Proceedings
Seminar on

Environmental Investigations
Denmark's Great Belt Link

Copenhagen
February 14, 1989

Selskabet for
Risikovurdering

Ingeniørhuset
Vester Farimagsgade 29-31
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INTRODUCTION

The present publication is issued more than a year after the seminar "Environmental Investigations for the Great Belt Link"!

This delay has been made by intension in order to be able also to publish some of the actual recordings and observations carried out during the first phases of the construction works. It has thereby also been possible to benefit from including detailed papers and reports prepared during the last year so the publication thereby could be more complete.

We thank our authors for their written contributions.

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American Society of Civil Engineers

The 1989 Annual Civil Engineering Convention
New Orleans, October 1989

DENMARK's GREAT BELT LINK

The Three Main Structures

- Eastern Railway Tunnel
- Western Railway and Motorway Bridge
- Eastern Motorway Bridge

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1. INTRODUCTION

Construction of the Great Belt Link (the fixed link across Great Belt in Denmark) is one of the largest transportation projects going on in Europe at present, and the largest construction undertaking in Denmark to date. The total cost is estimated to 2.5 billion US$ (1989).

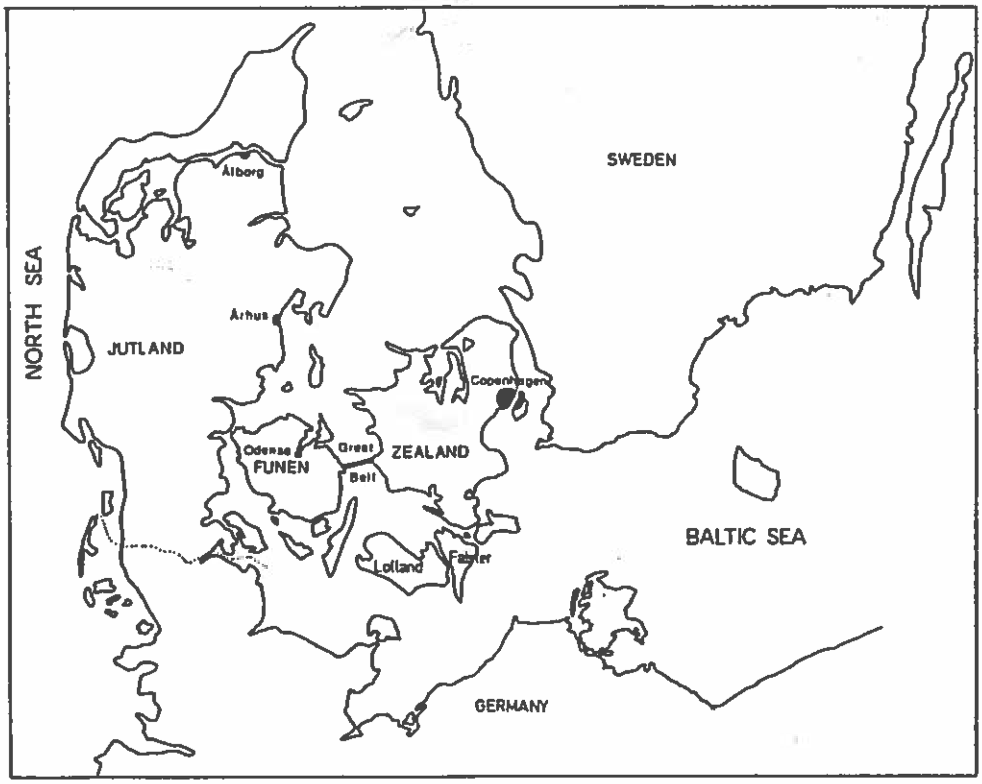


Fig. 1. Project Location

The island of Funen is already linked to the main land of Jutland, and thereby to the European continent, by two major bridges, but the island of Zealand, home of the Danish capital Copenhagen, can only be reached by sea or by air. The Great Belt Link will provide an east-west transportation connection essential for further economical and commercial development of Denmark.

The location of the project is shown in fig. 1.

The construction of the Great Belt Link is the first major step towards an improvement of the northern European transportation network, which may later be completed by fixed links across Øresund to Sweden and across the Baltic Sea to Germany. Both rutes are heavily travelled by ferry boats today to serve north-south traffic needs.

Two other major bridges, Storstrøms Bridge from 1937 and Farø Bridges completed 1985, connect Zealand with the southern islands of Lolland and Falster just north of Germany.

On June 12th 1986 an agreement between the conservative/liberal Danish government and the social-democrats for establishment of the Great Belt Link was entered into. The agreement comprised a main time schedule and established the overall configuration of the crossing. The link should comprise a double track railway and a 4-lane motorway with emergency lanes.

Construction of the fixed crossing should be in two phases. The railway should be opened for service in 1993 and the motorway link in 1996.

A special share holding company - The Great Belt Link Ltd.- owned by the Danish state should manage design and building of the fixed link together with the running of the road crossing, whereas the Danish State Railways should manage the running of the rail crossing. The link will be paid by the users by toll from road traffic and compensations from the Railways. The necessary loans for establishment of the link are expected to be paid off over 30 years for the rail part and much earlier for the road part.

The fixed link will include three major construction projects.

From Zealand to the island of Sprogø in the middle of Great Belt, crossing the busy international shipping lane to the Baltic Sea, it has been decided to construct a tunnel for the train and a high level bridge for the motorway.

From Funen to Sprogø, a combined low level railway and motorway bridge will be built. The water here is relatively shallow, 10-25 m.

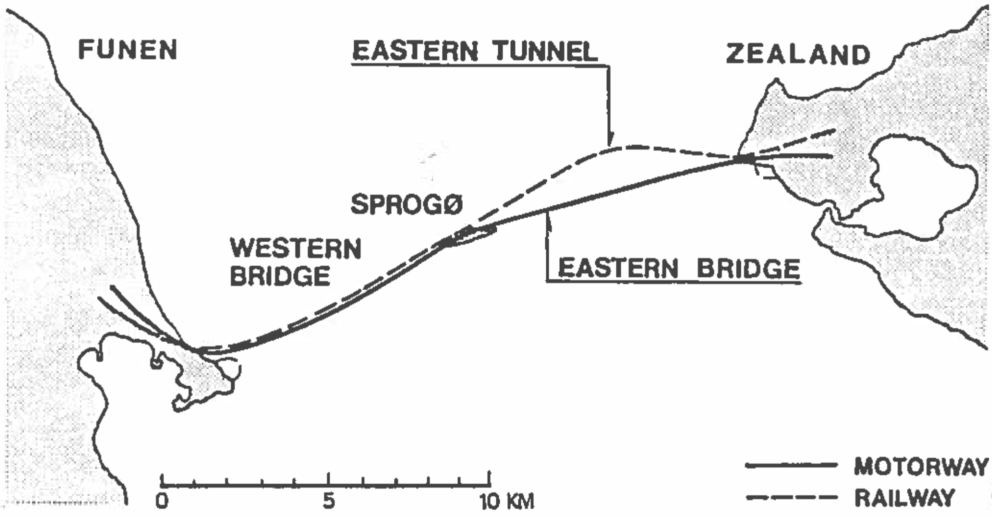


Fig. 2. The Main Components of the Great Belt Link

The master plan established for implementation of the fixed link is shown in fig. 3.

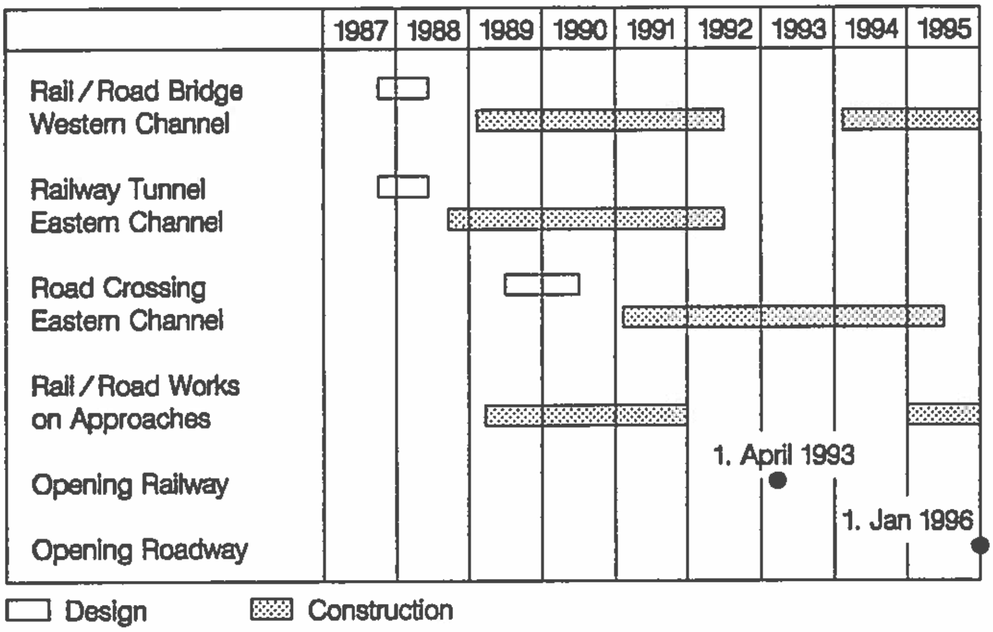


Fig. 3. The Great Belt Link Master Plan

Railway Tunnel

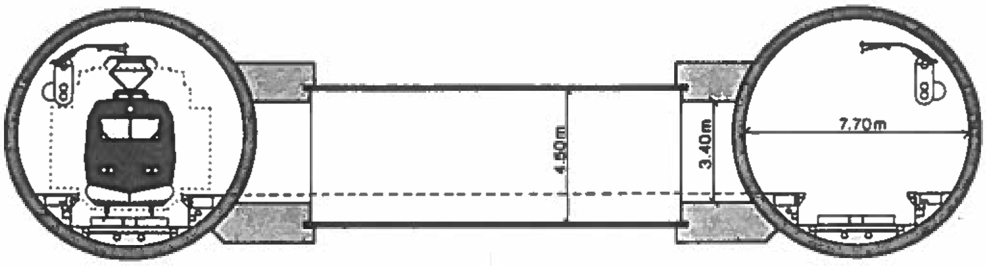
For the railway tunnel 3 different solutions were prepared for tender issue in February 1988:

- an immersed, rectangular concrete tube tunnel
- an immersed binocular shaped steel tube tunnel
- a twin bored tunnel lined with concrete segments

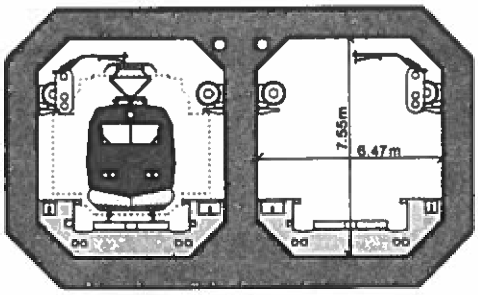
The tender designs were prepared by two joint ventures, COWIconsult-Parsons Brinckerhoff International for the immersed tunnel solutions, and COWIconsult-Mott, Hay & Anderson International for the bored tunnel solution.

Fig. 4 shows cross sections of the three tendered solutions.

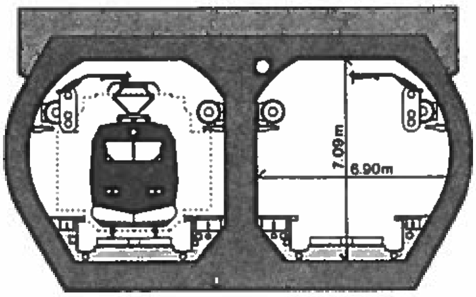
After tender evaluation, including technical, economical and enviromental considerations, the bored tunnel was selected for construction and a US$ 400 million construction contract was signed in November 1988 with the Danish-led Monberg & Thorsen Group (MTG). The Joint Venture COWIconsult-Mott Hay & Anderson International was awarded the detailed civil design, tender design of mechanical systems including ventilation, and general supervision and engineering follow-up during construction.



BORED TUNNEL



IMMERSED CONCRETE TUNNEL



IMMERSED STEEL TUNNEL

Fig. 4. Tender Designs for the Eastern Railway Tunnel

Western Bridge

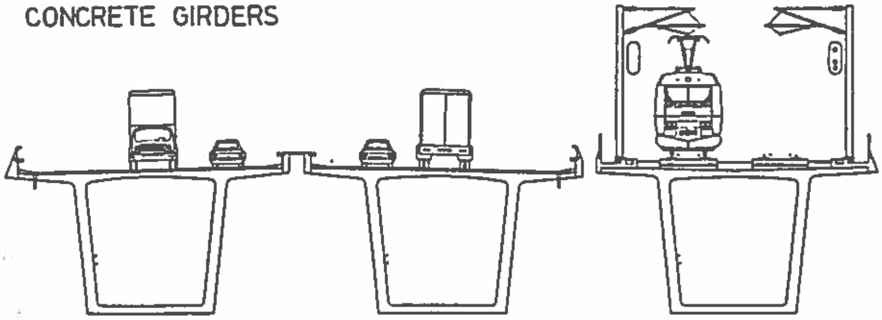
The Tender Design for the combined western railway and road bridge was completed in April 1988 by a joint venture between COWIconsult, Carl Bro Group and Leonhardt, Andrä und Partner.

Three different solutions were elaborated:

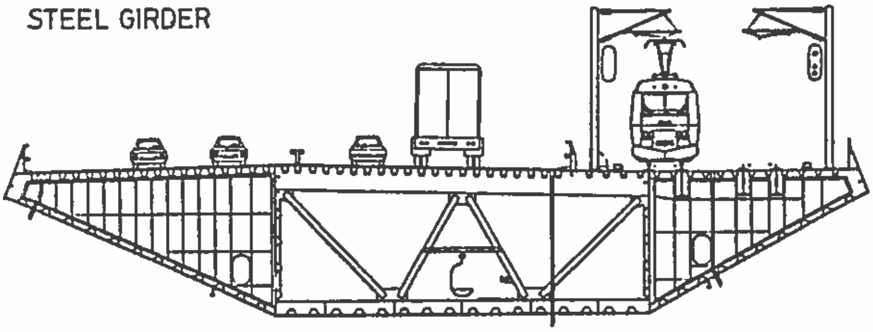
- a triple concrete box girder bridge (105 m spans)
- a single box steel girder bridge (105 m spans)
- a composite concrete deck/steel truss girder bridge (144 m spans)

Fig. 5 shows superstructure cross sections for the three tendered solutions.

CONCRETE GIRDERS



STEEL GIRDER



COMPOSITE GIRDER

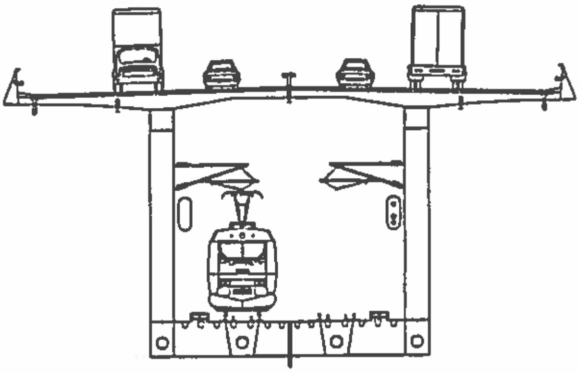


Fig. 5. Tender Designs for the Western Bridge

After tender evaluation an alternative concrete solution proposed by one of the bidders was chosen and a US$ 400 million construction contract was signed in June 1989 with the Danish-led European Storebælt Group.

Eastern Bridge

It is presently expected that two solutions will be elaborated based on conceptual designs prepared in 1987 by COWIconsult.

The two conceptual designs, a cablestayed bridge and a suspension bridge is shown in fig. 6.

Tender design is scheduled for completion by spring of 1990 and construction contract is expected to be awarded in the spring of 1991 for completion in 1996.

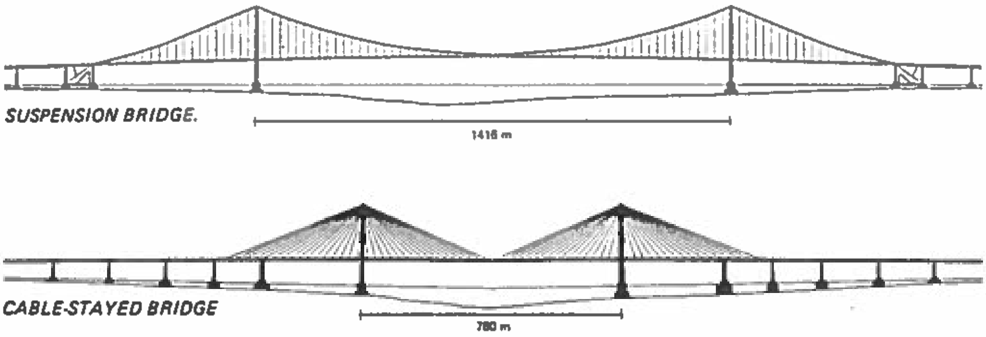


Fig. 6. Eastern Bridge Alternatives

2. RAILWAY TUNNEL

The tunnel will consist of 7.7 m diameter separate tubes for trains in each direction, with cross passages at 250 m intervals for mechanical and electrical equipment and emergency escape routes.

The spacing between the tube centres is 25 m narrowing down to 9.5 m at the portals. A section in the tunnel and cross passage is shown in fig. 7. Sumps are provided at every 2 km. All linings for tunnels and sumps are segmentally bolted linings.

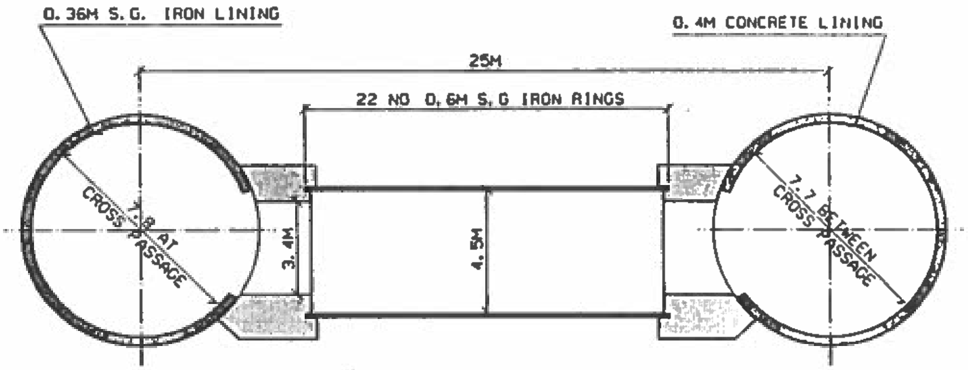


Fig. 7. Cross Section in the Bored Tunnel

The approximately 8.0 km length of tunnels are carried out as TBM driven tunnels over the central 7300 m with short transitions of cut and cover tunnels at each end totalling 650 m.

The main tunnels will generally be lined with a 400 m thick segmental reinforced concrete lining with 6 segments plus a key as shown in fig. 8. The lining is designed to be waterproof for the full hydrostatic pressure of 8 bar. Water tightness is obtained by use of gaskets between segments.

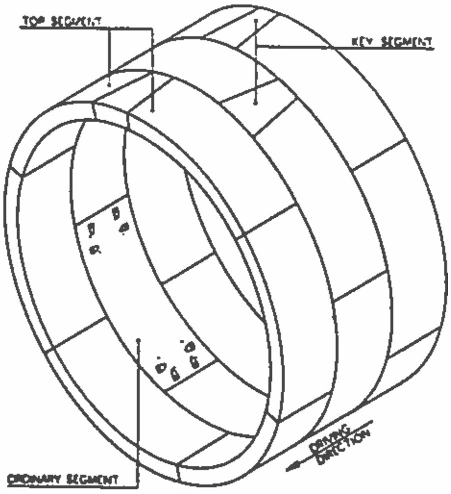


Fig. 8. Segmental Lining

The geological conditions in the Eastern Channel are shown in fig. 9. The channel is a glacial erosion channel formed in layered strata of glacial tills and upper paleocene marls underlain by lower paleocene limestones.

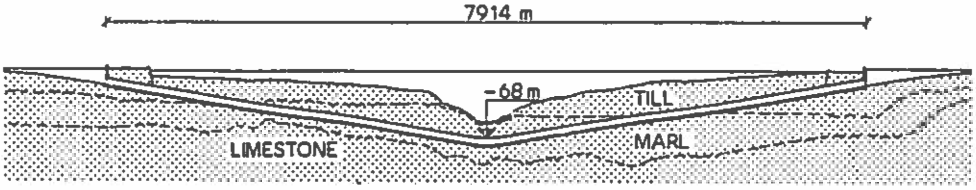


Fig. 9. Longitudinal Geological Profile

The till incorporates meltwater deposits containing water at pressures up to 4 bar. it also contains granitic boulders up to and possibly exceeding 3 m. The marl is sometimes highly fissured with hydrostatic pressures up to 8 bar.

The following interesting features have been selected for a more detailed description:

- The tunnel boring machines
- Sharing of construction risk
- Lining durability
- Deep open ramps

Tunnel Boring Machines

The contract includes delivery of 4 full face tunnel boring machines (TBMs) designed for the very onerous ground conditions and up to 80 m water depth. The machines will start from the cut and cover sections at the portals and meet below the deep channel.

In order to deal effectively with the ground conditions and still maintain a reasonable rate of progress, the TMBs must be versatile, robust and high-powered, able to drive the required length of tunnel without major breakdown. The TBMs will be of the EPBS type (Earth Pressure Balanced Shield). To achieve acceptable rates of progress in good ground conditions, an open mode of operation is being called for.

However, as the machines also need to be able to work under high hydrostatic pressures in the meltwater pockets and in the fissured marls with highest permeability, efficient operation in closed mode will also be necessary. The ability to switch rapidly from open to closed mode is essential.

Longitudinal section in the TBM is shown in fig. 10.

The more unique features of these sophisticated machines are the boulder handling, the mode switch and the main bearing seals.

The primary design parameters for the full face cutterhead are that they should be able to cope not only with till and marl soils, but also with large boulders imbedded arbitrarily in the till. The granitic boulders can reach compressive strengths of 200 MPa and diameters exceeding 3 m. The cutterheads are therefore designed with peripheral bearings for a high torque and unsymmetrical impact loads resulting from the grinding of large boulders, whereas smaller boulders up to a diameter of 0.4 m are allowed to pass through.

The cutterheads will be equipped with a combination of exchangeable disc cutters and drag bits specially engineered for optimum performance in the variable soil strata.

Pressure in the working chamber is regulated by an automatic system which monitors and controls both the extension speed of the thrust jacks and the rotation of the screw conveyor.

The special muck conveyor with separately working tandem screws and two plug zones enables graduated and rapid switches of working mode from fully open to fully closed.

In open mode only the first screw is used, which is helical on the first part allowing boulders up to 0.4 m, and provided with a central shaft on the last part. Large boulders are removed from a boulder trap.

In closed mode both screws are employed and plug zones activated. The first plug between the screws is generated by different speeds of the screws. The plug length can be varied by longitudinal shifting of the second screw, enabling also excavation of the plug. The second plug is generated in the second screw by a casing rotator working at different speed to the screw and forms an additional adjustment and safety.

