 4 (Proceedings International Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 159-168.

Johannesson, L., Stevens, R. & Alexanderson, J.H. in press: Sediment characteristics in a micro-tidal, harbour-estuary environment, Göteborg, Sweden. *Estuaries* (planned publ. June 2000)

Larsson, L.B. & Stevens, R.L. 1999: Time-dependent changes of PCB and mercury in harbour channel sediment, Göteborg, Sweden. Accepted for publication in CATS 4 (Proc. Intern. Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 71-80.

Rosenbaum, M.S. & Stevens, R.L., 1998. Problems arising from silt within harbours. GeoScientist, 8(12), 22, ISBN x 24 042 706 7, ISSN 0961 5628.

Rosenbaum, M.S. & Stevens, R.L., 1999. Problems of silt and siltation in harbours. In: Turnock, D. (Ed.) Geographies of the Future. Annual Conference of the Royal Geographical Society - Institute of British Geographers, Leicester, 167.

Stevens, R.L. 1999: H-SENSE: sediment perspectives upon harbour sustainability. Accepted for publication in CATS 4 (Proc. Intern. Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 617-624.

Stevens, R.L., Engström, L.T., Brack, K. 1999: Harbour sediment documentation for future, undefined purposes. Accepted for publication in CATS 4 (Proc. Intern. Congress on Characterisation and Treatment of Sediments, Antwerpen, Sept. 15-17, 1999), 551-560.

Yang, Y. & Rosenbaum, M.S., 1999. Spatial data analysis with ANN: geoenvironmental modelling of harbour siltation. In: Shi, W., Goodchild, M.F. & Fisher, P.F. (Eds.) Proceedings of the International Symposium on Spatial Data Quality (ISSDQ'99), Hong Kong, 18-20 July, 534-541, ISBN 962 367 253 5

Scientific papers submitted/under review (international journals)

Brack, K.: Organotin compounds in sediments from the Göta älv estuary. Submitted to Water, Air, and Soil Pollution.

Brack, K. & Johannesson, L.T.: Mercury and methylmercury in estuarine sediment and porewater, Göteborg Harbour, SW Sweden. Submitted to Applied Geochemistry.

Burton, C.L. and Rosenbaum, M.S.: Decision support to assist environmental sedimentology modelling. Submitted to Environmental Geology, H-SENSE Special Volume.

Burton, C.L. Rosenbaum, M.S. & Stevens, R.L.: Sedimentological considerations for predictive modelling. Submitted to Bulletin of the International Association of Engineering Geology and the Environment.

Johannesson, L.T. Stevens, R.L. & Eriksson, K.L.: The influence of an urban stream on sediment geochemistry in Göteborg Harbour, Sweden Submitted to Environmental Geology, H-SENSE Special Volume.

Johansen, L.M. Schrader, H. & Alve, E. Characterising state of pollution in the Bergen Harbour Area (Western Norway) with benthic foraminifera and sediment facies distributions. Submitted to Environmental Geology, February 2000.

Paetzel, M., Nes, G., Øystein Leifsen, L. & Schrader, H: Sediment pollution in the Vågen, Bergen harbour, Norway. Submitted to Environmental Geology, H-SENSE Special Volume.

Stevens, R.L.: Silt problems in harbours. Submitted to Jefferson, I. (ed.): Problems with silt and siltation. Thomas Tellford.

Stevens, R.L.& Ekermo, S.: Sedimentation and erosion in connection with ship traffic, Göteborg Harbour, Sweden. Submitted to Water and Maritime Engineering.

Yang, Y., Rosenbaum, M.S. & Burton, C.L.: An intelligent database for managing geoenvironmental change within harbours. Submitted to Environmental Geology (H-SENSE Special Volume).

Yurkovskis, A.: Remixing in the lower reach of the Venta River – Ventspils Harbour (Baltic Sea), effects on nutrient cycling and transport. Submitted to Environmental Geology (H-SENSE Special Volume).

Scientific papers in preparation for journal submission

Brack, K., Johannesson, L.T. & Stevens, R.L.: contaminant distribution and long-term fluxes in the recent sediments of Göteborg Harbour, Sweden (For Environmental Geology).

Burton, C.L. Rosenbaum, M.S and Stevens, R.L. Sedimentological considerations for predictive modelling (For Bulletin of the International Association of Engineering Geology and the Environment).