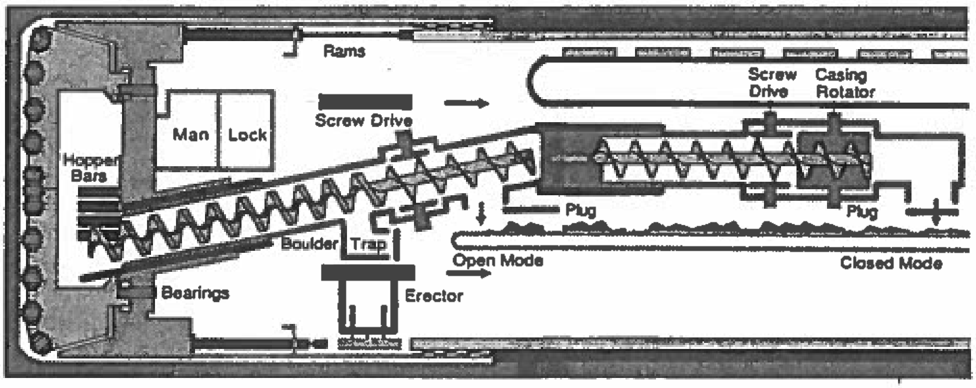


Fig. 10. Section in Tunnel Boring Machine

The tandem screw can be retracted and the working chamber closed during works in the front or maintenance of the screws.

A man lock and emergency transport is provided.

For installing the tunnel lining, the TBM´s segment erector is able to rotate through 360 degrees, and pick up segments from an overhead conveyor magazine. Supply to the conveyor magazine is ensured by a crane system lifting segments from rail cars in the tunnel. The system will be capable of installing a complete lining ring in less than 25 minutes.

Sharing of Construction Risk

Although extensive borings have been made for alignment selection and along the selected alignment, such boreholes only represent facts at the discrete locations of the borings between which an interpolation must be made. Therefore, there is a risk of encountering unforeseen conditions.

In compliance with sound contracting principles, the economical construction risks should be shared so that the Contractor assumes all risks regarding methods and temporary conditions over which he exercises full control. The Owner (the Employer) carries the risks for the naturally given ground characteristics to the extent it deviates in actuality from the basis given in the tender documents.

This ideal split of responsibility is, however, not directly applicable in connection with a bored tunnel project since the ground is a complex non-homogeneous material with constantly varying parameters, which, in spite of probings ahead, will not be known until the cutterhead actually enters into the ground. And even then the ground is not necessarily inspectable, if the TBM is operating in closed mode.

A rather unique risk sharing has therefore been incorporated in the construction contract.

According to this, the Contractor assumes the risks associated with :
- TBM design, testing, commissioning and delivery
- TBM progress, to be demonstrated during initial testing
- TBM operation, maintenance, including replacement of disc cutters and drag bits
- TBM crew
- Ground probing ahead

whereas the Employer assumes the risks associated with :
- Overall TBM performance requirements
- Reduced progress due to soil conditions (provided that the TBM is in full operational state, operated by qualified crew, has passed acceptance test etc.)

Lining Durability

Special emphasis has been given to the long term durability of the concrete lining exposed to aggressive environment. Investigations have revealed that while carbonation, bacteriological and sulphate attack, alkali-aggregate reaction, and stray and induced current corrosion were all potential corrosion parameters, by far the most serious risk seems to be reinforcement corrosion due to chloride ingress.

The tunnel segments are exposed to ground water chloride levels of 19.000 ppm (1.9%), being a medium high chloride concentration, and sulphate levels of 2.700 ppm being a rather severe concentration needing Type V-sulphate resistent cement according to the ACI specifications.

The aggressivity of the environment and the resulting concentration of chlorides and sulphates on the inner surface of the tunnel is illustrated in fig. 11.

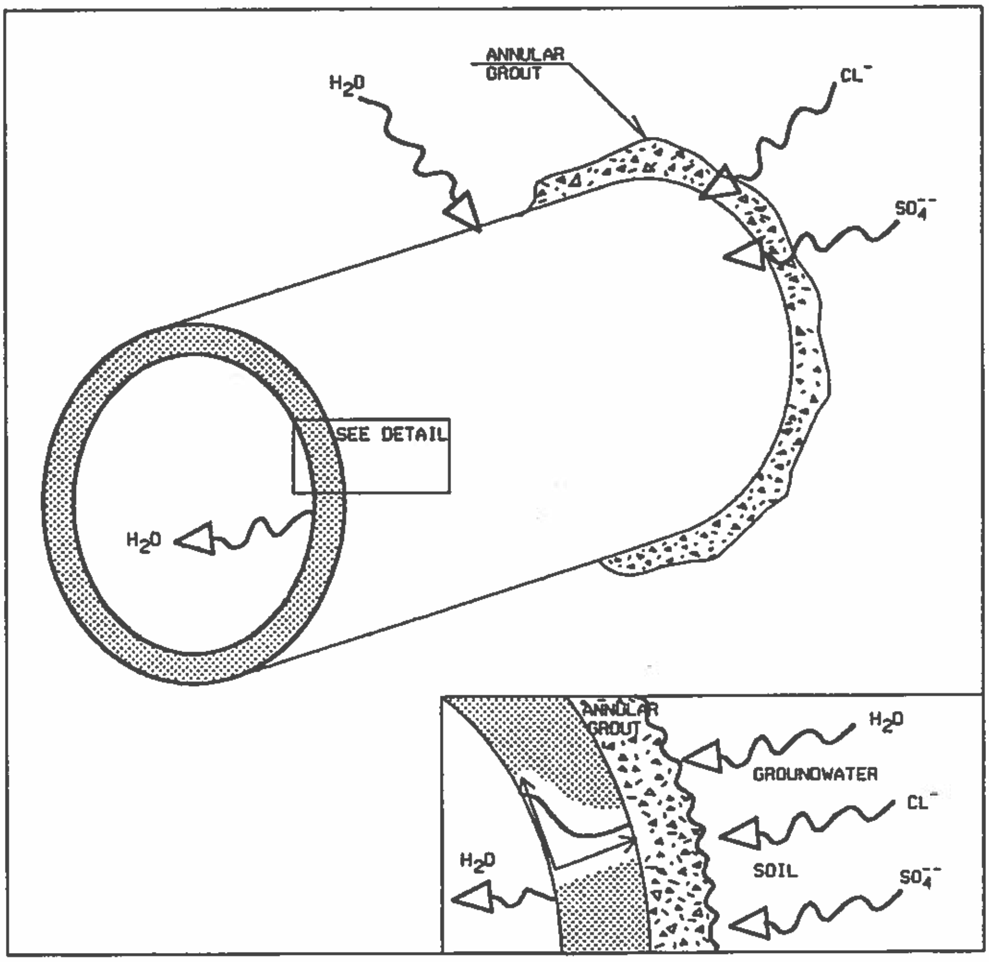


Fig. 11. Aggressivity of Environment

A Multistage Protection strategy has been adopted with chloride barriers, each with its own either high or low degree of reliability:

- The first barrier is the annular grout filling the gap between the P.R.C. segments and the soil. By specifying a well formulated tixothropic grout, with a relatively high level of C_3A-content, some chlorides will be bound chemically, and some sulphates will be bound by a sulphate reaction at a location where such reactions with possible expansions do no harm, and even might be beneficial.

- The next barrier is the segment concrete composition and quality for which a very low diffusion coefficient of 600 x 10^{-15} m^2/s, and a permeability of 25 x 10^{-15} m/s has been specified. This ensures a very slow transport through an uncracked segment. Furthermore, a three powder cement mix with OPC, Micro Silica (MS) and Flyash (Pfa) has been specified. This improves the impermeability and is advantageous in preventing sulphate attacks. A relatively low C_3A-content of 3-5% has been specified in order to reduce expansions from sulphate attack and at the same time obtain some advantage from chloride binding.

- As water with dissolved agents reaches the inner, drying surface, the water evaporates leaving behind the chlorides to concentrate. This is especially critical in joint areas. When high Cl^--concentrations reach the inner layer of reinforcement, corrosion may occur, with the great risk of subsequent spalling of the concrete cover. Therefore it has been decided to use fusion bonded epoxy coating of the welded reinforcement cages. The fluidized bed dipping technique for complete reinforcement cages has been adopted.

- A 100 year actual service life of epoxy coating is so far unproven. Although the technology of epoxy coated rebars has been used in bridge building for 15-20 years, in particular in USA, it has not previously been used in tunnel linings. Therefore, the electric bonding of all reinforcement in the fully welded cages is provided, with the advantage of facilitating later installation of cathodic protection based primarily on external anodes, if required.

Deep Open Ramps

The tunnel is approached at each end by open ramps which are constructed as an open cutting and carry the railway tracks down to about 14.5 m below sea level at the tunnel entrance.

At Sprogø the 1.5 km long ramp will be constructed on land reclaimed by hydraulic filling with sand won from the sea bed.

Layout of the ramp is shown in fig. 12 and a cross section at the portal building is shown in fig. 13.

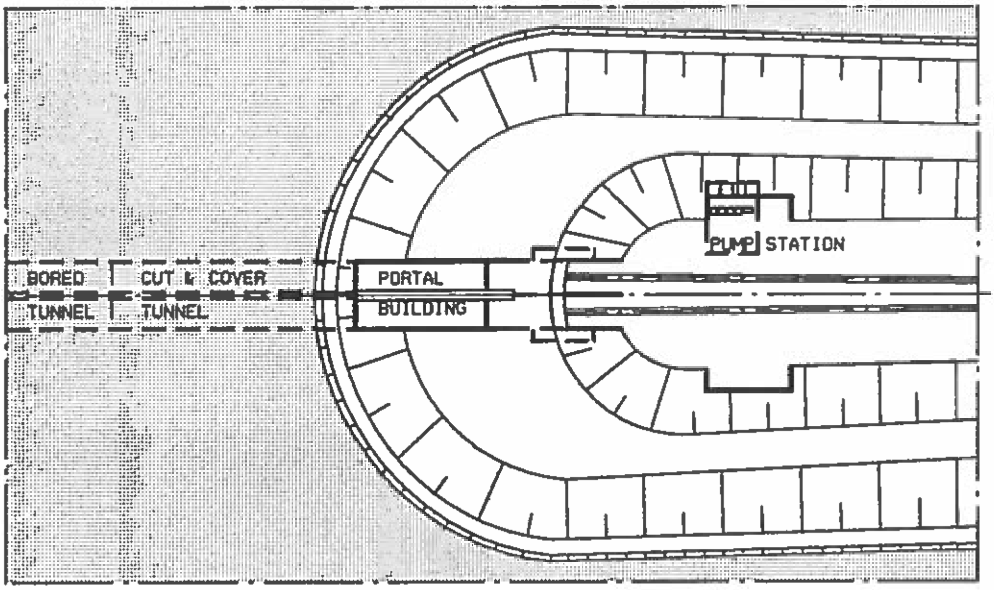


Fig. 12. Plan of Ramp

To protect the ramp against wave action and weather induced high water, the Great Belt being non-tidal, the ramp is surrounded by a dike with its crown 4 m above sea level. The dike is provided with coastal protection around the reclaimed area and landscaping works.

Seepage trough the sand dikes at Sprogø is reduced by a sheet steel pile wall driven into the upper impervious till of the former sea bed and a clay core in the area around the portal. Any residual seepage will be picked up by a system of sub-soil drains.

Artesian uplift from the aquifer underlying the till in which the lower ramp is constructed is releaved by a network of 150 pressure relief wells which are bored down to about 30 m below sea level.

A surface water drainage system is designed to protect the tunnel against the ingress of rainwater from a storm with an estimated return period of 1000 years by a combination of storage basins and submersible pumps with a total capacity of 2.5 m^3/sec.

The aggressive nature of the ground water requires that there are separate surface and groundwater drainage systems, which flow to separate sumps in a pump station situated adjacent to the portal building from which the drainage water is pumped to the sea.

At Halsskov the geometry of the 1.3 km long ramp is similar, but because of the more protected location, the dikes have a crown level 2 m above sea level as opposed to 4 m at Sprogø.

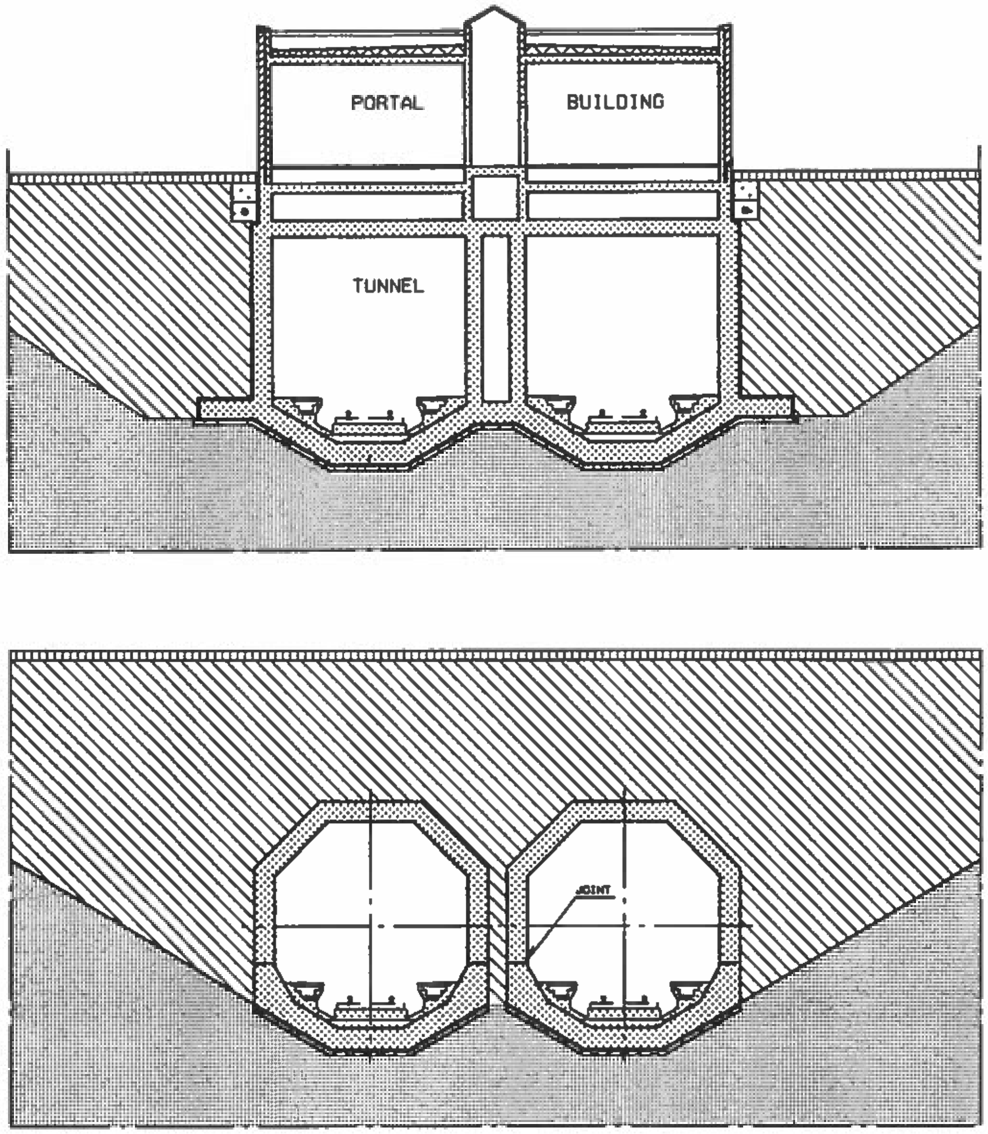


Fig. 13. Section in Portal Building and Cut & Cover Tunnel

The dikes will be constructed from compacted till from the excavation of the lower ramp.

The system of drainage installed will be similar to that of Sprogø, except that the lower permeability of the aquifer underlying the till means only 120 pressure relief wells.

3. WESTERN BRIDGE

West of Sprogø the Great Belt Link combines in the 6.6 km long high speed railway and 4-lane motorway bridge from Sprogø to Funen.

Fig. 14 provides a perspective view of the bridge alternative now being constructed by the European Storebælt Group.

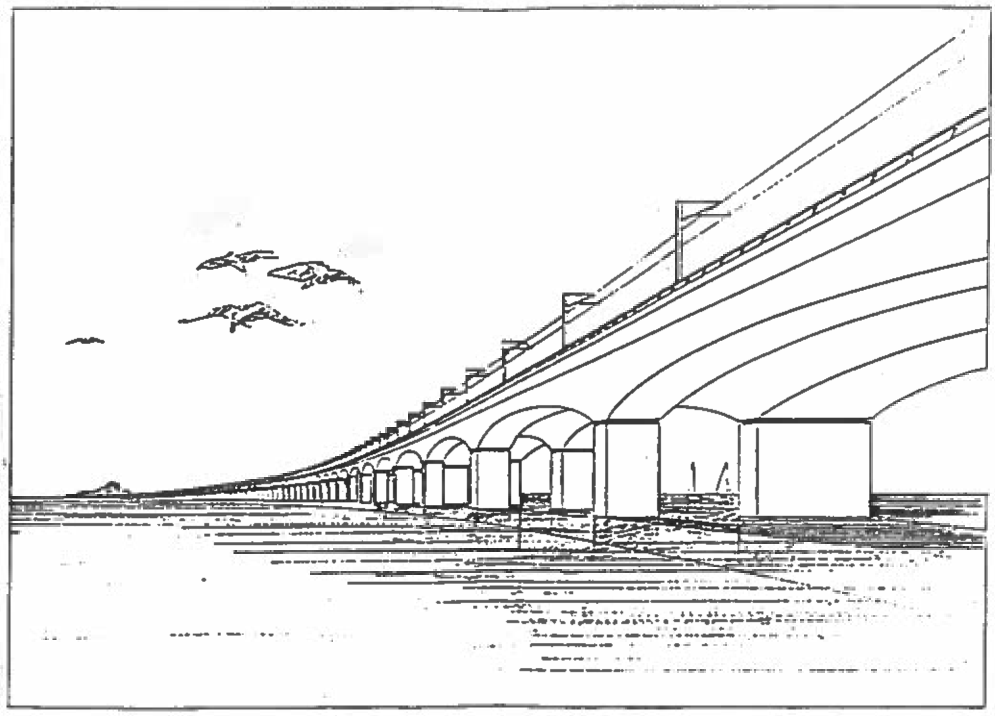


Fig. 14. Perspective View of Western Bridge

Below are presented certain special features related to construction of a highspeed railway bridge under semi offshore conditions:

- Prefabrication and installation
- Bridge expansion joints
- Hydraulic buffers
- Dynamic interaction train/bridge

The presentation includes features studied and developed for the Client's tender designs by the Joint Venture COWIconsult-Carl Bro Group-Leonhardt, Andrä und Partner, and which are presently being further developed for the alternative construction design by the contractor.

Prefabrication and Installation

The overall concept has been based on prefabrication of all main elements and installation by large capacity marine equipment.

A total of 310 pre-fab units shall be cast comprising 62 caissons, 124 pier shafts and 124 bridge girders.

The prefabrication yard located in a harbour near the bridge site has 6 fabrication lines, 2 for superstructure girders, 2 for caissons and 2 for pier shafts. The layout of the yard is shown in Fig. 15.

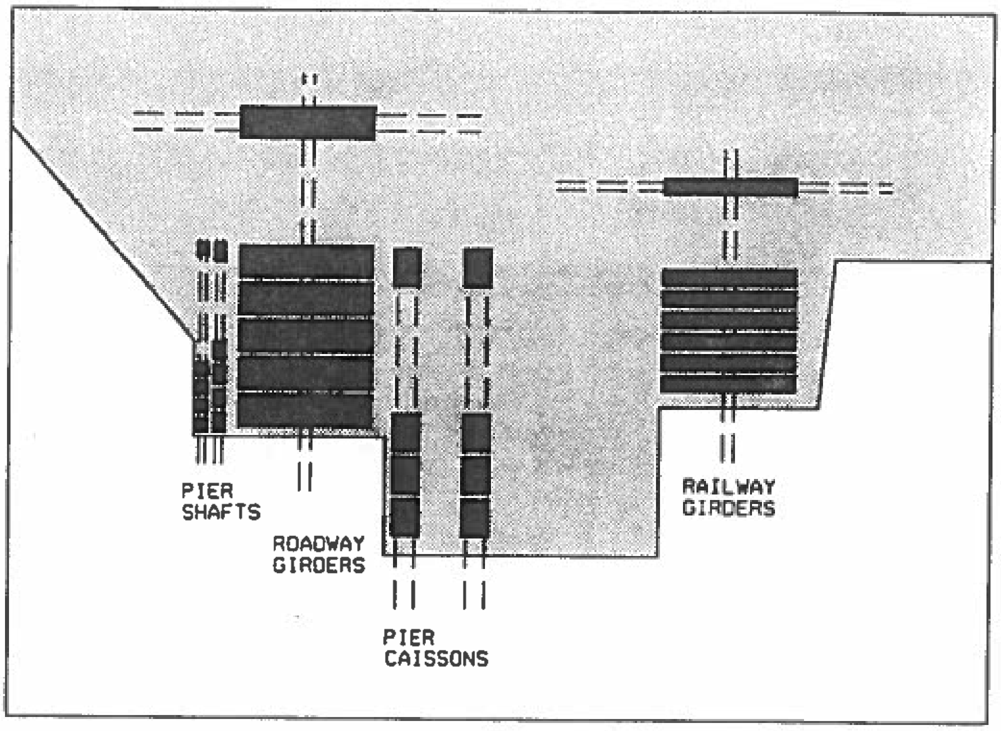


Fig. 15. Prefabrication Yard

All elements weighing up to 5800 t will be cast, moved, stored and loaded out on piled trackways. The top surface of the trackways will be greased steel and the load moving force will be provided by gribber jacks or by strand jacks. This means that heavy gantry cranes or the use of a drydock as a production site for caissons can be avoided.

Fig. 16 shows a vertical section in caisson and pier shaft after installation.

The caissons consist of a cellular open top base and a shaft capped by a 2 m thick plinth sized to receive the pier shafts. All caissons have identical grid dimensions at the base in order to achieve industrialized production based on slipforming. However, the cantilever of the 1.2 m thick bottom plate can be varied to provide foundation areas from 550-700 m^2 as required.

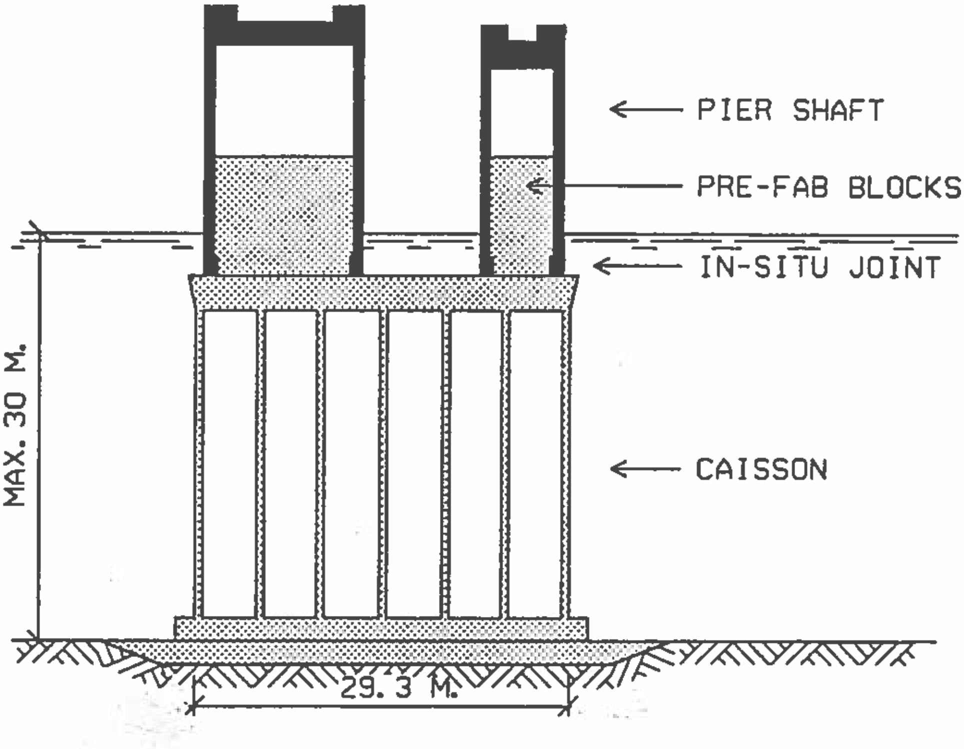


Fig. 16. Caisson and Pier Shaft

The pier shafts have rectangular hollow cross sections with a constant wall thickness. The pier shafts are capped by a 2.5 m plinth. In the lower part of the pier shafts, concrete fill is provided by prefabricated blocks, 100 mm less in length and width than the inside shape of the shaft. The 50 mm annular space between blocks and shaft walls shall be grouted.

The superstructure elements are 110.4 m long haunched box girders with depth decreasing parabolically from 8.55 m at the piers to 5.10 m at midspan for the railway girder. The corresponding dimensions for the roadway girder are 7.20 m and 3.75 m, respectively. Each girder will be assembled from three large prefabricated pieces comprising one pier head and two identical cantilever units. These elements are connected through 1.0 m wide wet joints cast in the prefabrication yard.

Fig. 17 and 18 show sections in the bridge superstructure.

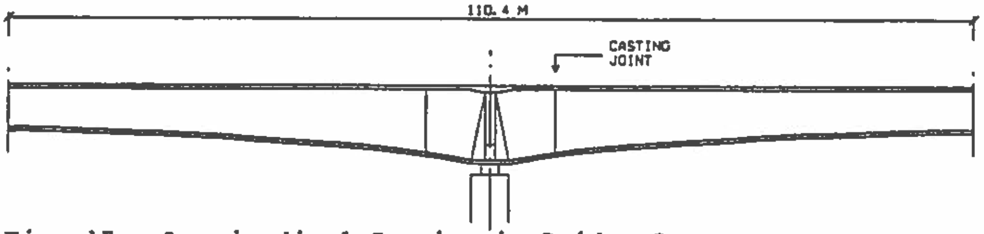


Fig. 17. Longitudinal Section in Bridge Superstructure

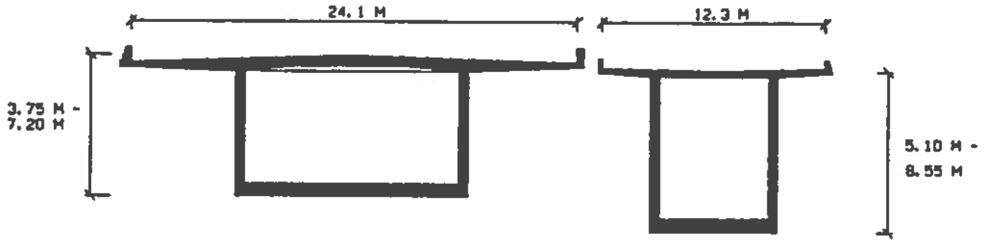


Fig. 18. Cross Section in Bridge Superstructure

The installation of the bridge elements will be performed by means of a large U-shaped crane vessel with overall dimensions of 80 x 80 m and a lifting capacity of approx. 6000 t. This vessel will place all 310 units, i.e. caissons, pier shafts as well as bridge girders.

The caissons, weighing up to 5600 t, will be placed by the heavy lift vessel on compacted, levelled stone beds of 1.5 m to 5.0 m thickness. Soft superficial layers will be excavated.

After placing and sandfilling a caisson, the pier shafts including the pre-fab concrete blocks are placed on top. The two elements are then connected by a wet joint cast within dewatered cofferdams approximately 3 m below waterline.

The bridge girders weighing up to 5800 t will be lowered and placed on temporary elastomeric bearings. After placing on the temporary supports, jacks will take over the girder weight and provide fixity for out-of-balance loads. Finally, after casting the in-situ mid span joint and applying temporary prestressing, the girder will be lowered onto its permanent bearings.

Bridge Expansion Joints

For the benefit of low construction and maintenance costs and a high travelling comfort, modern bridge technology develops in the direction of bridge continuity over as many spans as possible and a minimum number of expansion joints.

For the combined road and rail bridge the overall expansion arrangement, as shown in fig. 19, is primarily governed by the available railway expansion joint structures with proven performance.

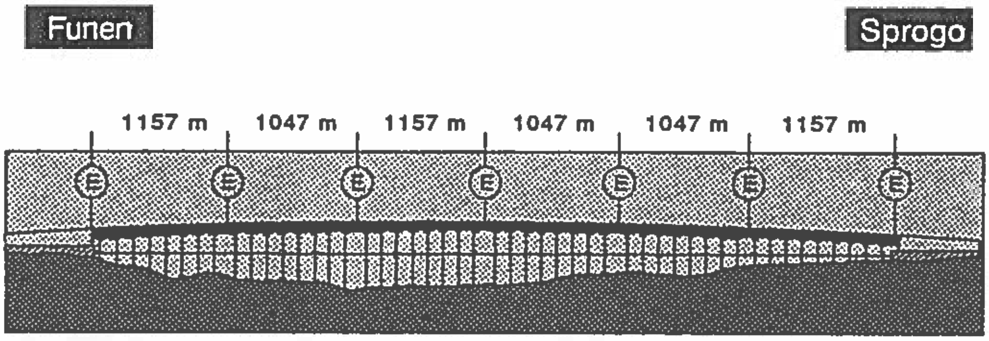


Fig. 19. Expansion Sections in the Superstructure

The expansion joints connecting the continuous superstructures of about 1200 m length will move between ±350 mm and ±600 mm. A total movement capacity of up to 1200 mm has so far only been seen in Japan for the Honshu-Shikoku Bridge Project. Rail expansion joints for that project provides movement capacity up to 1500 mm.

The major requirements to the Western Bridge railway expansion joints and track structures are:

- Movement
  - Rail dilatation, <1.5 m

- Angular rotations
  - Freight trains, < 120 km/h, < 6 o/oo
  - Passenger trains, 160 km/h, < 5 o/oo
  - Passenger trains, 200 km/h, < 4 o/oo

- Vertical radius of rail
  - > 500 m

- Comfort level
  - Vertical acceleration $2.0\ m/sec^2$ for passengers
    $2.5\ m/sec^2$ for engine driver

The requirements to angular rotation, vertical radius of rail and comfort level are parallel requirements focusing on a high comfort level and high safety of operation.

The railway expansion joint arrangement as shown in fig. 20 and 21 are capable of meeting these requirements, and are based on development of experience gained in Japan and West Germany.

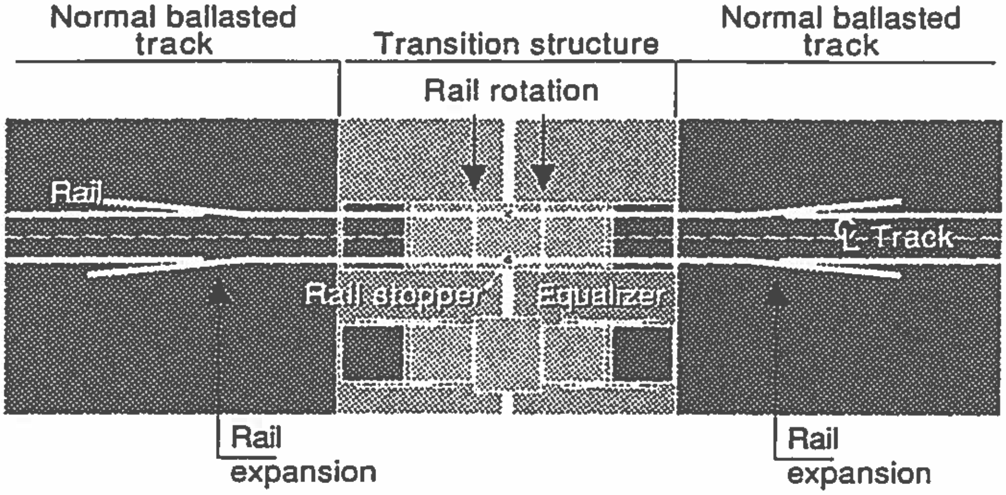


Fig. 20. Plan of Railway Expansion Joint

This joint consists of a transition rail and an outside rail which can move relative to each other. The transition rail is assisted by two side rails in order to allow for a span of up to 720 mm in total or ±360 mm as respective movement. The shown double joint arrangement can handle movement of ±720 mm or up to 1440 mm in total and covers thus the need of the Western Bridge.

The total movement of the joint is absorbed in two places and thus reduced to the half at each location.

To minimize the angular rotation, and maximize the radius of rail curvature, the angular rotation is absorbed at two locations as well.

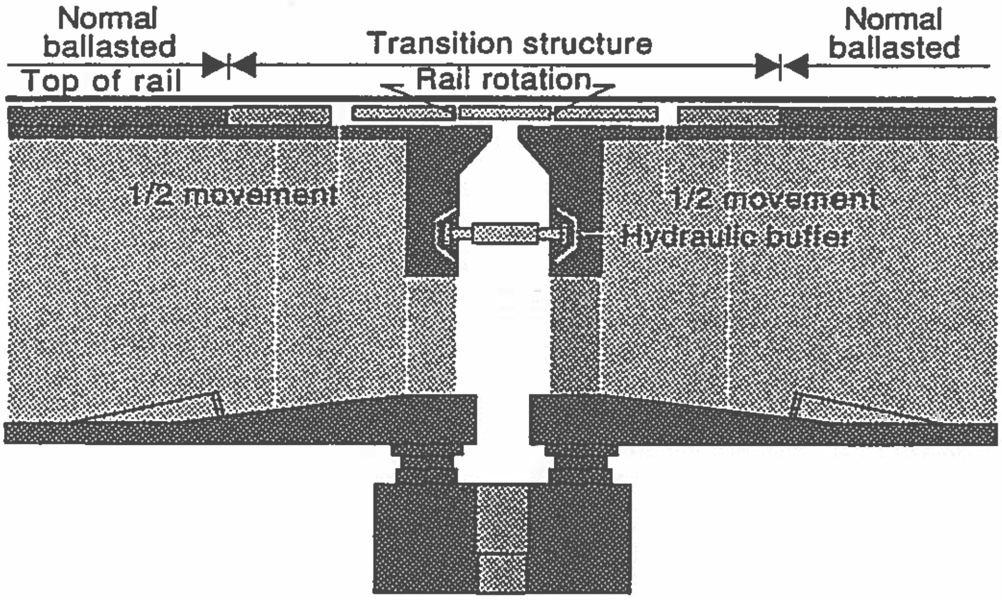


Fig. 21. Section in Railway Expansion Joint

The main elements of the joint are:

- Two transition rails being symmetric about the centre line of the joint which are supported by the transition beams in vertical and longitudinal direction.
- Three steel transition beams which are kept in the centre of the joint permanently by two pairs of equalizers; these are double acting, interconnected hydraulic cylinders which subdivide any joint movement into two equal parts.
- Two special closing slabs, which form the transition to the normally ballasted track and support the equalizers.
- Two hydraulic buffers, which are needed for absorption of braking forces.

The arrangement allows for access and exchange of parts for maintenance.

The railway expansion joint is an essential part as regards the safe operation of the railway. The joint is a new development and it has been decided to install and test a prototype of the rail expansion joint in the Danish State Railways´ main line.

Hydraulic Buffers

In all railway joints two hydraulic buffers are arranged. Each buffer is designed for one half of the maximum braking force and is blocking sudden movements from the braking or acceleration of trains.

The buffers are not developing any restraint forces from slow thermal movements of the superstructures.

The two buffers in each joint are limiting the longitudinal movement within the joint to 30 mm under braking conditions.

Dynamic Interaction Train/Bridge

Extensive dynamic investigations have been carried out in order to check whether the comfort level for passengers crossing the bridge by train will be as required.

The dynamic behaviour of the train is influenced by two main effects:

- rail irregularities
- superstructure deflections

Different trains to operate on the bridge were modelled.

A typical model is illustrated in fig. 22 for the IC3 train set. Such a model consists of the carbody, the secondary suspension between carbody and bogie, the bogies and the primary suspension between bogie and axle. The train velocity considered was in the range of 160 to 200 km/h.

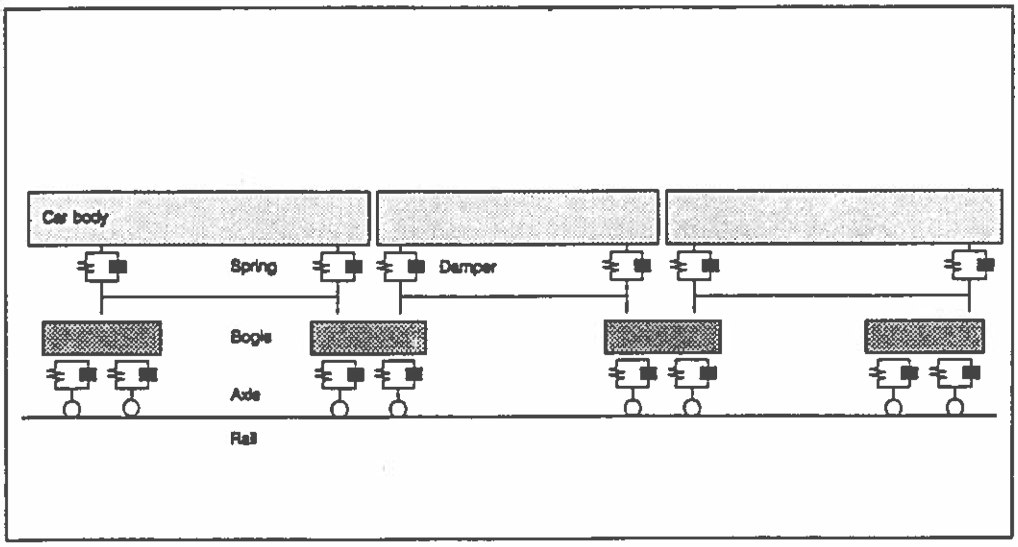


Fig. 22. Model for Dynamic Interaction between IC-3 Train Set and Bridge

The vertical acceleration due to track irregularities have been studied using a power spectra for the track imperfections which has been established by DB (German Railways) and verified by SNCF (French Railways) for conditions on lines, on ground. No spectra are available for bridge structures although a reduced level of irregularities is to be expected.

The study followed two different ways of investigation: the time history calculation and the Fourier acceleration spectra investigation. The latter showed dominant vehicle eigenfrequencies in the range of 1.4 - 1.8 Hz for the carbody movements and smaller ones at 4-5 Hz for bogie bounce movements.

For the 6,612 m long Western Bridge the calculated accelerations amounted to

1.20 - 1.60 m/sec^2	for passenger trains	and
1.30 - 1.70 m/sec^2	for locomotives.	

A study of vertical accelerations due to bridge deflections has been undertaken by the Technical Headquarter (BZA) of DB on behalf of the consultants.

Some main results are illustrated in fig. 23. The graph shows the vertical acceleration for an IC-3 train set passing the bridge at 200 km/h. The following can be seen from the graph:

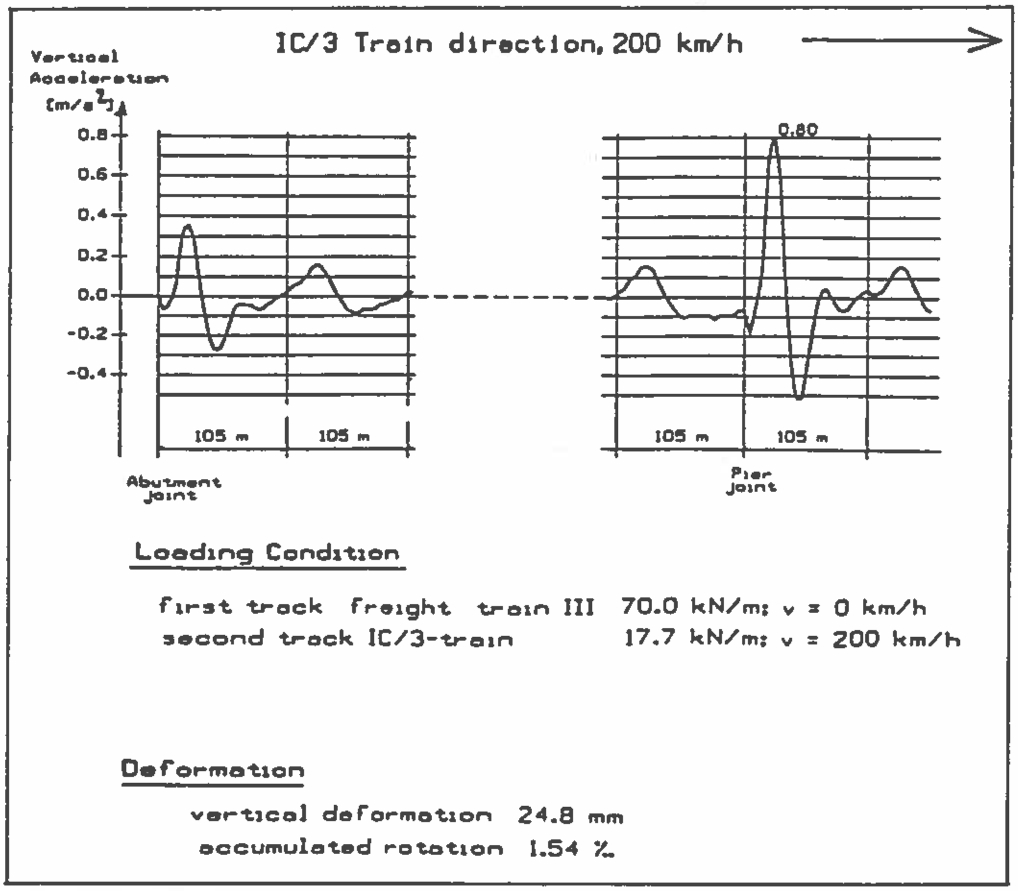


Fig. 23. Plot of vertical acceleration for concrete tender design

- the acceleration at the abutment joint is about half of the acceleration at the pier joint,

- the peak values are reduced to very small accelerations within one period, which is equivalent to a frequency of 1 Hz or a travel distance of about 50 m.

The results of the two separate investigations of vertical acceleration were finally combined on the basis of root mean square values and the dominance of either one or the two effects. The resultant peak accelerations comply with the established comfort level criteria, and can be rated into the high quality comfort class for train operation at velocities of up to 200 km/h.

It should be mentioned that the given deformation restrictions:

- $\leq$ 4 o/oo for v = 200 km/h
- $\leq$ 5 o/oo for v = 160 km/h

were found to be practically equivalent to the comfort level requirements.

4. EASTERN BRIDGE

The third major component of the Great Belt Link is the high level bridge across the Eastern Channel. This will be the most spectacular part of the link. It will be visible at great distance and the impact on the seascape will be considerable.

As experienced with earlier major Danish bridge projects, such as the Little Belt Bridge and the Farø Bridges, an open cooperation between engineer and architect is essential for achieving a bridge design in harmony with the environment. In this case the project architect are the Danish architects Dissing & Weitling.

The conceptual design solutions for cablestayed and suspension bridge alternatives, on which the tender design will be based, are shown in fig. 24 and 25.

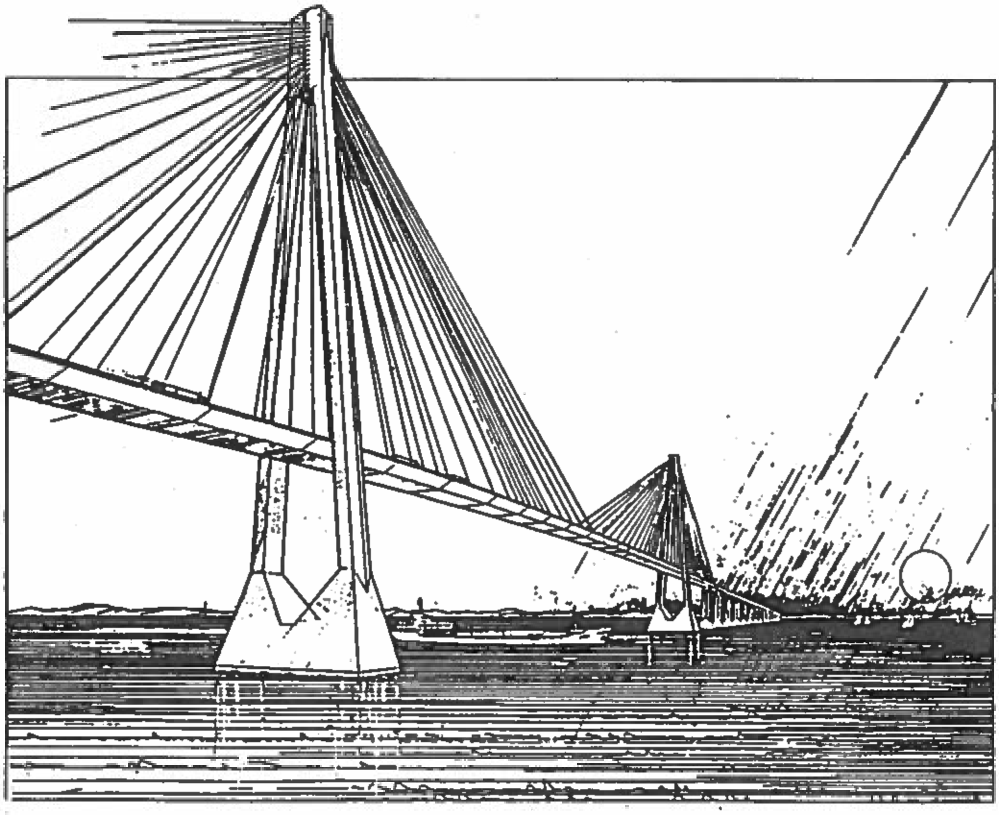


Fig. 24. Perspective View of Cablestayed Bridge

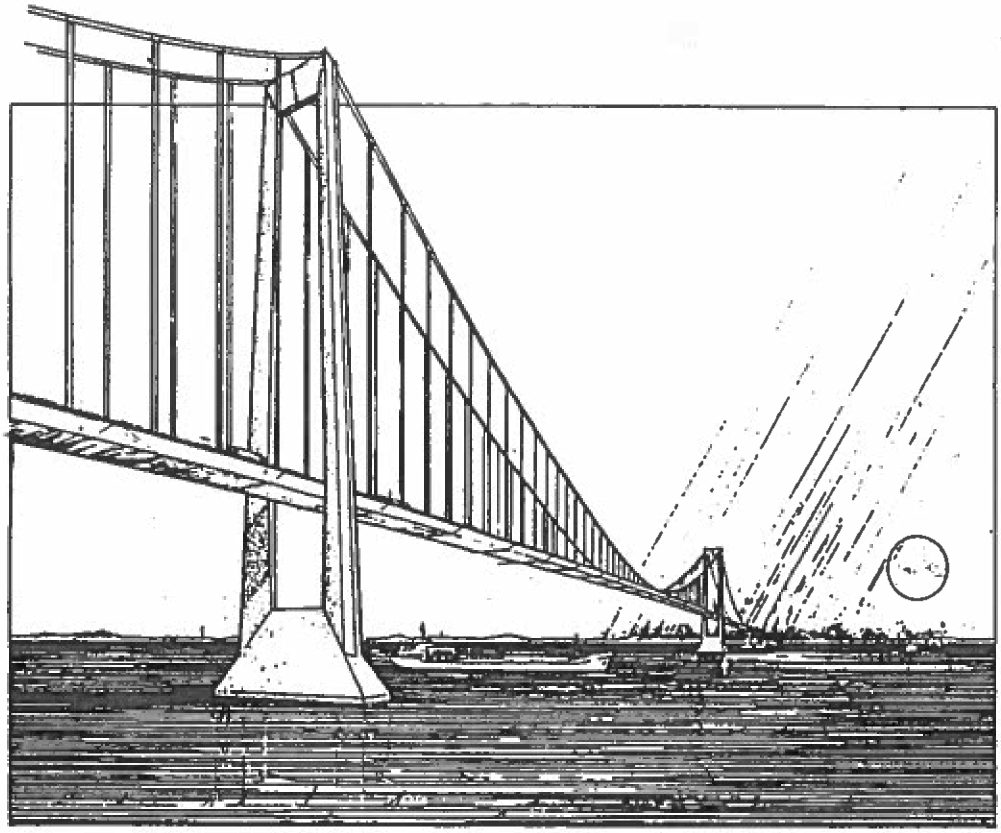


Fig. 25. Perspective View of Suspension Bridge

Below are presented the following features of particular importance for the tender design of a long span motorway bridge:

- Cable technology for cablestayed bridge
- Cable technology for suspension bridge
- Anchor blocks for suspension bridge
- Wind engineering
- Corrosion protection by dehumidification
- Ship collision risks

Cable Technology for Cablestayed Bridge

Span lengths of 900 m and more are under evaluation for the Eastern Bridge. In the design of cablestayed bridges with very large spans, the following matters are accentuated:

- Flexibility of the structure due to reduced effective modulus of elasticity for long inclined cables

- Wind load on cablestays

- Wind induced oscillations of cables

The construction experience for cablestayed bridges is up till now limited to the span length of 465 m for the Annacis Bridge in Canada. However, the design work is ongoing at present for the Pont de Normandie in France with a 856 m main span. An overview of long span cablestayed bridges constructed during the last 30 years is given in fig. 26.