Johannesson, L.T. Stevens, R.L. & Eriksson, K.L.: The influence of an urban stream on sediment geochemistry in Göteborg Harbour, Sweden (For Environmental Geology).

Larsson, L & Stevens, R.L. Changes in the distribution of PCB and Hg influenced by Ship-induced turbulence in Göteborg Harbour (For Environmental Geology, H-SENSE Special Volume).

Maurenbrecher, P.M. & Alvarez Grima, M.: Estimating error in geophysical sub-bottom profiling.

Mueller-Karulis, B., Seglinš, V. & Poikane, R.: Heavy metals in the Ventspils harbour. (For Environmental Geology Special Volume).

Paetzel, M. & Schrader, H.: Natural vs. Human induced facies-change in recent, shallow water sediments of the Store Lungegårdsvannet (Western Norway). (For Environmental Geology, H-SENSE Special Volume).

Schrader, H.: Foraminifera distribution in the Byfjorden, Bergen Harbour. (For Environmental Geology Special Volume).

Stevens, R.L. & Jonsson, R.: Sediment transport paths and siltation problems in Ventspils Harbour, Latvia. (For Environmental Geology, H-SENSE Special Volume).

Student Theses

Brack, K. 1999: Characterisation of facies and their relation to Holocene and recent sediment accumulation in the Göta älv estuary and Archipelago. Department of Geology, Göteborg 1999, Earth Sciences Centre, Göteborg University, A46. ISSN 1400-3813.

Brack, K. 2000: Göta älv estuary – evaluation of anthropogenic and natural influences. Ph.D. dissertation, Kiel Univeristy, 146 pp.

Ekermo, S. 2000: Accumulation and provenance of sediment in Göteborg Harbour. Department of Geology, Göteborg 2000, Earth Sciences Centre, Göteborg University, ISSN 1400-3821.

Engström, L. 1999: Sedimentology of Recent sediments from the Göta älv estuary - Göteborg harbour, SW Sweden. Department of Geology, Göteborg 1999, Earth Sciences Centre, Göteborg University, A40. ISSN 1400-3813.

Eriksson, K. 1999: Sedimentological and geochemical changes along the Stream Kvillebäcken and at its mouth within Göteborg Harbour. Department of Marine Geology, Göteborg 1999, Earth Sciences Centre, Göteborg University.

Jonsson, R. 2000: Sediments and Sedimentation processes in a disturbed esturine environment, Ventspils Harbour, Latvia. Department of Geology, Göteborg 2000, Earth Sciences Centre, Göteborg University, B216. ISSN 1400-3821.

Johansen, L.M. 1998: Bentiske foraminiferer og forurensing i Bergen havnebasseng, vest Norge. Master-Thesis Department of Geology, University of Bergen, March1998, 136 pp., with English abstract.

Leifsen, L. Ø. and Nes, G. 1999: The influence of external forcing on sedimentation and trace metal pollution in the Vågen, Bergen harbour (Norway). HSF-College, Semester thesis, May 1999.

Mathisen, A. & Torfinn Prestmo, H. 1999: Environmental sedimentology in the Vågen, Bergen harbour (Norway). HSF-Collelge, Sogndal, Semester thesis, May 1999. (in Norwegian).

Wever, T.P.A. 1999: Seismic interpretation of H-Sense data and sub-bottom characterisation using CHIRP sonar technology. Delft University of Technology, Master's thesis. Faculty of Civil Engineering and Geosciences, Applied Earth Sciences, Engineering Geology, Delft, February 1999.

Abstracts

Brack, K. & Stevens, R.L. 1998: The Göta älv estuary - sediment and heavy-metal distributions. Marskat Meeting Wilhelmshaven, Germany November 2, 1998

Engström, L.T. & Stevens, R.L. 1998: Sediment character in a harbour estuary, South-Western Sweden. Norsk Geologisk Forening, Vintermøte in Aarhus, Denmark, January 1998.

Johansen, L.M. & Schrader, H. 1998: Benthic foraminiferal assemblage distributions vary with pollution grade in the Bergen harbour area, Western coast of Norway. Norsk Geologisk Forening, Vintermøte in Aarhus, Denmark, January 1998

Maurenbrecher, P.M. Wever, T. and Degen, B.T.A.J., 1998: Harbour sediment mapping using CHIRP reflection surveys in Norway and Sweden. European Environmental and Engineering Geophysics Society Meeting in Barcelona, Spain, September, 1998.