No.	Bridge	Country	Main Span (m)
1	Severin	Germany	2 x 302 = 602 ✱
2	Kniebrucke	Germany	2 x 318 = 636 ✱
3	Flehe	Genmany	2 x 324 = 648 ✱
4	Annacis	Canada	465
5	Yokohama	Japan	460
6	Skarnsund	Norway	530
7	Nogoyu	Japan	600
8	Pont de Normandie	France	856
9	Storebaelt	Denmark	900/1200

✱ Only one pylon

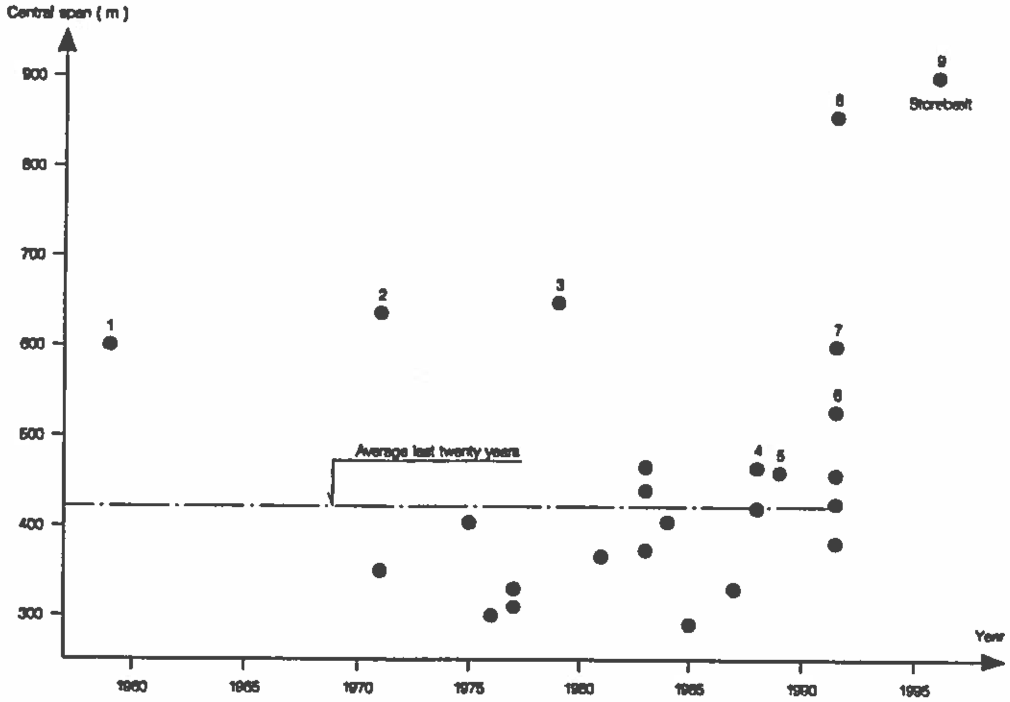


Fig. 26. Long Span Cable Stayed Bridges. State of the art

For the very long spans it is necessary to reduce the flexibility and prevent the stay cables against wind induced oscillations by stiffening ropes as shown in fig. 27.

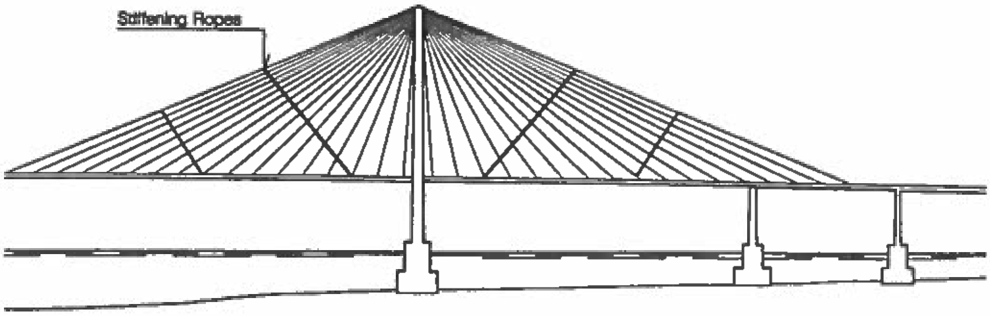


Fig. 27. Principle Arrangement of Stiffening Ropes

The design of the stiffening girder for the final structure and for the construction stage is highly influenced by the transverse windloads from the cablestays. For a 900 m main span more than half the wind load transmitted by the box girder is introduced by the cablestays. Therefore, compact stay cables with a low wind shape factor are preferable. For the Eastern Bridge the following types are considered at present:

- Locked coiled cables, zinc coated min. 300 g/m^2.

- Parallel wire cables, based on 7 mm wires, zinc coated min. 300 g/m^2 arranged in a PE-duct or extruded polyethylen covering.

- Parallel strands cable, based on zinc coated, 7 wire-strands. Various protection systems based on PE-sheathing/ducts have been developed for this system.

The three stay cable types are shown in fig. 28.

The key safety elements are the cablestays and great attention must be given to the corrosion protection, including protection of the cablestay anchorages in the box girder and at the tower top. These are the most fatigue sensitive parts of the stays.

The stay cables will be arranged in two fan shaped cable plans. The stiffening girder is outlined to be suspended by stay cables at 24 m distance, i.e. approximately 290 m^2 of bridge deck per stay cable.

A fundamental requirement to the design is the allowance for replacement of a cablestay without any temporary restriction to the traffic or any modifications to the structure.

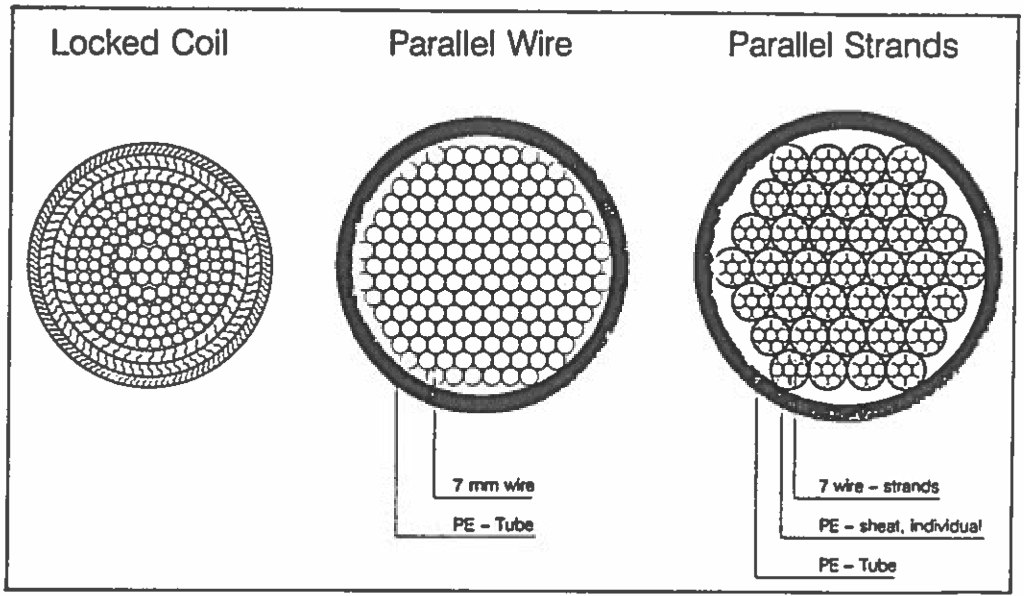


Fig. 28. Stay Cable Alternatives for Cablestayed Bridges with 900 m Main Span

Cable Technology for Suspension Bridge

It is likely that the span length for the suspension bridge concept will be fixed in the range of 1300-1600 m. The total length of the cables from anchor point to anchor point will then be 2500-3000 m. The tender design will be based on the following two, well proven construction methods:

- Erection of prefabricated parallel wire strands (PWS):

  Following this method the galvanized wires, normally dia. 5 mm, are assembled into a parallel wire strand (typically 127 wires), cut to a specified length, socketed and sealed for transportation to the site. Prefabricated cables are widely applied in the Japanese suspension bridges, and the longest prefabricated cables until now are 1780 m for the Minami Bison Seto Bridge. However, successful test fabrications have been performed for 4000 m long cables planned for the Akashi Bridge in Japan.

- Aerial spinning of cables (AS):

  Following this method the 5 mm galvanized wires are wound around a travelling spinning wheel. The aerial spinning method has always been used for the construction of large suspension bridges in the United States and Europe (except for the Little Belt Bridge where prefabricated cables were used). In Japan, the spinning method has up till now only been introduced for the Shimotsui-Seto Bridge.

The alternative main cable solutions are shown in fig. 29.

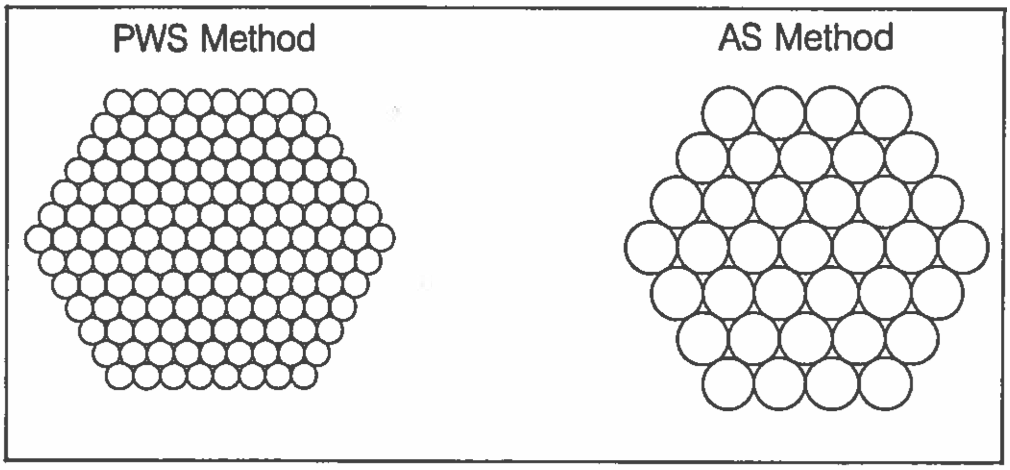


Fig. 29. Main Cable Alternatives for Suspension Bridge with 1400 m Main Span

Erection of prefabricated cables may half the effective erection period compared to aerial spinning. This can lead to a saving of 3 months construction time. Further, the work above sea level is sensitive to wind. Experience from cable spinning under unfavourable climatic conditions shows an essentially higher risk of delay compared to erection of the more compact prefabricated cables.

One of the advantages using the aerial spinning method is, however, that the cable anchorages can be designed more compact.

The final selection of cable design will be based on cost-benefit analyses where the construction period, construction costs and owner´s risk will be considered.

Anchor Blocks for Suspension Bridge

The anchor block concept proposed for the suspension bridge is a large cellular sandfilled caisson placed on a bed prepared of crushed stone. In order to avoid the solid appearance as seen for many suspension bridge anchor blocks, the upper part of the blocks has been shaped as a open frame structure. The proposal is shown in fig. 30.

The water depth at the anchor block positions is expected to be 12 m, and soil conditions are, under a thin postglacial cover, preconsolidated glacial boulder clay down to approximately -30 m underlain by a very firm calcareous tertiary clay.

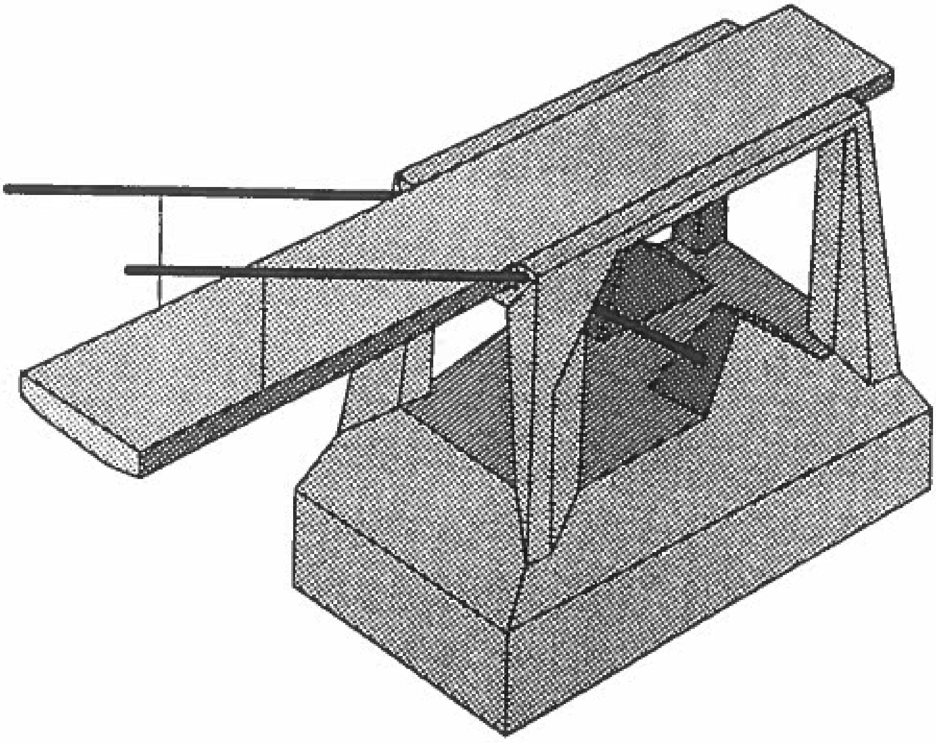


Fig. 30. Anchor Block

Therefore, the stability of the natural soil deposits is of no importance in relation to the risk of sliding along the thin weakened zone of the exavated boulder clay surface. This problem has lead to a wedge shaped stone bed in order to reduce the shear stress in this layer.

In the critical mode of failure as shown in fig. 31, the anchor block slides together with a part of the stone wedge along the thin weakened layer of clay till. This mode of failure is kinematically admissible.

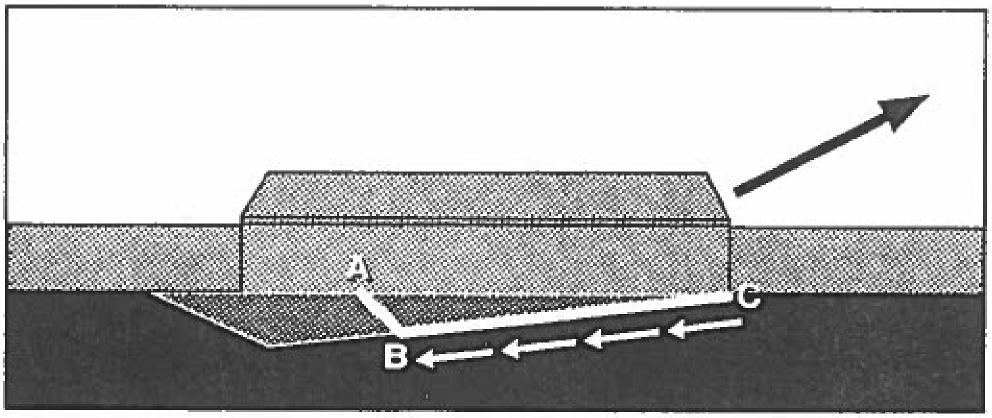


Fig. 31. Sliding of Anchor Block, Failure Mode

If the stress distribution perpendicular to BC can be sustained by the anchor block, and does not violate the failure criterion in the stone wedge or the underlaying firm clay, the rupture figure is also statically admissible.

Hence, different locations of the contact point A may correspond to different statically and kinematically admissible modes of failure with completely different factors of safety against sliding.

As the dead load of the anchor block is designed to secure that there is compression along the entire area of the block based on an elastic stress distribution, it might be tempting to regard the rupture calculations assuming partly no contact as unrealistic.

The more favourable reaction distribution assuming full contact may, however, be regarded as unstable because a random deformation effect may cause that the other reaction distributions will be possible.

The general answer to the discussion of the safety against sliding of the anchor block is that the analysis should not be based on elastic deformations, but rather on a rupture mechanism assuming a minimum contact area, which is just sufficient to support the anchor block without causing failure in the structure or the underlaying preconsolidated clay.

Wind Engineering

On site measurements of 10 min. average wind velocity and wind direction have been performed continuously during 12 years and supplemented during the last 5 years by 3 sec. maximum gust recordings in 70 m level, corresponding to the future level for the bridge girder.

Substantial reductions of characteristic design wind velocities corresponding to a 35% reduction in velocity pressure, compared to current valid codes, have been calculated from measurements and are presently being reconciled before final inclusion in the design basis.

Turbulent characteristics are being analyzed presently.

Experience from Danish and foreign bridge sites have been evaluated in order to assess the inconveniences for the users due to wind exposure.

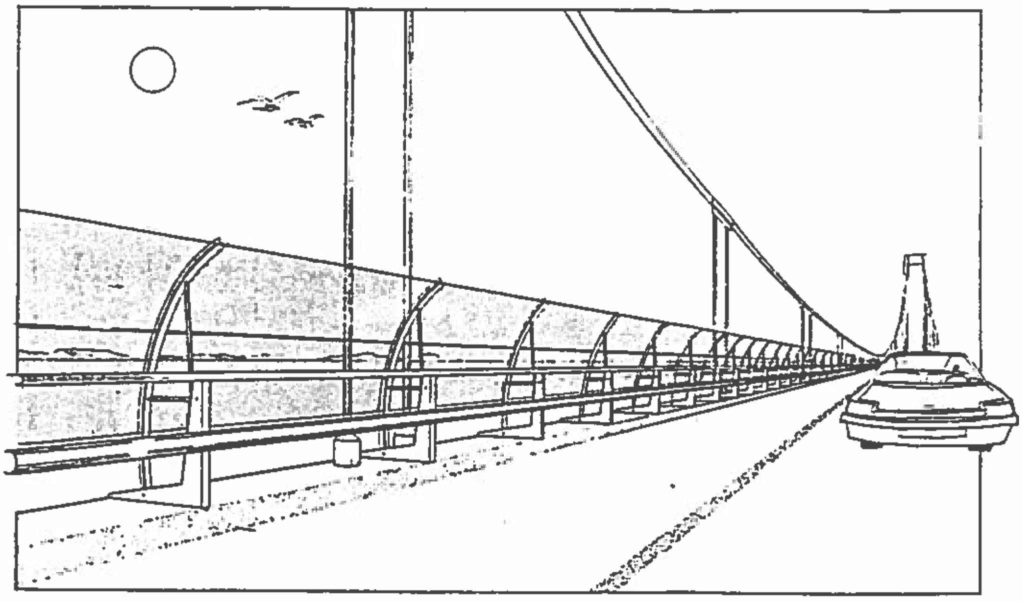


Fig. 32. Bridge with Wind Screens

Driving speed is likely to be restricted for wind speeds in the interval 15-20 m/s mean cross winds at girder level and restricted passage for light vehicles may happen for velocities in the range 20-25 m/s.

Based upon wind measurements, the expected time of inconveniences is estimated for a bridge girder with and without a 2.25 m high perforated wind screen for a typical light lorry. The time of inconveniences can be reduced by a factor of more than 5 if wind screens are provided.

The expected time of passage restriction for light vehicles on a bridge without screens is comparable to the present statistical average time of ferry closure on Storebælt and the present assumption is that windscreens are not considered necessary. Windscreens may, however, be installed after a period of operation, if experience prove it necessary.

Section model investigations of catastrophic responses of conceptual designs for a 1400 m suspension bridge and a 780 m cablestayed bridge have been made and results are being analyzed.

Wind screens (50% perforation generally and completely open at the lowest 0.6 m) have been fitted on the model and tests performed corresponding to normal, iced up and iced up plus snow accumulation conditions.

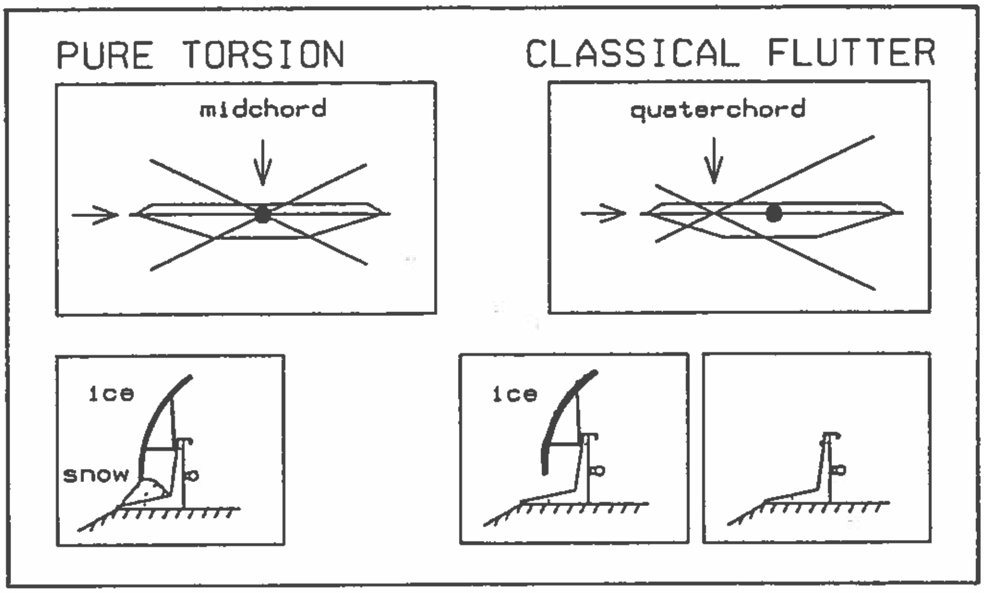


Fig. 33. Bridge Girder Wind Response with Iced-up and Snowblocked Wind Screens

Test results are in accordance with the expected values for a girder without windscreens. Furthermore, the tests revealed that windscreens can be arranged with only minor reductions of critical wind velocities even for iced up conditions, whereas dramatic reductions of critical wind velocities were registered when the airflow below the windscreens were obstructed by snow.

Corrosion Protection by Dehumidification

The stiffening girder for the main bridge is a closed steel box girder with interior stiffeners and a smooth compact exterior surface exposed to rain, ice, salt and pollution. This affords an essential reduction of future maintenance work.

For traditional external and internal surface treatment the cost may be up to 10% of the superstructure construction cost. Regarding maintenance of steel bridges, the costs for surface treatment may amount up to 50% of the total operation costs.

COWIconsult has developed a non-traditional protective system for steel bridges which minimizes construction costs as well as maintenance costs. The system is based on

- External surfaces: traditional protection by painting
- Internal surfaces: corrosion protection by circulation of dehumidified air. All painting work are omitted inside the box girder.

Such a system, based on dehumidification plants inside the bridge girder, was installed for the first time in the box girder for the Lillebælt Bridge completed in 1970. Until now such systems have been installed or is under execution in the following major bridges:

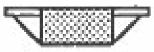
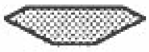
Bridge	Country	Bridge type	Year of completion
Lillebælt	Denmark	Suspension	1970
Farø	Denmark	Cablestayed	1985
Fiskebæk	Denmark	Steel	1987
Askøy	Norway	Suspension	1992
Gjemnessund	Norway	Suspension	1993
Pont de Normandie	France	Cablestayed	1993
Great Belt	Denmark	Suspension or Cablestayed	1996

The system has now been in operation for nearly 20 years with good results. The Eastern Bridge will be designed with dehumidification plants in the steel box girders, steel towers and tower tops.

In the design of cablestayed and suspension bridges, the advantage of the dehumidified air can be utilized also in the protection of the cable anchorages within the box girder, which is normally the most corrosion critical part of cable-stays and suspenders.

In fig. 34 three types of cross sections often used in bridge design are shown

- open truss
- central box girder with cantilevered bridge deck
- full width box girder

Surface Areas			
A_D deck area	26 m^2/m	26 m^2/m	26 m^2/m
A_E external painted area	94 m^2/m	65 m^2/m	36 m^2/m
A_E / A_D	3.6	2.5	1.38
Protection: external area	painted	painted	painted
internal area	——	dehumidified	dehumidified

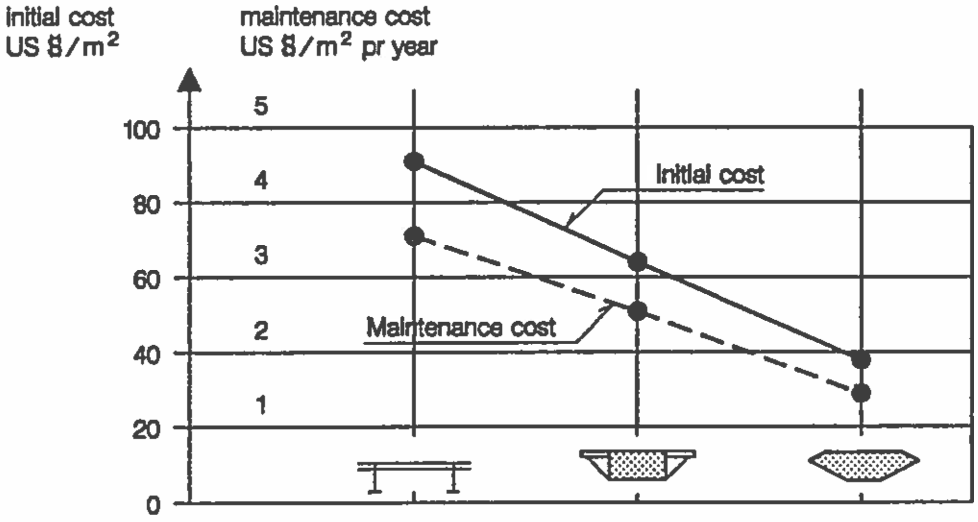


Fig. 34. Corrosion Protection of 3 Different Girder Types

As shown in figure 34, the external exposed surface for an open truss superstructure is 3.6 times the deck area, whereas the ratio for the Great Belt cross section is only 1.4. The costs for corrosion protection and maintenance are also indicated in the figure.

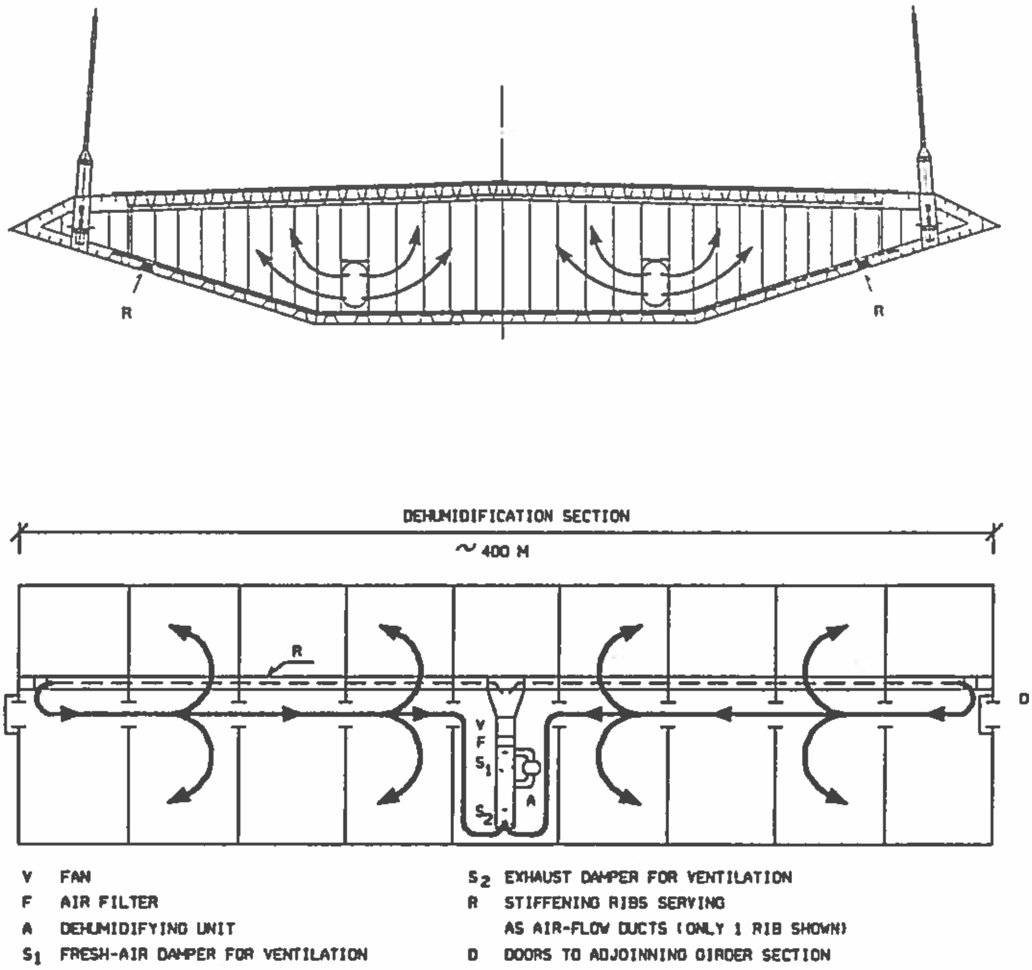


Fig. 35. Dehumidifying and Circulating System
Principle arrangement

The function of a dehumidification system is in principle as follows:

Each plant comprises a fan system for circulation of the entrapped air, and a dehumidifier unit equipped with hygroscopic filters of a capacity suitably adapted to the air volume.

Intake of air to the box from the outside, and exhaust from the box, are controlled by dampers which, to ensure proper functioning, should be operated automatically. Fresh air is only taken in to the extent it is required in order to equalize pressure outside and inside and, when needed, to improve the inside-air quality in connection with inspection of the interior of the box girder.

When air received from the inside is passing the ventilation system, a minor part of the air is led via a by-pass through the dehumidifier unit. This is controlled in such a manner that the relative humidity (RH) of the inside-air is always below the specified level of 40%. According to experience, no corrosion will develop if the steel surfaces are exposed to air below 60% RH.

Ship Collision Risks

More than 20,000 vessels a year - up to 350,000 DWT - will pass the navigation span, and the navigational conditions are not straight forward. A traffic separation zone is established but the total width of the channel is only 1500 m.

In order to assess and minimize the risk of ship collision a series of investigations are taking place, a.o.

- Ship manoeuvres under various navigational conditions
- Means of improvement of navigational conditions
- Magnitude of ship collision forces and severity of collisions
- Worldwide survey of experience from similar bridges.

A general assumption for the evaluation of the collision risk is that passage of a normally controlled large ship in the international Route T must not be substantially more complicated because of the presence of the bridge.

In order to investigate this assumption, a great number of real time manoeuvreing simulations and radar simulations under various navigational conditions, including very extreme conditions, have been carried out.

Different emergency manoeuvres have been simulated:

- turning circle to port
- crash stop by full astern
- zig-zag shift manoeuvres

Simulation of bridge passages were carried out with experienced local pilots in manouvering situations also involving two ships meeting or overtaking.

In addition to straightening of the navigation channel and introducing advanced navigational aids, worldwide experience have shown that the safety can be substantially improved by introducing a Vessel Traffic Service System (VTS).

An outline of such a system including radar installations to protect the Eastern Bridge and also the Western Bridge has been worked out.

The actual magnitude of the collision forces is subject to diverging opinions. For the Great Belt a comprehensive investigation of ship collision forces have been performed by Norske Veritas (Norway) by use of advanced computer programmes. Preliminary results suggest that the level of ship collision design forces assumed earlier could be on the unsafe side, but further studies will be needed to confirm this.

Statistical studies regarding the severity of collision are being carried out introducing the "Heinrich ratio" concept. The Heinrich ratio is the proportion of serious accidents out of all accidents recorded.

In parallel to the mentioned specific studies, a worldwide survey is taking place in which bridge owners are being interviewed regarding ship collision experience.

5. OVERALL RISK ANALYSES

There has been made a series of "overall" risk analyses with the purpose of establishing risk acceptance criteria to assure adequate and consistent safety levels throughout the various parts of the crossing.

Two types of safety aspects have been considered in particular:

- service disruption risk to the crossing
- fatality risk to the users of the crossing

The acceptance criterion regarding disruption is that the probability of disruption lasting more than one month shall not exceed a certain level.

The loss to society as well as the loss to the owners in case of accidental disruption have been estimated. This is to be used to determine areas where improvement of safety beyond the risk acceptance criteria is cost effective.

The acceptance criteria regarding fatalities have been based on the general philosophy that the increase of risk level when passing the crossing compared to the risk one is subject to when passing the same stretch of road or section of railway on land shall be insensible. This is understood in the way that the additional risk shall not exceed the statistical uncertainties of the risk level on land.

For design purposes, the accepted overall risks are to be divided up and distributed over the various parts of the crossing and the different types of risks, i.e. train accidents, fire and explosion, structural failure, ice impact, ship collision etc.

For the two bridges, ship collision represents the most important risk element.

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ASCE
Annual Convention 1989.
New Orleans, October 8-11.

DENMARK's GREAT BELT LINK

Environmental and Hydrodynamic Issues

by

Jacob Steen Møller

Head of Coastal and Environmental Division

Danish Hydraulic Institute

THE GREAT BELT LINK

ENVIRONMENTAL AND HYDRODYNAMIC ISSUES

by

Jacob Steen Møller, Ph.D.

Head Coastal and Environmental Division

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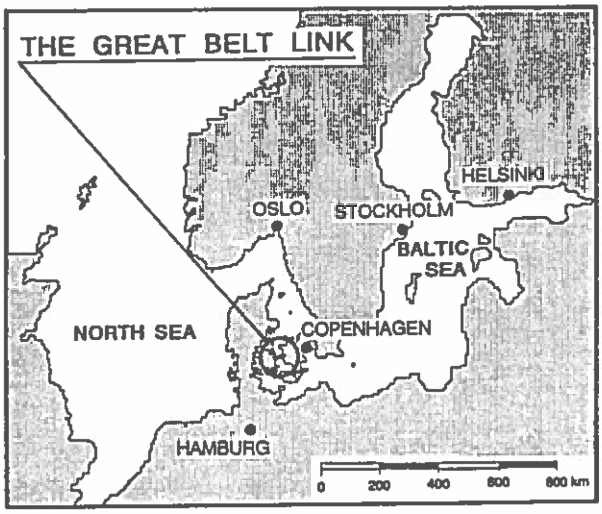
ABSTRACT

Environmental studies initiated in conjunction with construction of the link across the Great Belt have initiated remarkable opportunities for technical developments. A law passed in the Danish Parliament to impose a design criteria of 'zero far field effect' on the Great Belt Link, has challenged the ability to model the hydraulic effects of the Link on the stratified flow regime in the Great Belt. The paper describes how the challenge of zero effect is met by design of compensation dredging determined by the use of highly sophisticated numerical models.

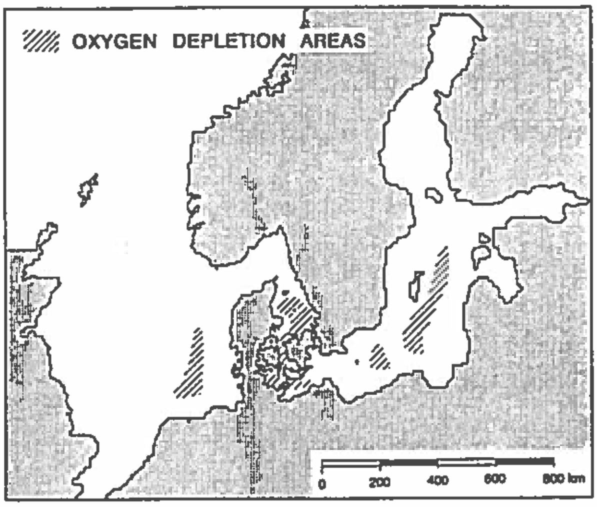
INTRODUCTION

During the past 50 years or more Danish civil engineers have developed a strong tradition for and expertise in large scale bridge and tunnel projects both in and outside Denmark. Recently they have started yet another large link project, namely that of linking the two main islands of Denmark by a combined bridge and tunnel across the 18 km wide Great Belt. Not only will this link connect Copenhagen with the Danish mainland of Jutland, but also with the European continent.

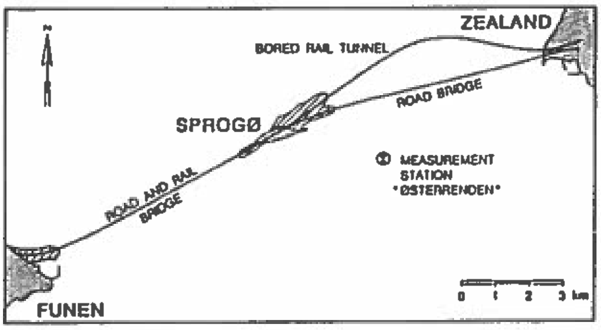
In a joint venture with the Danish consulting engineering firm LICengineering A/S, DHI is in charge of a variety of consulting services for the AS Storebæltsforbindelsen, including special hydraulic and environmental aspects of the project. The AS Storebæltsforbindelsen is the builder of the Great Belt Link with the Danish state as the sole shareholder.



The Great Belt is the main outlet from the Baltic Sea. At the site of the Link the small island of Sprogø divides the Belt into an eastern and a western channel. The Link will consist of a combined road and rail bridge across the western channel. On Sprogø the traffic is divided and the road traffic continues to Zealand on an elevated bridge, whereas the rail traffic will continue in a bored tunnel beneath the 70 m deep eastern channel.



Since the Great Belt is forming the transition between the saline North Sea and the brackish Baltic Sea, the Belt can be considered the "Gibraltar Strait" of the Baltic Sea. Because of this, delicate location changes in the flow conditions of the Great Belt due to the Link will influence the hydrography and hence the aquatic environment of the Baltic Sea.



ENVIRONMENT

The potential effects of restricting the flow through the belt by building causeways and bridge piers have raised concern for the environment of the Baltic Sea. This concern has lead to a new and very strict approach to the environmental impact design criteria; the so-called zero effect solution or the "zero solution" which is included as § 5 in the Act of Parliament concerning the Great Belt.

§ 5 :

".. THE WORK IS TO BE CARRIED OUT... IN SUCH A WAY THAT THE WATER FLOW THROUGH THE GREAT BELT SHALL REMAIN UNCHANGED... FOR THE SAKE OF THE MARINE ENVIRONMENT OF THE BALTIC."

The above legal requirement is interpretated into the following requirements to the design of the Link:

1. The water flow through the Great Belt must not be changed by the Link
2. The salt balance for the Baltic Sea must not be changed by the Link.

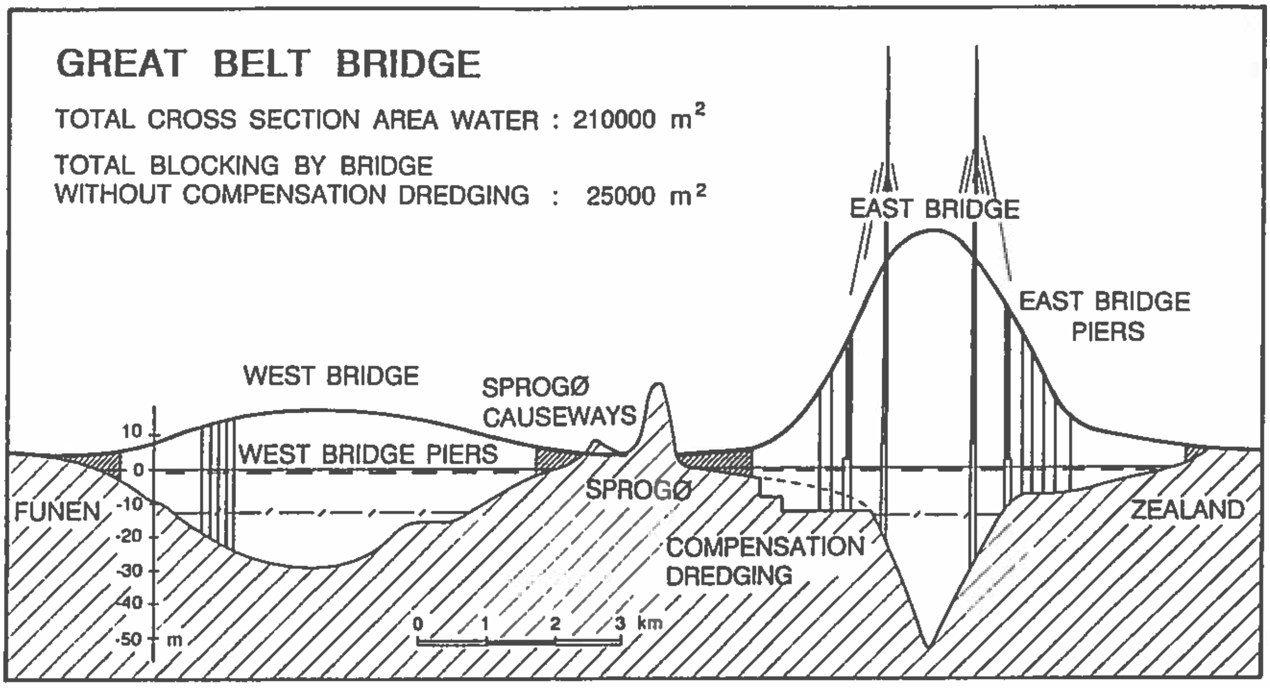
Hereby the environmental design requirement for the far-field was reformulated into a purely hydraulic requirement, because if 1 and 2 are fulfilled then no biological changes are caused by the Link.

The technical hydraulic requirements to the link involve that the hydraulic resistance of the Great Belt be unchanged, but also that the mixing between the surface layer and the bottom layer in the Great Belt be unchanged. The reason why this is necessary is explained below. It appears that the zero solution concept only deals with the far field. Of course, local environmental effects cannot be completely avoided. The environmental impact in the near field is treated traditionally but strictly by reducing the impact to an acceptable level concerning environmental and economical factors.

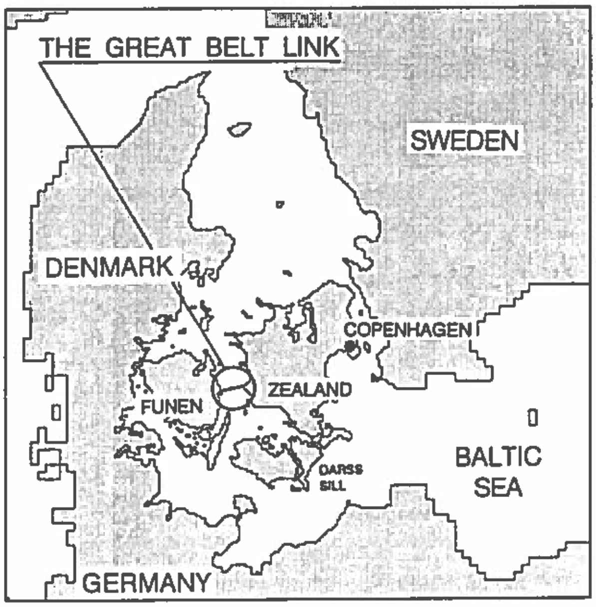
BALTIC HYDROGRAPHY

Why are the possible hydraulic effects of the Link causing serious concern ?

To understand this a brief look of the hydrography and biology of the Baltic is needed.

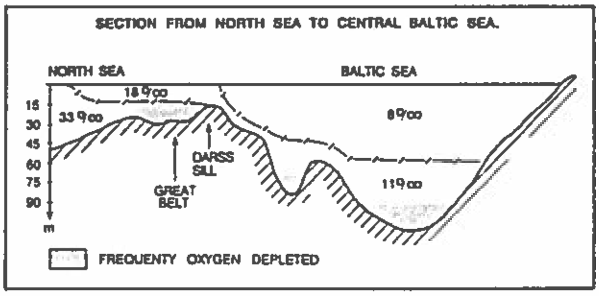


Due to surplus fresh water input to the Baltic Sea and the narrow connection to the North Sea and the Atlantic Ocean the Baltic Sea is brackish and stratified.