Maurenbrecher, P. M., Rosenbaum, M. S. and Book, Sofia, 1998: Information System for a multi-discipline harbour sedimentation project H-SENSE. GeoInfo VI, Washington D.C., 9-14 September1998.

Nes, G., Paetzel, M., Schrader, H., Sivertsen, Ø. 1999. Pollution vs sedimentology in the Vågen, Bergen harbor, Norway. Norsk Havforskers Forenings (Association of Norwegian Oceanographers) Årsmøte, Geilo November 3-5, 1999.

Paetzel, M. & Schrader, H. Recent facies change in the Store Lungegårdsvannet (Western Norway): A switch from oxic to anoxic bottom conditions.

Paetzel, M. & Schrader, H. 1999: The H-Sense project: Harbours - silting and environmental sedimentology: The Bergen harbour. Norsk Geologisk Forenings 16. Landsmøte, Stavanger 6-8 January 1999.

Paetzel, M., Nes, G., Øystein Leifsen, L. & Schrader, H. 1999: Sources of sediment pollution in the Bergen harbour, Norway. Engineering Geology of Construction in a Changing Environment in Nottingham (UK), 8-11 September 1999.

Poikane, R. & Müller-Karulis, B. 1999. Heavy metals in the Ventspils Harbour (The Baltic Sea). Marine Monitoring Centre, Institute of Aquatic Ecology, University of Latvia, Baltic Marine Biologist Symposium, Klaipeda, June 20 - 25, 1999.

Rosenbaum, M. & Stevens, R.L. 1999: Engineering geological problems arising from silt within harbours. GeoScientist, 8(12), 22.

Stevens, R.L., Ekermo, S. & Jonsson, R. 2000: Sediment sources and fluxes in two, non-tidal harbour settings. Sixth Intern. Conference on nearshore and Esturarine Cohesive Sediment Transport Processes, 4-8 September 2000, Delft, The Netherlands.

Stevens, R.L. & Larsson, O. in press: Marine Stratigraphy in the Göteborg Archipelago, Sweden: Holocene developments related to sea level, sediment supply, environmental setting and anthropogenic influences. Amer. Assoc. Petr. Geologists. Meeting. Denver, Colo. June 2001.

Stevens, R.L. & Johannesson, L.T. in press: What do you mean by Bioavailability? Amer. Assoc. Petr. Geologists. Meeting. Denver, Colo. June 2001.

Weaver, T.P.A. 1999: Seismic interpretation of H-Sense data and sub-bottom characterisation using CHIRP sonar technology. Memoirs of the Centre of Engineering

Geology in the Netherlands, No. 177, Faculty of Civil Engineering and Geosciences, Applied Earth Sciences, Engineering Geology, Delft University of Technology, Delft, February 1999.

Popular Science Publications

Stevens, R.L. 1998: "Hamnar sedimentet i hamnen är det ingen tillfällighet". HavsUtsikt 2/98, p. 6.

References

Bonham-Carter, G.F., 1994: Geographical Information Systems for Geoscientists: Modelling with GIS. Kidlington:Pergamon, New York, 398pp.

Boström K.W., Burman B., Ponter C., Brandlöf S. & Alm B. 1978: Geochemistry, mineralogy and origin of the sediments in the Gulf of Bothnia. Finish Marine Research 244: 8-36.

Boust, D., Johanneau, J.-M. & Latouche, C. 1981: Interpretation methods of bulk heavy metal contents in estuarine and littoral sediments. Bulletin de l'Institut de géologie du Bassin d'Aquitaine 30: 71-86.

Brack, K. & Stevens, R.L., 1999: Environmental significance of sediment units and their variability in the Göta älv estuary. In: De Schütter G (ed.) 4th International Conference on Characterisation and Treatment of Sediments (CATS 4), 299-308.

Brian, R., Murphy, R.J. & Kyle, S.W., 1982: Anthropogenically derived changes in the sedimentary flux of Mg, Cr, Ni, Cu, Zn, Hg, Pb, and P in Lough Neagh, Northern Ireland. Environmental Science Technology 16, 23-30.