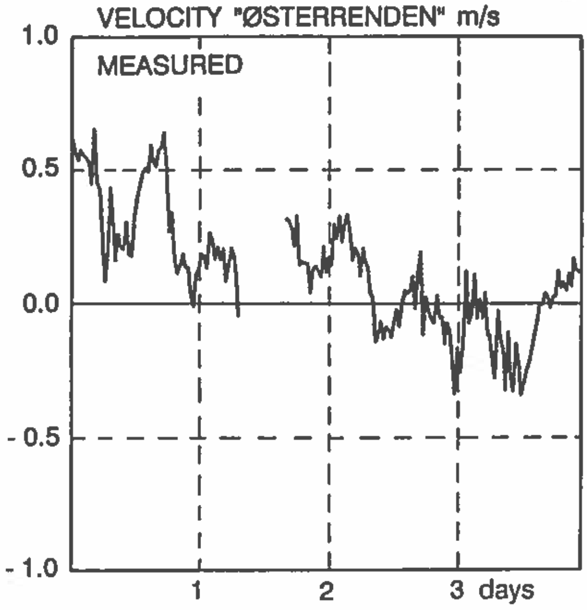
The transport by mixing of oxygen into the bottom water is restricted by the stratification. This combined with eutrofication of the Baltic and Danish straits has lead to oxygen depletion in large areas.

The stratification of the Baltic Sea and the oxygen supply to the lower layers is maintained by the flow conditions in the Danish straits.



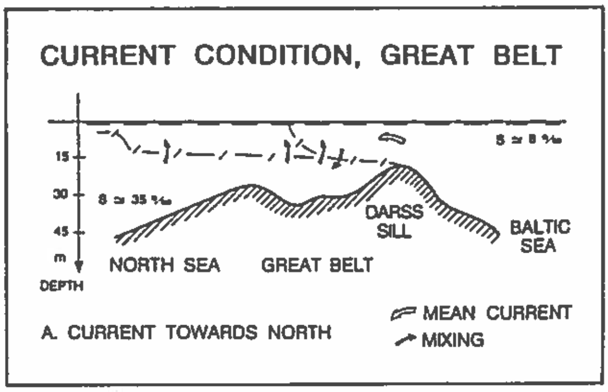
The current in the Great Belt is governed by the following three mechanisms:

1. The meteorological forcing
2. The tidal forcing
3. The fresh water surplus of the Baltic.

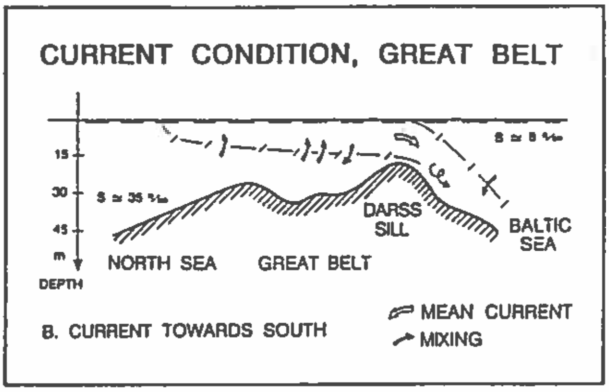


The fresh water surplus forces a mean current from the Baltic of 1.4 · 10^4 m^3/s. But the shifting weather conditions dominated by low pressures travelling from the North Atlantic towards the east forces the water to oscillate in and out of the Baltic through the Danish straits with irregular intervals. The amplitude of these oscillations reaches 2 · 10^5 m^3/s thus totally dominating the instantaneous current condition in the Great Belt.
The oscillating flow creates the stratification of Great Belt waters:

By northbound current the Baltic brackish water will flow into the Great Belt.



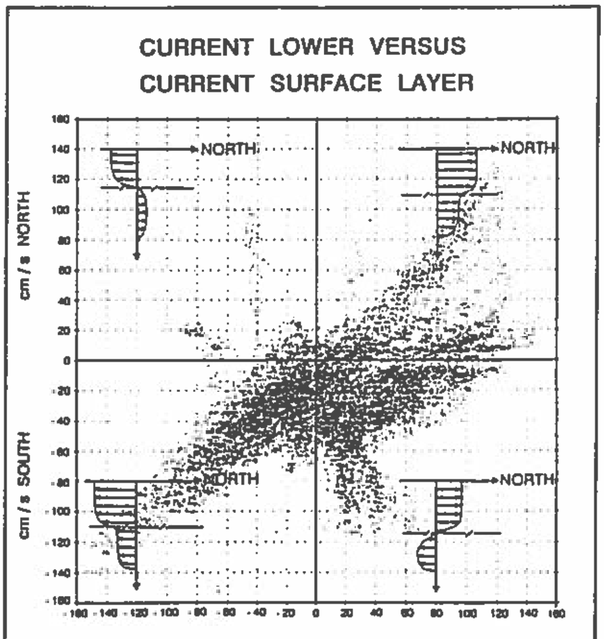
The water will experience a very strong mixing. As the brackish water is lighter than the saltier water coming from the north, it will tend to lie on top of the water mass in the Belt.



By southbound current the surface layer will be forced southwards through the Great Belt while mixing with the saltier bottom water. When passing the Darss-sill the surface layer, which has got a high salt content on account of the mixing, will plunge under the brackish Baltic water. At the same time some of the bottom water is pulled over the sill.

The mixing between the layers in the Great Belt is caused by turbulence generated by wind and current.

This varying current picture is a condition for the layer division which is nearly always observed in the Great Belt. The plunging salt water forms a dense bottom current and feeds the Baltic lower layers with salt and oxygen.



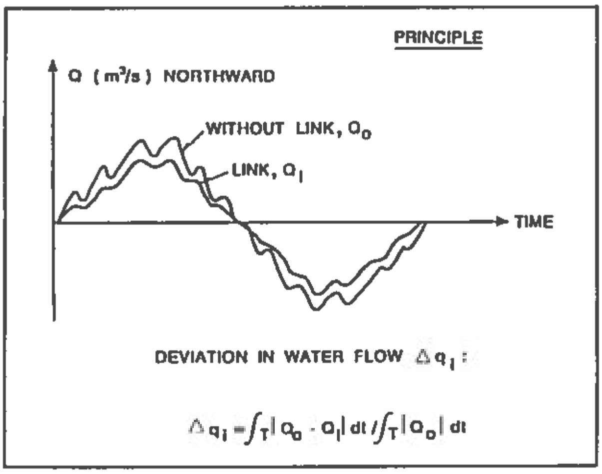
SCATTER DIAGRAM OF THE CURRENT IN THE LOWER LAYER, -30 m, VERSUS THE CURRENT IN THE UPPER LAYER, - 7 m. MEASUREMENT STATION "ØSTERRENDEN" IN THE GREAT BELT.

The current in the upper and lower layers of the Great Belt can flow in the same direction and opposite to each other depending of the strength relationship between the driving forces.

ZERO SOLUTION

The basic idea of the zero solution is to keep the hydrography of the Great Belt and hence the Baltic Sea unchanged by the Link. This is achieved by compensating the flow resistance and mixing due to the piers and causeways by dredging.

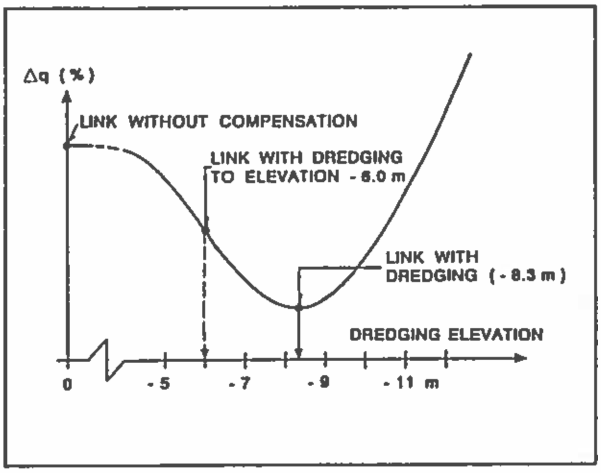
The problem now arises, how to determine the size and location of the compensation dredging. This engineering design work is carried out according to the following principle.



DEVIATION IN WATER FLOW Δq_l:

$$\Delta q_l = \int_T |Q_0 - Q_l|\, dt \,/ \int_T |Q_0|\, dt$$

Given the boundary condition for the flow through the Great Belt the surface current is calculated as it is without the Link, and as it will be with the Link. By calculating the deviation in surface water flow, we have defined a measure of deviation from the zero solution. This measure will depend on the geometry of the Link; large piers and long causeways will increase the deviation.



Now for a given design of the Link we can introduce a dredging scheme and calculate the resulting deviation caused by the combined Link and dredging. If, for instance, the area to be dredged is kept constant the only parameter determining the efficiency of the dredging is the dredging elevation. By repeating the calculation of deviation for different dredging elevations the deviation is minimized.

Zero solution is reached for minimum deviation.

As demonstrated above not only the surface water flow but also the bottom water flow and the mixing must be kept unchanged by the Link. This is ensured by the use of a verified two layer numerical model.

NUMERICAL MODELLING

The environmental concern raised by the Ministry of Environment and by the green organisations such as Greenpeace and the Danish Society for Conservation of Nature make strong requirements of documentation for the methods used to determine the zero solution. To fulfil these requirements the design model must be able to calculate the effect of bridge piers and causeways on the density stratified flow.

MODEL REQUIREMENTS :

CALCULATE LINK EFFECT ON :

- TWO LAYER FLOW
- INTERNAL HYDRAULIC JUMP
- FLOW RESISTANCE (piers)
- EXPANSION LOSS (causeways)
- TURBULENCE PRODUCTION (mixing)
- VERIFIED MODEL (monitoring)

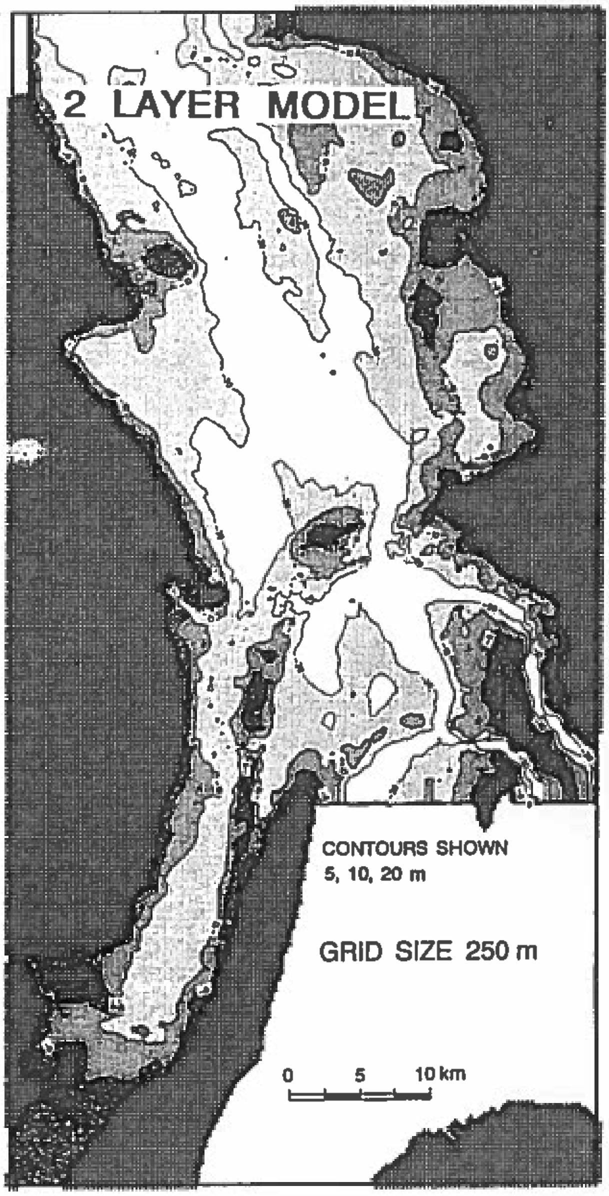
CHOICE OF MODEL :

DHI's MODELLING SYSTEM S22

Also the model shall be easy and fast to use to enable the design engineer to perform the iterative determination of the dredging.

The two layer modelling system S22 developed by DHI is used.

The system 22 is a numerical modelling system for the simulation of two-layer stratified flows in two horizontal dimensions. The system computes the surface levels, interface levels and flows in both layers. The mixing between the layers is described in terms of entrainment between the layers. Entrainment rates are determined on the basis of turbulence production for each layer.

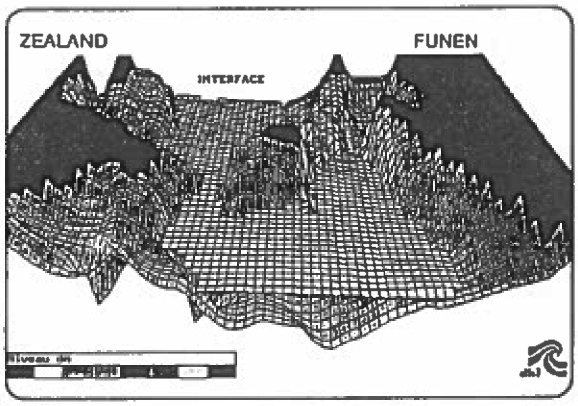


The equations solved by S22 are those of conservation of mass and momentum. The equations include the effects of:

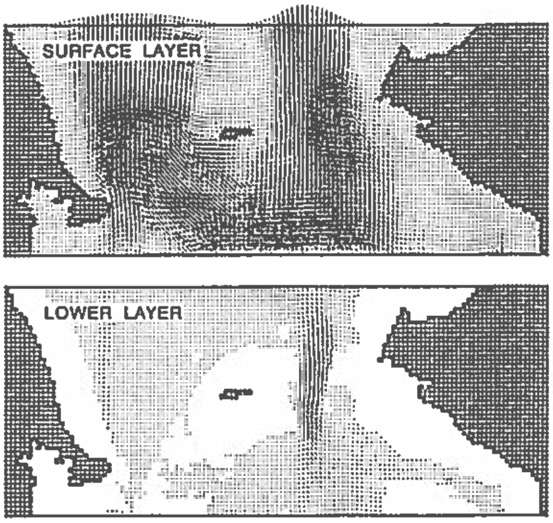
- Non linear convective and cross momentum terms
- Coriolis forces
- Wind shear stress
- Bed shear stress
- Interfacial shear stress
- Flow resistance due to bridge piers
- Interfacial mixing
- Turbulent momentum dispersion
- Horizontal density gradients.

The equations are solved by an implicit finite difference method.

Basic input data to the model are:



PERSPECTIVE OF INTERFACE. AS SEEN FROM NORTH. SIMULATION, S22



— 10 m³/s/m, S22 SIMULATION OF TWO LAYER FLOW.

1. Topography (Bed elevation at each grid point).

2. Initial (time = 0) surface and interface elevation, densities in the two layers.

3. Time series (for the period to be modelled) of surface and interface elevations and densities along the open boundaries of the model.

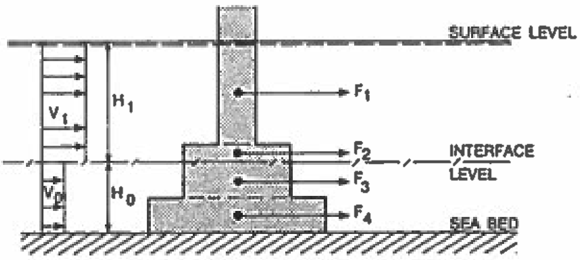
4. Time series of wind velocity and direction.

5. Specification of bed, interfacial and wind stresses, and mixing and dispersion coefficients.

The Link and the Compensation Dredging are included in model by corresponding changes in model topography. Bridge piers are included by subgrid scaling methods.

The Compensation Dredging is determined by an iterative process as described above by minimizing the deviation of water flow and the deviation of mixing through the Great Belt induced by the Link.

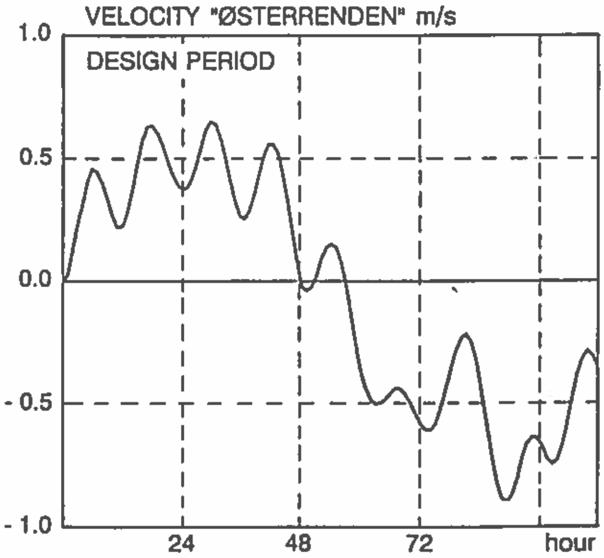
DRAG FORCE ON BRIDGE PIER
IN TWO LAYER FLOW.



DRAG FORCE IS CALCULATED FOR EACH SEGMENT OF THE PIER.

FORCE IS MODELLED AS 'SUB-GRID' FRICTION TERM IN NUMERICAL MODEL S22.

The calculations are performed using a design period representative for the varying current conditions in the Belt. The final compensation dredging is controlled by a sensitivity analysis in which design



period and model parameters are varied within physically reasonable values. Preliminary sensitivity tests show that the uncertainty of the method is comparable to the practical uncertainty of dredging.

VERIFICATION

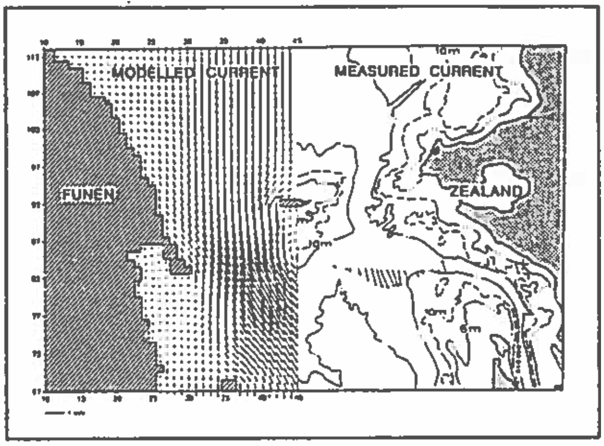
The method needs verification; will the model describe:

1. The flow in nature ?

2. The effect of link and dredging ?

These two questions are answered by comparing the model with field observations before beginning, and after 50% of the dredging is completed.

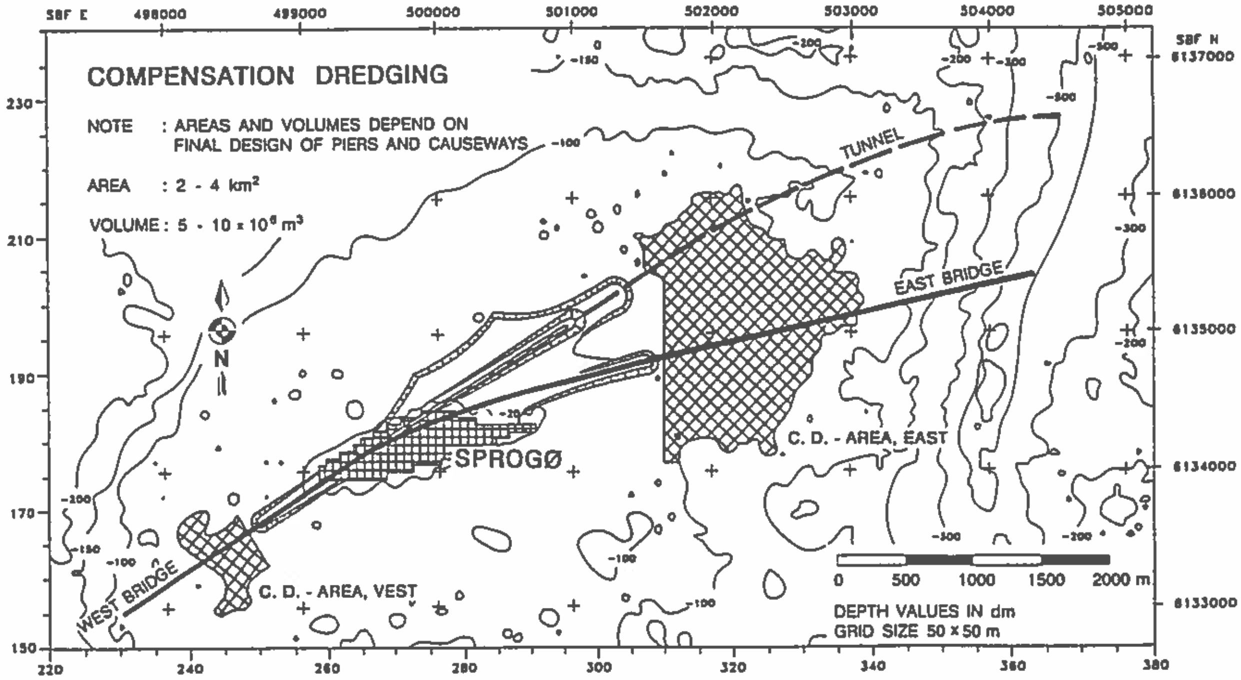
In practice model boundary data and verification data are assembled by a field monitoring programme. Simulations are carried out using measured boundary data. Modelled data are compared with measured data to check the performance of the model. Moreover a feedback mechanism is employed. If the results of the model verification show that the compensation dredging needs adjustment this may be done following the 'half way through' verification of the hydraulic effect of the dredging.



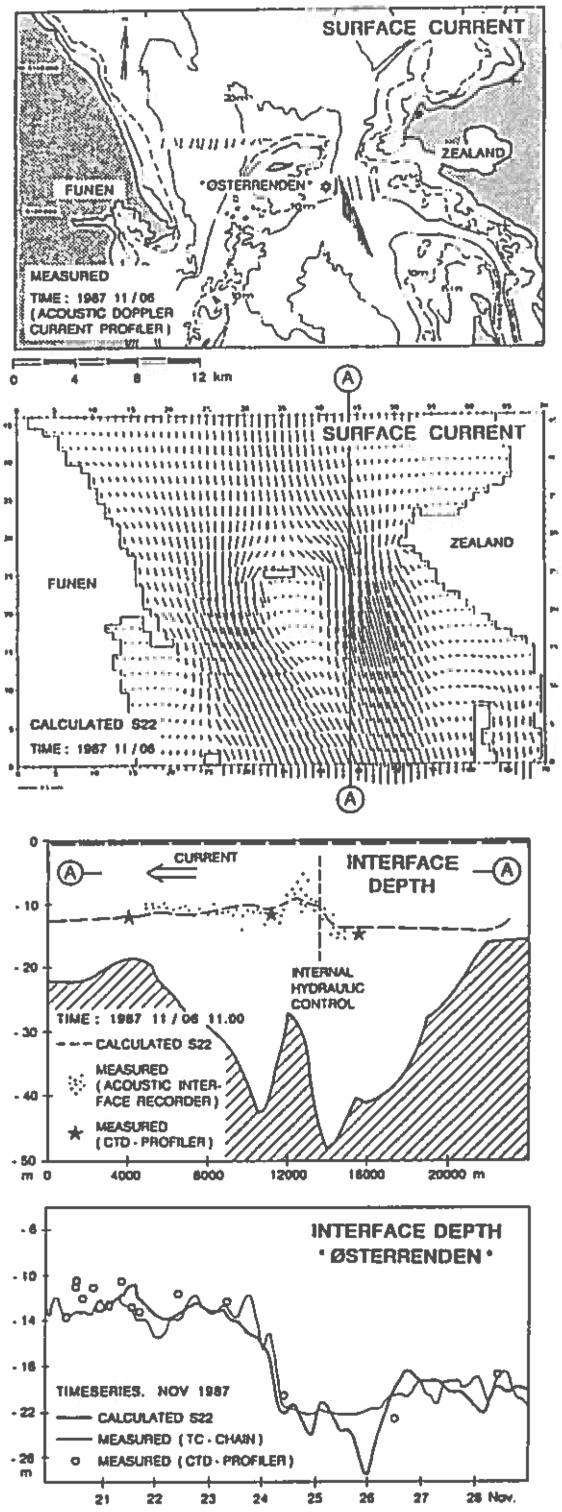
Preliminary results of the verification have shown good agreement between modelled and measured data.

The field data verification is believed to be the most comprehensive numerical model field data verification ever performed. The monitoring programme is especially designed to produce data for numerical modelling.

This provides the modelling engineer with a unique set of data which will eventually be of great value for further scientific development within numerical modelling of stratified flow phenomena.



MODEL VERIFICATION



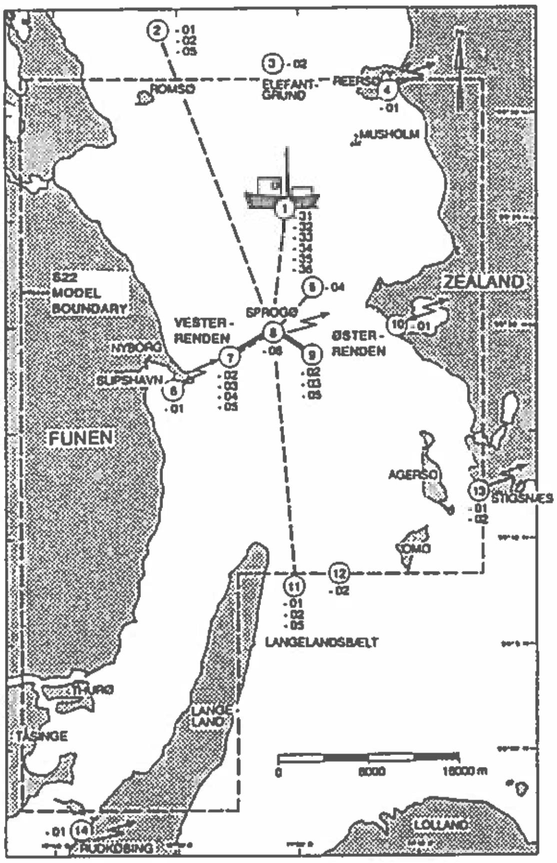
PRELIMINARY RESULTS OF MODEL VERIFICATION. BASED ON 1987 DATA

MONITORING

In order to achieve data for model verification, but also for design and forecast purpose a comprehensive monitoring programme is set up.

The monitoring programme includes long term deployment of instruments in the Great Belt. The instruments will provide data on stratification by measuring temperature, salinity, oxygen and turbidity along vertical strings. Vertical current profiles are obtained by Acoustic Doppler Current Profilers mounted on the sea bed and onboard a permanently deployed survey vessel. A newly DHI developed interface detecting instrument, the AIR (Acoustic Interface Recorder) is deployed onboard the survey vessel and at several sea bed positions.

From more than 100 sensors in the Great Belt area data are transmitted on-line to DHI where data analyses and reports (plots) are delivered by a menu driven window operated data aquisition system. This system gives direct access to all measured data. Also current, wave and weather forecasts are delivered through this system that will provide not only the modeller with data, but also the supervising engineer and the contracter with information for planning purposes.



GREAT BELT MONITORING PROGRAMME 1989 -1996

SYMBOLS

⑫	Station number
03	Instrument type
⇝	Public tele link
----	Radio link
═	Sea cable

Instruments, Fixed Stations

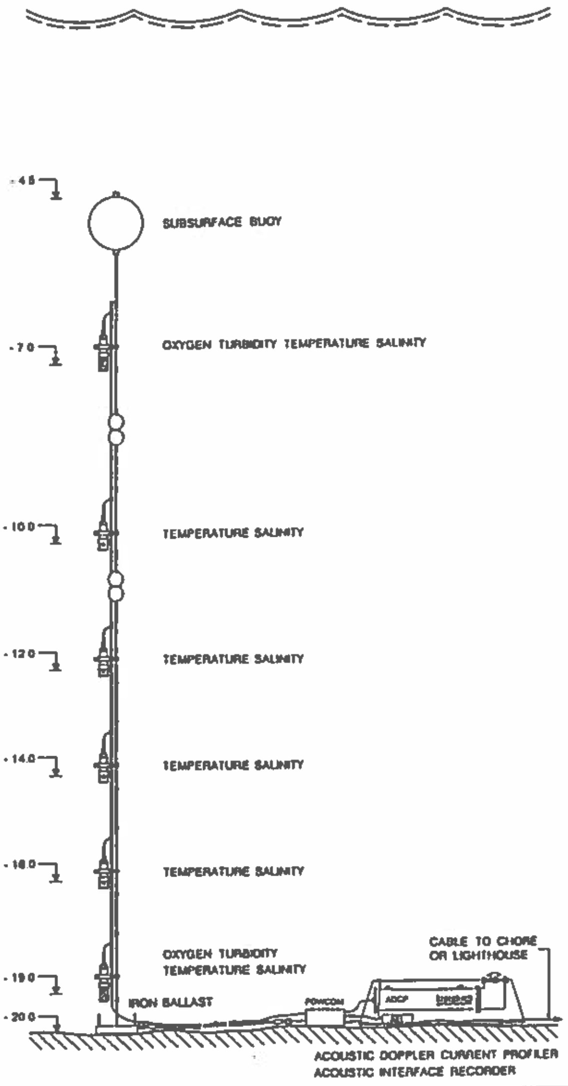
-01 WLR	Acoustic Water Level
-02 AIR	Acoustic Interface Level
-03 ADCP	Acoustic Doppler Current Profiler
-04 WR	Wave Rider
-05 TC	Temp., Cond., O_2, Turbidity String
-06 MET	Meteorological Station

Instruments, Vessel

-31 ADCP	Acoustic Doppler Current Profiler
-32 AIR	Acoustic Interface Recorder
-33 CTD	Temp., Cond, D_2, Turbidity, Flouros., Profiler,
-34 ES	Echosounder
-35 SYLEDIS	Positioning System
-36 EMCP	Electromagnetic Current Profiler

GREAT BELT MONITORING STATION 09

" ØSTERRENDEN "



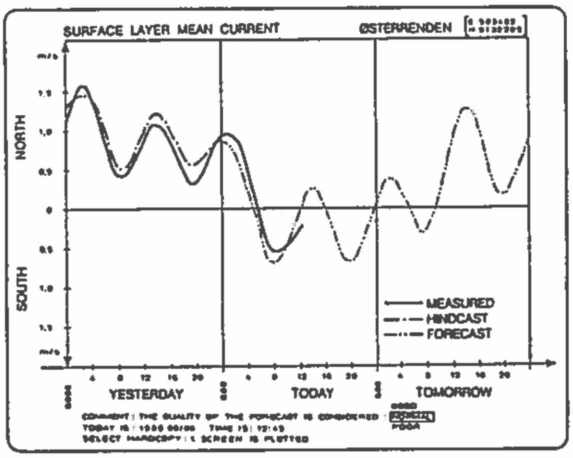
FORECAST

Together with monitored environmental data (current, wind, ice, waves, oxygen, turbidity etc.) forecasted current, waves and water levels are distributed on-line through DHI's data aquisition system. The forecast is based on a numerical model of the entire North Sea and the Baltic. The model is driven by astronomical tide on the Atlantic boundary and weather forecast delivered by the Danish Meteorological Institute.

The forecast provides water level forecast for the entire model area and is an integrated part of the Danish storm surge warning system protecting the vulnerable Southern Jutland coast towards the North Sea.

Current and wave forecast is provided for the Great Belt area and used to plan offshore operations and near-field environmental impact monitoring.

EXAMPLE OF CURRENT FORECAST FORMAT



NEAR FIELD EFFECTS

The near-field environmental impacts from the Link are associated with

- Mussel banks
- Herring spawning areas
- Stone reefs
- Eider ducks

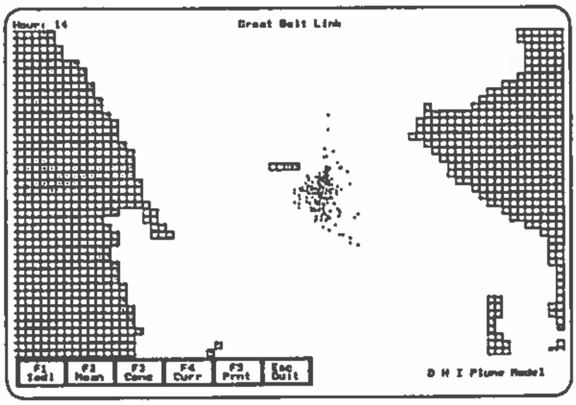
The concern is associated with both the permanent effects and the temporary effects induced by the construction works.

By the present outline of the Link the permanent effects are reduced to the area covered by the construction. This includes mussel banks and stone reefs which are considered of special value. The reinhabitation of the compensation dredging area will be followed by biological monitoring.

The eider duck population in the area is of great international interest since during winter time a major part of the Northern European eider population rests in the Great Belt area feeding on the mussel banks. These banks are believed to reestablish in the compensation dredging area, but the bird population will be protected against shooting and by traffic regulation, if necessary.

The temporary impacts caused by construction works are monitored and kept to a minimum by regulations included in contractor conditions.

The major temporary impact is caused by siltation due to dredging and land winning. This is reduced by:

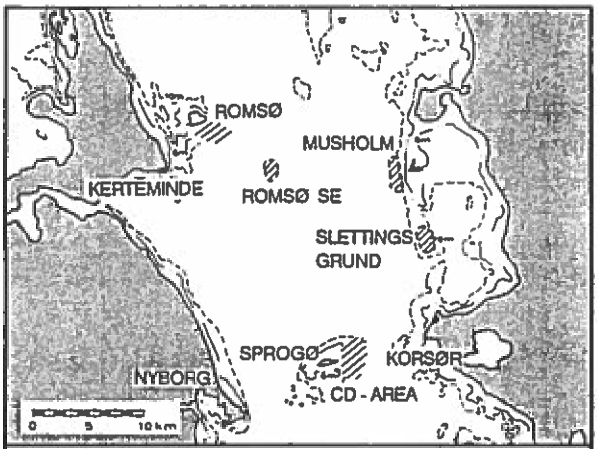


A LAGRANGEIAN SEDIMENT PLUME MODEL DEVELOPED BY DHI IS USED TO PLAN NEAR FIELD SUSPENSION AND SEDIMENTATION MONITORING

1. Reducing materials to be handled by reuse of compensation dredging material.
2. Siltation basins at Sprogø.
3. Close supervision followed by time and spacial constraints to dredging work.

An interesting aspect of the near-field environmental programme is the introduction of a feed back mechanism; the AS Storebæltsforbindelsen has agreed to accept that if unexpected impacts should occur, construction works, procedures and even parts of the project will be altered in order to minimize environmental impact.

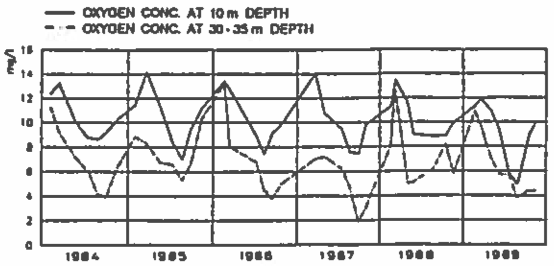
The total amount of material to be handled by dredging, sand extraction etc. is approximately 15 mio m^3.



SAND RESOURCE AREAS

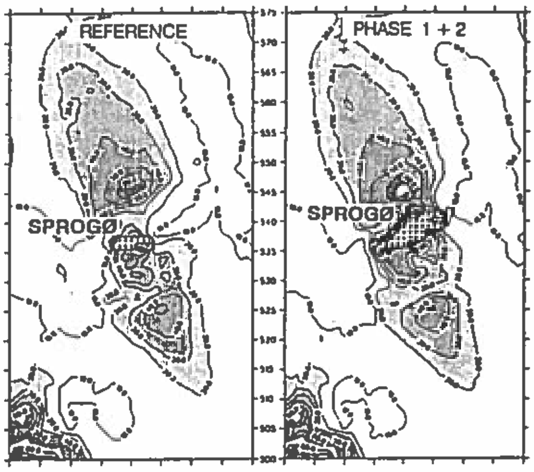
The total sediment spill is estimated to 2.3 mio m^3. This spill will spread and settle in Storebælt. About 2/3 origins from sand extraction at Romsø SE. As part of the spill nutrients will be released, the total spill of nutrients corresponds to approximately ½ year's discharge from nearby Nyborg town and catchment area.

The oxygen conditions in Storebælt are influenced by the general oxygen depletion conditions of the Danish waters.



RECORDED OXYGEN CONCENTRATION, ØSTERRENDE

The dredging activities may influence the low oxygen condition of the lower layer in July-October, but altogether effects from earth work activities on oxygen concentrations are only expected to be detectable during large operations which coincide with stagnant current conditions.



THE DISTRIBUTION OF FREQUENCY OF SPEEDS BELOW 0.1 m/s BEFORE AND AFTER THE LINK. CURRENT CHANGES MAY INFLUENCE THE EXTENSION OF MUSSEL AND ELLGRASS BEDS.

The sedimentation may cause changes in the soft bottom fauna. However, any such effects are expected to be of short duration only.

20% of the herring spawning area in Storebælt is influenced. Due to the other spawning areas in Storebælt, even total destruction of eggs around Sprogø is not expected to affect the stock of herring significantly.

CONCLUSIONS

The Great Belt Link project has initiated remarkable technical developments within hydraulics and environmental protection in association with major marine construction works.

The Great Belt Link project has introduced the concept of 'zero solution' meaning that any potential far-field effect on the marine environment shall be compensated in such a way that no effects will occur.

This policy is carried out in the Great Belt Link project by carefully compensating the hydraulic effect of the Link by dredging.

The dredging is designed by the use of advanced numerical models. These models are verified by comparison with field data from the Great Belt area.

Together with the development of numercial methods the project has initiated a comprehensive on-line monitoring programme and a current and water level forecast system covering the entire Baltic Sea and the North Sea.

Possible near field effects of the construction works are kept to a minimum by restricting the siltation by the use of compensation dredging materials in causeways and other land winning projects.

Mussel banks are expected to reestablish. The eider population may be protected by shooting regulations and traffic regulations.

The immediate environmental effects of the construction work are monitored and the impact is kept at a minimum. This is stated in the building contract.

ZERO BLOCKING SOLUTION FOR THE GREAT BELT LINK

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ABSTRACT. This paper presents a case of strait and estuary management where the building of a main causeway and a bridge and tunnel system will be made in such a way that environmental effects are minimized.

The particular case is the Great Belt Link in Denmark spanning the Great Belt, the main artery for water exchange to the Baltic Sea. Due to the sensitive environment of the Baltic the government of Denmark has decreed that the water exchange to the Baltic shall remain the same after the construction of the link. This means that the added resistance caused by the narrowing of the flow cross sections due to the construction of causeways and from bridge piers shall be compensated in such a way that the water exchange to the Baltic remains unchanged.

It is determined that the compensation will be made by increasing the flow cross section of the link by dredging. Areas and volumes of dredging have been determined by numerical calculations. It is demonstrated that although the flow in the Great Belt is a very complicated two layer flow it is possible to define a dredging pattern which compensates for all conditions, whether subcritical or supercritical.

Background

For many years there have been plans in the Kingdom of Denmark to connect the islands with bridges, tunnels or causeways. Some of the projects may, if carried out, affect the free flow through the Danish Straits between the Baltic and the North Sea, Fig. 1.

In general not much attention is given to the impact of bridges or causeways on the surrounding flow. However, the peculiar hydrography of the Danish Straits, with a distinct layered flow, results in a flow with a very small hydraulic resistance. Therefore the total resistance may be sensitive to small changes in geometry. For instance, the hydraulic head difference between the Kattegat and the Baltic is normally only 0.2-0.6m

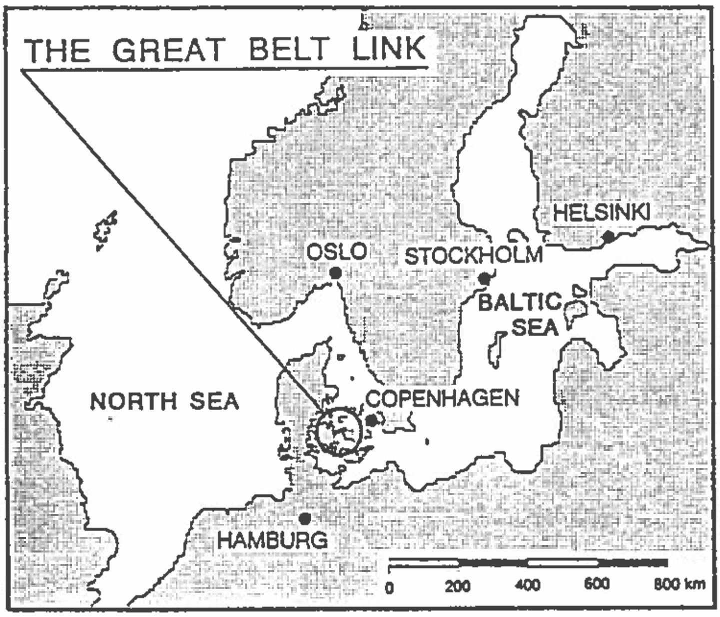

Figure 1. General map of the area.

over a length of 300 km with a flow rate of 100.000 m^3/s. Further, bridges built in the Straits will have to be designed for heavy ship impact and for ice loads which make the bridge abutments large, leading to increased blocking.

Most of the hydraulic loss in the Great Belt takes place through 4-5 narrows where the current becomes strong. The fixed link across the Great Belt will span the most constricted narrows of the Great Belt - the Halsskov-Knudshoved narrows, see Fig. 2. Since a large part of the salt influx to the Baltic (60-70%) passes through this narrow, concern has been expressed that the construction of causeways, tunnels and bridges may exert a large flow resistance. It is likely that the consequent reduction in the water exchange would significantly alter the hydrography and environment of the Baltic. To avoid such a change it has been specified in Paragraph 5 of the Danish law for contracting the link that *"The work is to be carried out ... in such a way that the water flow through the Great Belt shall remain unchanged ... for the sake of the environment of the Baltic Sea"*. This somewhat unprecise design criterion has been interpreted by DHI/LIC (1987) to be understood as:

"- The discharge (m^3/s) through the Belt must not be changed by the crossing.

- The salt balance (kg salt/s) for the Baltic must not be changed by the crossing."

This so called "Zero Blocking Solution" will ensure that no environmental impact on the Baltic, be it hydrographical or biological, will originate in the construction of the link.

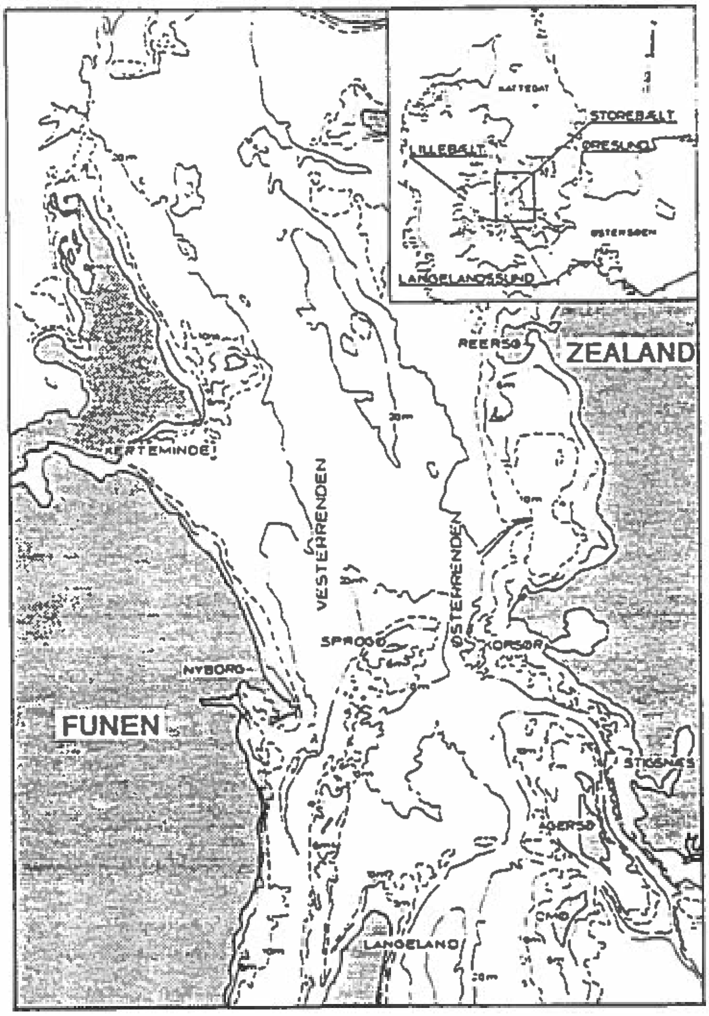

Figure 2   General map of the Link area

It is cheaper to build causeways than heavy duty structures like suspension bridges or immersed tunnels. Therefore there is an economical demand for letting part of the Great Belt link consist of causeways. This contradicts environmental interest which dictates as small a blocking of the flow as possible. A suitable compromise has been reached where causeways are only built in areas of water depth less than 6 metres and the blockage of these causeways and bridge piers has been compensated for by dredging.

Several proposals for compensation dredgings have been made. In the end it turned out that it would be most favourable to place the dredging in the Østerrende on the reef east of Sprogø Island, Figs. 3 and 4. This location was chosen because of high hydraulic efficiency of dredging and because materials from the area can be used for construction of causeways, etc. This implies that the constrictions of the flow in the Vesterrende will not be compensated in the Vesterrende (Western channel) itself but in the Østerrende (Eastern channel), though in such a way that the total flow through both the Østerrende and the Vesterrende remains unchanged.