Buckley, D.E. & Cranston, R.E. 1991: The use of grain size information in marine geochemistry. In: Syvitski, J.P.M. (eds), Principles, methods, and applications of particle size analysis, 311-331. Cambridge Univ. Press.

Cauwet, G. 1987: Influence of sedimentological features on the distribution of trace metals in marine sediments. Marine Chemistry 22: 221-234.

Degen, B. T. A. J., Deibel, I. K. & Maurenbrecher, P. M. 1996: Survey and containment of contaminated underwater sediments. *In:* Bentley, S.P. (ed.) Engineering geology of waste disposal, 77-86. Geological Society of London, Engineering Geology Special Publication, 11.

Dunn, O. J., 1964: Multiple Comparisons Using Rank Sums. Technometrics 6, 241-252.

Ebdon, D., 1977: Statistics in Geography. Basil Blackwell Ltd., 232 pp.

Ekermo, S. 2000: Sediment accumulation and mineralogy in Göteborg Harbour. Department of Earth Sciences, Göteborg University, Thesis B230, 33pp.

Engström, L.T. & Stevens, R.L. 1999: Multiparameter normalisation of geochemical data from Göteborg Harbour. In: De Schütter G (ed.) 4th International Conference on Characterisation and Treatment of Sediments (CATS 4), 159-168.

Harkness M., McDermott J., Abramowicz D., Salvo J., et al., 1993: In situ stimulation of aerobic PCB biodegradation in Hudson River sediments. Science, 259, 503-507.

Johannesson, L.T., Stevens, R.L. & Alexanderson, J.H., 2000: Sediment character in a micro-tidal, harbor-estuary environment, Göteborg, Sweden. Estuaries 23, 400-410.

Johansen, L.M., 1998: Bentiske foraminiferer og forurensing i Bergen havnebasseng, vest Norge. Master-Thesis Department of Geology, University of Bergen, March1998, 136 pp., with English abstract.

Krijgsman, A. 1996: Classification systems for sediment quality and dredged material handling, disposal and beneficial use in the Netherlands. Department of Port Maintenance, Port of Rotterdam, 4 pp..

Latvijas republikas vides aizsardzibas komiteja, 1992: Pagaidu instrukcija juras vides kontolei Latvijas Valsts ostas, kugu piestatnes un grunts apglabašanas vietas. Riga.

Lepland, A. & Stevens, R.L., 1996: Mineral magnetic and textural interpretations of sedimentation in the Skagerrak, eastern North Sea. Marine Geology 135, 51-64.

Lepland, A. Heinsalu, A. & Stevens, R.L. 1999: The pre-Littorina diatom stratigraphy and sediment sulphidisation record from the west-central Baltic Sea: implications of the water column salinity variations. GFF 121, 57-65.

Loring, D.H. 1991: Normalisation of heavy-metal data from estuarine and coastal sediments. ICES Journal of Marine Sciences 48: 101-115.

Magnusson, K., Ekelund, R., Dave, G., Granmo, A., Forlin, L., Wennberg, L., Samuelsson, M.O., Berggren, M. & Brorstrom-Lunden, E. 1996: Contamination and correlation with toxicity of sediment samples from the Skagerrak and Kattegat. Journal of Sea Research 35: 223-234.

Maurenbrecher, P.M., Degen, B.T.A.J., & Keasberry, J., in press: Interpretation of chirp acoustic profiles in a pilot survey of the contaminated lake bed deposits of the Ketelmeer, the Netherlands. European Journal of Environmental and Engineering Geophysics.

National Research Council, 1997: Contaminated sediment in ports and waterways: clean-up strategies and technologies. Committee on Contaminated Marine Sediments, Marine Board, Commission on Engineering and technical Systems, National Research Council.

Naturvårdsverket 1985: Muddring och muddermassor. Allmänna råd 85:4, Statens Naturvårdsverk, 70 pp.

Naturvårdsverket 1999: Bedömningsgrunder för miljökvalitet: Kust och Hav. Rapport 4914, Statens Naturvårdsverk, 134 pp.

Olausson, E. 1975: Man-made effect on sediments from Kattegat and Skagerrak. Geologiska Föreningen i Stockholm Förhandlingar 97: 3-12.

Prohic, E. & Kniewald, G., 1987: Heavy metal distribution in recent sediments of the Krka River estuary - An example of sequential extraction analysis. Marine Chemistry 22, 279-297.

Salomons, W., Schwedhelm, E., Schoer, J. & Knauth, H. 1988: Natural tracers to determine the origin of sediments and suspended matter from the Elbe Estuary. Water Science and Technology 20: 89-102.

Selmer, J-S. and Rydberg, L., 1993: Effects of nutrient discharge by river water and waste water on the nitrogen dynamics in the archipelago of Göteborg, Sweden. Marine Ecology Progress Series 92, 119-133.

Smith, S.L., MacDonald, D.D., Keenleyside, K.A., & Gaudet, C.L. 1996: The development and implementation of Canadian Sediment Quality Guidelines. IN: Munawar, M. and Dave, G. (eds). Development and Progress in Sediment Quality Assessment: Rationale, Challenges, Techniques and strategies, 233-249. SPB Academic Publishing, Amsterdam.

Stevens, R.L., 1999: H-SENSE: Sediment perspectives upon harbour sustainability. In: (eds.) The 1999 International Conference on the Characterisation of sediments (CATS 4),

Stevens, R.L., Bengtsson, H. & Lepland, A. 1996*:* Textural provinces and transport interpretation with fine-grained sediments in the Skagerrak. *Journal of Sea Research 35,* 99-110.

Stevens, R.L., Engström, L.T., Brack, K., Book, S. 1999: Harbour sediment documentation for undefined, future purposes. In: De Schütter G (ed.) 4th International Conference on Characterisation and Treatment of Sediments (CATS 4), 551-559.

Ulsts, V., 1998: Harbours – Silting and Environmental Sedimentology project. Report on the the study of sedimentation conditions and silting in the Ventspils Harbour during 1998. State Geological Survey of Latvia, Riga 13 pp. + 13 appendices.

Van der Loeff, M.M.R., Boudreau, B.P., 1997: The effect of resuspension on chemical exchanges at the sediment-water interface in the deep sea – A modelling and natural radiotracer approach. Journal of Marine Systems 11, 305 – 342

VandenHurk, P., Eertman, R.H.M. & Stronkhorst, J. 1997: Toxicity of harbour canal sediments before dredging and after offshore disposal. Marine Pollution Bulletin 34: 244-249.

Wallroth, J., 1996: Miljörapport enligt miljöskyddslagen för år 1996 avseende deponering av muddermassor. Göteborgs hamn AB.

Appendix 1: Site Descriptions

Göteborg harbour

Göteborg Harbour and archipelago are located on the Swedish west coast (Fig. 1). The estuary is a non-tidal, salt-wedge estuary. The surrounding geology of the valley is characterised by glaciomarine and marine clays and exposed Precambrian bedrock; thus the river supplies mainly fine-grained material to the harbour and archipelago. The Port of Göteborg in the largest harbour in the Nordic countries. Harbour activities have effected the sedimentary and geochemical processes occurring in the estuary, e.g. sediment in-filling is an evident problem, requiring harbour and channel dredging almost every other year.

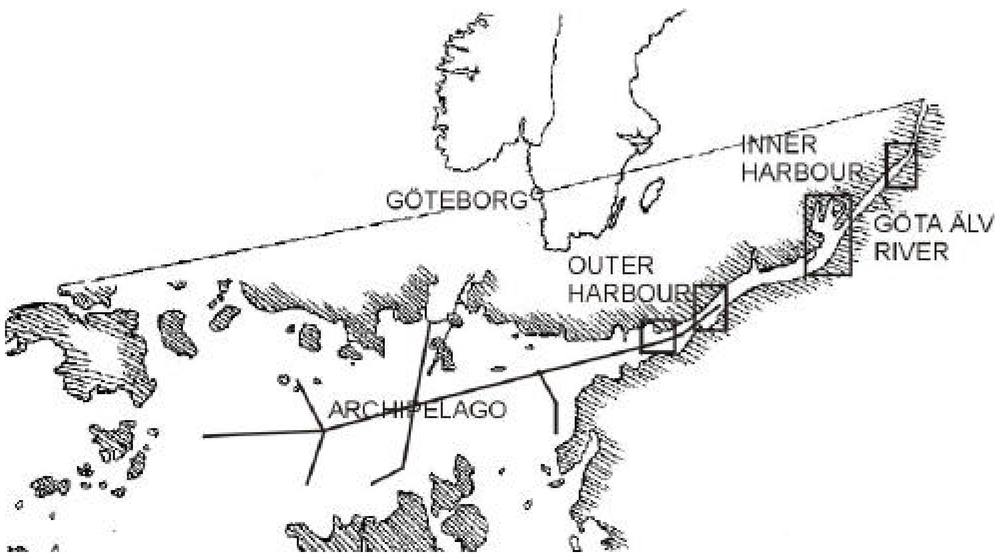


Fig. 45. *Study area and sampling schemes. The boxes represent the dense sampling areas in the harbour and the lines represent the profiles sampled in the archipelago.*

Göteborg Harbour is situated in the estuary and river mouth of the Göta älv River. The outer harbour reaches into the archipelago that is situated outside the estuary. Conditions differ between these two different areas: The water depth increases both continuously and stepwise outwards, and at the river mouth, the river channel widens and is replaced by an archipelago with both open and sheltered settings.

The city of Göteborg was founded at the outlet of the Göta älv River in 1621. During the 19th century, Göteborg was industrialised and the population expanded from 13 000 in 1800, to 130 000 in 1900, to 500 000 today. Both riverbanks are exploited for vessel docking. In the 1960's and 1970's the harbour of Göteborg was built into the archipelago.

Diverse industries were established along the Göta älv River during the 19th and early 20th century. The river was dammed and regulated in connection with the building of hydroelectric power plants. The harbour has been repeatedly dredged since 1830. Maintenance dredging is today done every fourth year in the harbour (ca. 80 000 m^3 on a yearly average). The dumping site for uncontaminated dredged sediment is situated in the archipelago.

With a mean flow rate of 550 $m^3 s^{-1}$ the Göta älv is the largest river in Sweden and the seventh largest river in Europe, comparable in size to the Elbe, Garonne and Seine. Although the Göta älv is considered less polluted by toxicants than many other European rivers, its sediments are a continuing source of elevated concentrations of priority organic pollutants and heavy metals. It has been estimated that approximately 23,000 effluents from industry and municipalities discharge into the system.

The Göta älv estuary is a salt wedge estuary, where the river influence dominates over tidal and wave processes, in part protected from the open sea by an extensive coastal archipelago. The salt wedge and related water stratification are of crucial importance for the transport of both particulate and dissolved phases with the river outflow. With mixing of salt and fresh waters, especially at the turbidity maximum, extensive flocculation and geochemical precipitation can occur. Because the in-flowing bottom waters are typically weaker than the outflow, this type of estuary is a particularly effective trap for sediments and some dissolved species.

The estuary has been used for boat traffic since the Middle Ages, although the present harbour was established first in the 19th century. Today, the Göteborg harbour is the largest of the Nordic countries (yearly 12,000 ships, 30 M tons cargo, 4 M passengers). Since the natural depth of the estuary before dredging was 2-3m, maintenance dredging is necessary to keep the fairway deep enough, as controlled by echo soundings. In addition, larger dredging has occurred with new construction and to prevent excessive turbidity, as with the new water-jet ferries. The dredging masses are deposited in three alternative sites depending upon their toxicity. Although the Göta älv River is well monitored with respect to current flow, sedimentation dynamics have received only limited consideration, mainly in connection with erosion along the river and specific geotechnical problems within the Göteborg harbour (Sundborg & Norrman 1963).

In the Göta älv River valley, consolidated Late Weichselian and postglacial clays with a thickness of commonly more than 10 m cover the underlying rock basement. Recent sediments are mostly fine-grained (silty clay) and organic-matter rich. They have a thickness of some decimetres up to ca. 80 cm. In the river (inner harbour) and in the outermost archipelago, coarser sediments (sandy silt and silty sand) can also be found.

Bergen harbour

The Bergen harbour is a highly polluted low tidal fjord system at the Norwegian west coast and until 1999 received untreated sewage from more than 100 000 householdings and from industry. During the last 500 years the harbour has undergone a variety of human induced environmental changes. These include (a) strong trading boat traffic prior to WW-II, (b) military boat bunkering and traffic during WW-II and (c) less strong cruise-, speed- and small-boat traffic after WW-II. In addition, the building and population history including shifts in industrial activity during this century is well documented. This historical control offers the opportunity for detailed investigation and modelling of sediment component sources, supply and distribution.

The Bergen Harbour consists of three main parts, namely the Vågen in the North, the Puddefjord with the Store Lungegårdsvannet in the South and East and the Byfjord in the West. The Vågen, Store Lungegårdsvannet and the Puddefjord are the shallow parts with water depths not exceeding 25 meters and the Byfjord displaying steep slopes and water depth of up to 350 meters.

The Vågen is the oldest part of the Bergen Harbour system reaching back beyond the Hanse time in the Middle Ages having all the time had a relatively high marine traffic. The Puddefjord and Store Lungegårdsvannet were "separated" in the early 1900 and the Puddefjord was increasingly been populated by industry along its shorelines and by increasing ship traffic since the 1900^{th} century. A major industrial slow down and modification did occur in the late sixties and seventies.

Only very recently has the collection and treatment of raw sewage been shifted from a direct injection along the Vågen, Puddefjord and Store Lungegårdsvannet shore lines; since 1999 raw sewage is collected into huge tunnel and pipe systems and it is centrally been mechanically and chemically treated (1999-2000).

The Bergen Harbour and its surrounding areas have a wide range of bottoms including soft clay and organic matter rich sediments over sand and carbonate shell rich bottoms to recently filled in bottoms with sharp edged pebbles to hard grounds that are populated by molluscs and red and brown algae.

Gradients between these facies and the distribution of these facies can be sharp and within short distances. The inner parts of the Vågen and the Puddefjord that are characterised by a basin configuration contain fine grained water rich and organic matter rich sediments grading into a silled outer part that consists of coarser sandy sediments.

The setting of the Bergen harbour is well suited for comparison with those from the Göteborg harbour study as both environments (a) are located at the Scandinavian west coast, (b) lay in low-tidal zones, (c) receive industrial and municipal sewage waste, (d) include city areas of more than 500 year historical human development and (e) are sheltered from open sea influence.

Ventspils Harbour

The Ventspils harbour is located in the mouth of the river Venta on the west coast of Latvia. With an annual cargo turnover of 40 000 000 it is one of the largest harbours in the Baltic Sea. Ventspils Harbour is connected to the Russian oil pipeline system, the harbour handles oil among a variety of other goods including metals, wood and chemical products. The harbour consists of an inner harbour that takes up the lower reach of the Venta River and an outer harbour formed by two jetties constructed between 1900 and 1905, that segregate the outer harbour basin from the sea. During the development of the harbour, the jetties were covered by tetrapod coatings and several piers have been constructed in the outer harbour. To facilitate the access of large vessels, an entrance channel was constructed starting from the Venta mouth and continuing into the sea for 5 km. The harbour is still under substantial development. During 1997 and 1998 extensive dredging works were conducted in the harbour and the entire harbour basin had been deepened to increase the area accessible to ocean going vessels and the construction of a cargo terminal is also under way. The outer harbour starts at the Venta mouth and is separated from the Baltic Sea by breakwaters in the Southwest and Northeast leaving only a narrow opening (approximately 80 m wide). In the central part of the outer harbour water depths reach approximately 17.5 m shallowing to 13 - 7 m at the basin edges.

Ventspils harbour can be subdivided in five relatively separate areas: Open Sea proper, Main Harbour facilities, Harbour Channel, Vessels turning area and River flow. These areas are different by interrelations between the sea and river influence (waters and sediments), silting intensity and port authorities managed channels depths.

Deepening in the area, extracted amount of sediments, thousands m^3.

Year	Open Sea proper	Main Harbour facilities	Harbour Channel	Vessels turning area	River flow
1999	106.550	26.600	43.050	5.400	14.200
1998	156.900	13.950	Construction works		
1997	37.370	-	10.750	-	13.200
1996	146.510	1.500	44.650	39.400	1.200
1995	201.870	40.500	128.999	26.500	169.190
1994	198.100	159.94			
1993	530.45	-	94,454	94.700	
1992	351.367	-	37.400	-	-
1991	272.750	-	30.660	7.650	-
1990	905.170[1]	-	-	33.755	47.800
1989	557.450	-	35.850	18.075	31.600
1988	411.781	124.740	110.510	34.874	23.525
1987	309.720	-	91.590	40.155	-
1986	101.590	-	-	19.800	19.650
1985	64,000	220,250	-	-	-
1984	424.420	62.250	127.924	7.375	

[1] Heavy early spring storms recorded