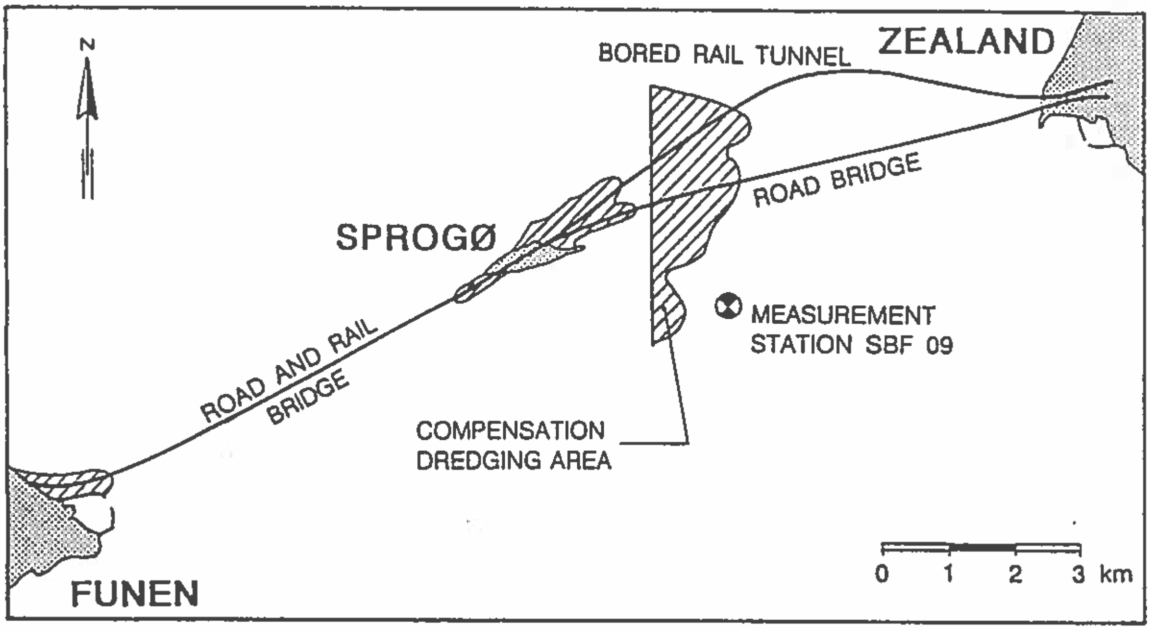

Figure 3 Typical project for the fixed link

Further, it is necessary to specify that the salt flux through the cross section and therefore the mixing between the upper brackish layer and the lower saline layer remains the same after the completion of the fixed link.

In order to document the prescribed effect of the compensation dredging, a series of investigations and some additional research have been completed:

- Hydraulic laboratory tests to determine the mixing between layers in stratified flow due to bridge piers, flow contractions and immersed tunnel elements.
- Hydraulic laboratory tests with subcritical and supercritical stratified flows in order to determine the types of flow which could be expected.
- Field measurements in the Halsskov-Knudshoved narrows to verify the findings from the laboratory tests and the preliminary hydraulic calculations.
- Set-up of a detailed two-layer mathematical model which can determine flow changes due to causeways and due to resistance from

bridge piers and immersed tunnel elements and which can further determine the compensating effect of dredging.
- Verification of the mathematical model by simulating a period in which field measurements took place and compare the calculated results with the measured results.

The results and conclusion of the above investigations are described in the present paper except the verification of the model and the field investigations which are described by Farmer and Møller, 1990.

HYDROGRAPHY

To obtain a non-blocking link across the Great Belt it is necessary to have an intimate knowledge of the hydrography of the Baltic, Danish Straits, and specifically of the Great Belt. With reference to Farmer and Møller (1990) we briefly state the following:

Due to surplus of fresh water input to the Baltic Sea and due to the narrow connection to the North Sea, the Baltic Sea is brackish and stratified. The transport by mixing of oxygen into the bottom water is restricted by the stratification of the Baltic. This has led to oxygen depletion in large areas. The stratification of the Baltic and the oxygen supply to the lower layers are maintained by the flow conditions in the Danish Straits. The current in the Great Belt is governed by 1) The meteorological forcing, 2) The tidal forcing, 3) The fresh water surplus of the Baltic.

The fresh water surplus forces a mean current from the Baltic of 1.4 x 10^4 m^3/s. But the shifting weather conditions dominated by low pressure travelling from the North Atlantic towards the east force the water to oscillate in and out of the Baltic through the Danish straits with irregular intervals. The amplitude of these oscillations reaches 2 x 10^5 m^3/s thus totally dominating the instantaneous current condition in the Great Belt. The oscillating flow maintains the stratification of Great Belt waters: By northbound current the Baltic brackish water will flow into the Great Belt. The water will experience a very strong mixing. As the brackish water is lighter than the saltier water coming from the north, it will tend to lie on top of the water mass in the Belt. By southbound current the surface layer will be forced southwards through the Great Belt while mixing with the saltier bottom water. When passing the Darss-sill the surface layer, which has got a high salt content on account of the mixing, will plunge under the brackish Baltic water. At the same time some of the bottom water is pulled over the sill. The plunging salt water forms a dense bottom current and feeds the Baltic lower layers with salt and oxygen.

The mixing between the layers in the Great Belt is caused by turbulence generated by wind and current. The current in the upper and lower layers of the Great Belt can flow in the same direction and opposite to each other depending on the relative strengths of the driving forces.

PRINCIPLES FOR ZERO BLOCKING SOLUTION

As described in Farmer and Møller (1990) the general behaviour of the flows between Kattegat and the Baltic are known in principle, but the details of the exchange over the sills at Darss and Drogden to the Baltic are still poorly understood. To prevent changes in the water exchange of the Baltic it is vital to ensure that the conditions at the Darss will remain unchanged. In order for these conditions to remain unchanged it is necessary to specify that the conditions at the boundaries of the Great Belt remain unchanged. In fact, changes are only allowed in a rather narrow area around the fixed link. In practice an area plus/minus 15 km north and south of the link is defined as the area in which changes are allowed, whereas areas outside this area shall remain unaffected. This area is called the near field in the following.

The problem is therefore reduced to calculate the effect of the link and the compensation dredging in this small area in such a way that flows across the boundaries to the near field remain unchanged. This criterion can be further refined with reference to the normal hydrodynamic laws by expressing that the total specific flow resistance within the near field shall remain the same.

However, in order to obtain a zero solution it is also necessary to specify that the mixing between layers remains the same. From hydrodynamic laboratory tests, field observations and theoretical analysis it has been found that the mixing between the layers in stratified flow is nearly proportional to the produced turbulent energy (Bo Pedersen, 1986). Bo Pedersen states that the Bulk Flux Richardson Number, R_f, defined as the ratio between the gain in potential as well as turbulent kinetic energy due to entrainment and the energy available for the turbulence production is a constant for subcritical, two layer flow. When this theory of constant efficiency of the mixing process is applied to the Great Belt, the problem of keeping the mixing unchanged is reduced to the problem of keeping the production of turbulent energy constant. We realise that the theory claiming a constant efficiency factor, R_f, for the mixing is debatable, however, several laboratory experiments and observations made in conjunction with the Great Belt link project support the simple assumption of a constant R_f. (See the paragraph below on mixing).

In the case of the flow through the Great Belt the production of turbulent energy is proprotional to the hydraulic energy loss. An important implication of the theory is that the mixing efficiency R_f is independent of the cause of the energy loss, be it bottom or interfacial shear, resistance from piers or expansion of flow lines and separation downstream of headlands and causeways. Only when the flow becomes supercritical is the efficiency increased.

The above findings are important because they state that so long as the hydraulic loss remains the same in areas with stratification then the mixing will remain the same.

The problem of determining compensation dredging is therefore reduced to determining the resistance from the link and then compensating for this resistance by dredging. Further, since the mixing is not important for the dynamics (balance of forces) it can be neglected in the equations of motion. Therefore the hydrodynamic calculations can be made to a sufficient degree of accuracy by a two-layered hydrodynamic model without including mixing for the near field.

ANALYSIS

The analysis centers on *resistance* due to expansion and friction loss and on *mixing* under subcritical and controlled conditions. Both shall remain the same in the near field over the typical time scales for in- and outflows to the Baltic. The analysis recognizes that changing salinities, interface levels, tilt of interfaces shall be taken into account and that the zero blocking solution shall be valid irrespective of all these different changes. All elements except controlled flow mixing are included in the numerical two-layer model used for the design of the compensation dredging. The model is the S22 model developed by Danish Hydraulic Institute ((Abbott, 1979), Farmer and Møller (1990)). An important advantage of S22 is that it takes the flow expansion in narrows correctly into account. This is important since it is one of the major contributions to the hydraulic resistances.

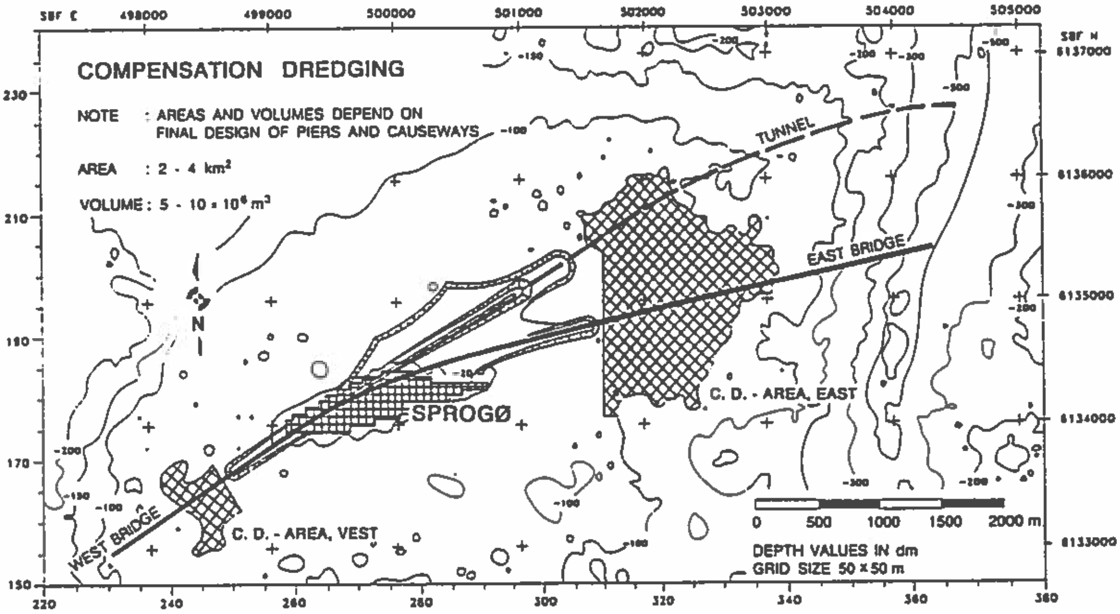

Figure 4. Typical compensation dredging. The dredging is included in the numerical model by corresponding change in topography. DHI/LIC (1988).

FLOW RESISTANCE

The flow energy loss can most easily be dealt with directly by means of the numerical model. In the case of a link the resistances due to bridge abutments, bridge piers and protruding tunnel elements are simply determined by plugging their resistance characteristics into the mathematical model.

The problem now arises of how to determine the size and locations of the compensation dredging. This design work is carried out according to the following principle. Given the boundary conditions for the flow through the Great Belt the surface current is calculated with and without the link. By calculating the deviation in surface water flow, we have defined a measure of deviation from the zero solution. This measure will depend on the geometry of the link; large piers and long causeways will increase the deviation. The deviation is defined in Figure 5.

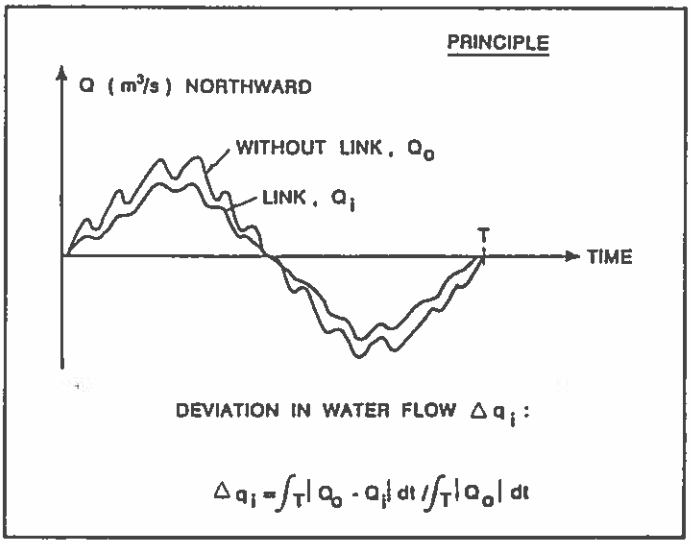

Figure 5. Principle of determining discharge deviation.

Now for a given design of the link we can introduce a dredging scheme and calculate the resulting deviation caused by the combined link and dredging. If, for instance, the area to be dredged is kept constant the only parameter determining the efficiency of the dredging is the dredging elevation. By repeating the calculation of deviation for different dredging elevations the deviation is minimized.

Zero solution is reached for minimum deviation, see Fig. 6. The principle raises two theoretical concerns: 1) Not only the surface water flow, but also the bottom water flow and the mixing deviation must be minimized, 2) how are the boundary conditions for the flow defined?

The first problem is solved by calculating both the minimum deviation for discharge (both layers) and the minimum deviation for mixing (both layers). In the ideal case they will occur for the same dredging scheme. In practice they differ about ± 0,3 m in dredging level. This is within the practicable limits of dredging accuracy and a 'mean' level is chosen.

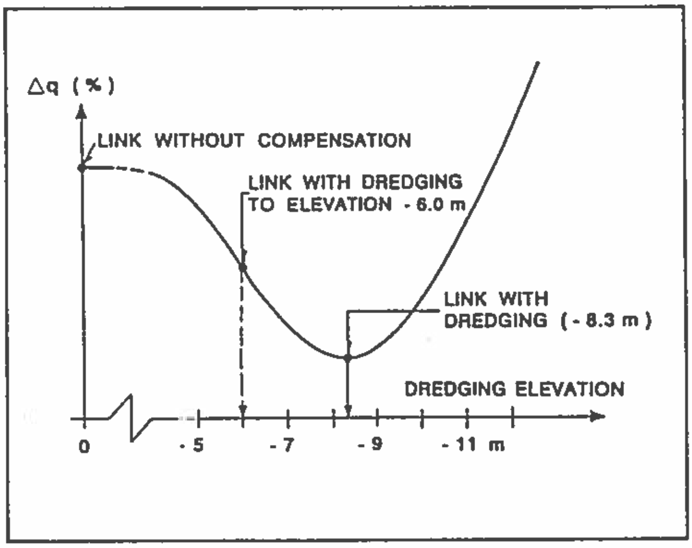

Figure 6. Principle of defining zero solution dredging.

The second problem is solved by introducing a design period, T, where the flow field parameters vary in a statistically typical way. A set of boundary data selected from measured time series of water level, interface and wind is used as boundary conditions for the numerical model. The statistics of the calculated resultant exchange flows are compared with long term measured time series of exchange flows and a subset of $T = 10$ days showing statistics similar to the observed statistics is selected as boundary conditions for the design period.

The boundary conditions are not changed during the repetitive calculations necessary to define the minimum deviation. It can be argued that boundary conditions should be influenced by the resistance imposed by the construction. This, however, has no impact on the determination of the minimum deviation and hence the final zero solution dredging. To illustrate this we consider a simple conceptual model for channel flow.

In the model in Figure 7 the head loss ΔH_{AB} is the boundary condition for the model and the equation $\Delta H_{AB} = KQ^2$ is the model. ΔH_{AB} is determined by external forcing like wind fields and fresh water runoff in the basin and tidal motions in the sea. If K is increased due to construction works in the channel then ΔH_{AB} will be changed. By compensating the flow resistance K is decreased. At the point of zero solution ΔH_{AB} is unchanged. It is seen that by keeping ΔH_{AB} independent of K during the minimizing calculations the model will specify the correct zero solution.

An example of discharge calculation for the chosen design period without the link is shown in Fig. 8. In Fig. 9 is shown the change in discharges by inserting the link shown in Fig. 3. The effect of dredging is shown in Fig. 10, where the flow deviations are depicted as functions of the dredging depth for the dredging shown in Fig. 4.

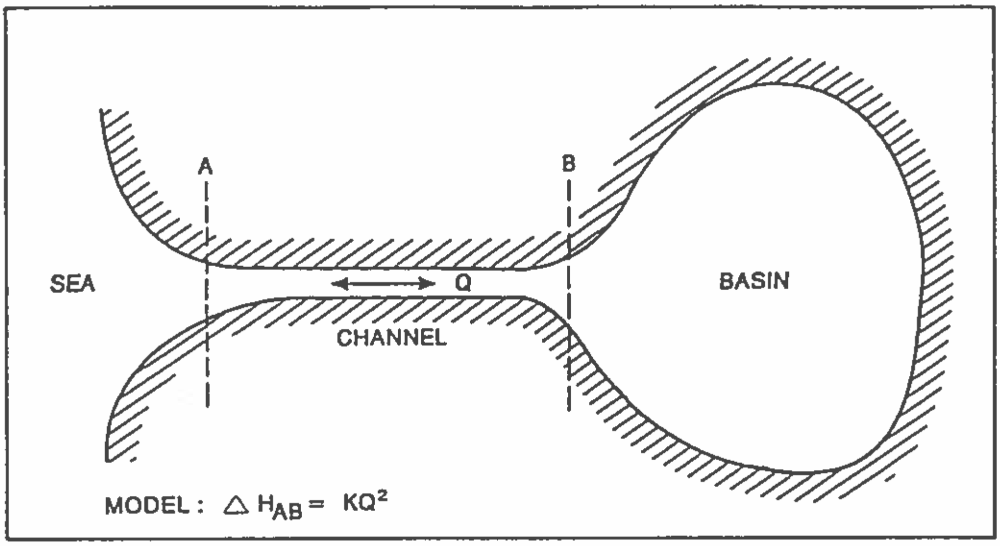

Figure 7. Conceptual model ΔH_{AB} is the head loss between A and B. K is resistance factor, Q is discharge.

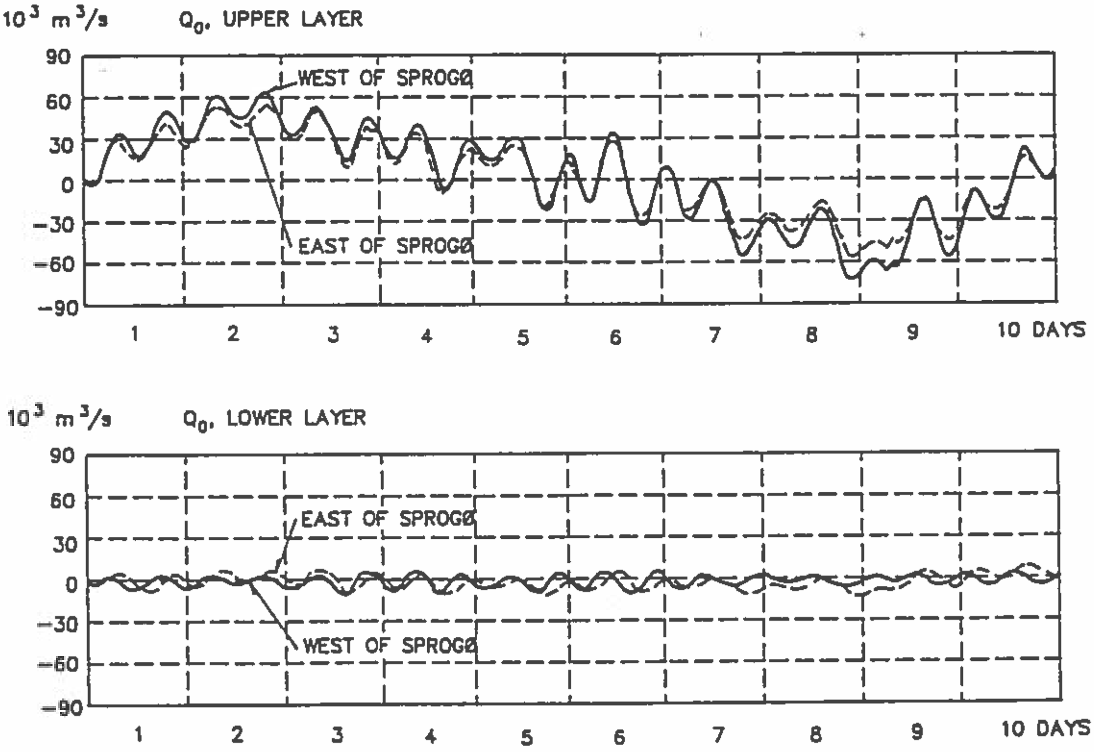

Figure 8. Undisturbed calculated discharges, Q_o, for 10 day design period. Positive discharge is flow from the Baltic, Negative discharge is flow towards the Baltic. DHI/LIC (1988).

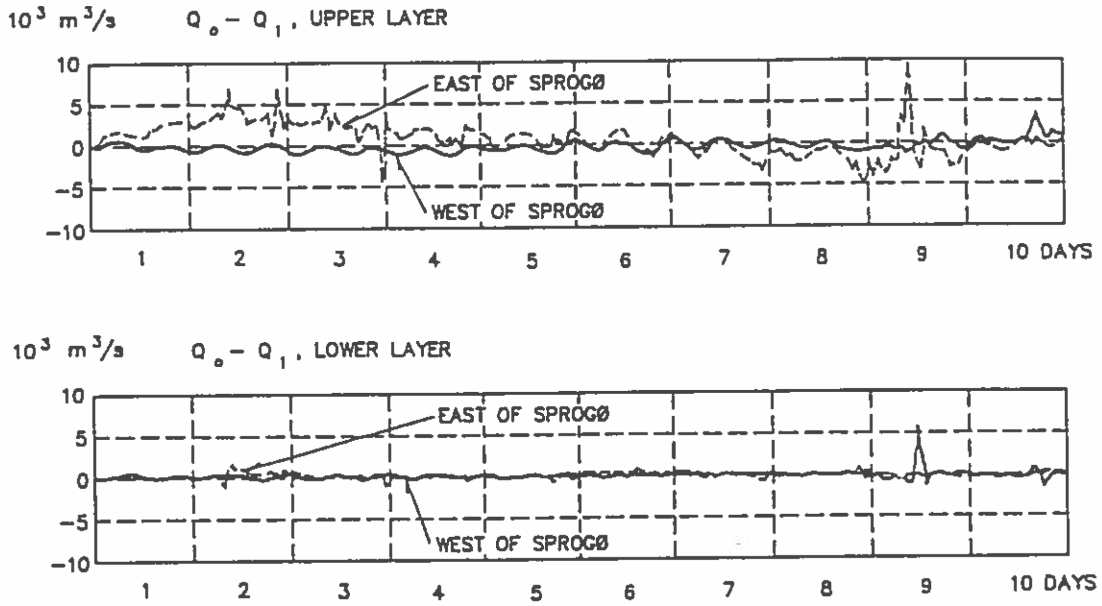

Figure 9. Difference between undisturbed discharge, Q_o, and discharge with link, but without compensation dredging, Q_i. DHI/LIC (1988).

MIXING, SUBCRITICAL FLOW

In the Great Belt where both layers are flowing the mixing between the layers is caused by entrainment from the lower layer to the upper layer and from the upper layer to the lower layer. This entrainment is calculated following the theory outlined by Bo Pedersen (1986). Bo Pedersen introduces the Bulk Flux Richardson Number, R_f, which for the two layer flow through the Great Belt can be reduced to:

$$R_f = 0,5\Delta\rho_o ghQ_e/PROD \tag{1}$$

R_f is the Bulk Flux Richardson Number, which can be looked upon as an efficiency factor for the mixing process, $\Delta = (\rho_o - \rho_1)/\rho_o$, ρ_o is the density of the bottom layer, ρ_1 is the density of the surface layer, g is acceleration of gravity, $\frac{1}{2}h$ is the average lifting height of the entrained water, PROD is the production of the turbulent kinetic energy, and Q_e is the entrainment discharge.

The Bulk Flux Richardson Number, R_f, is evaluated by Bo Pedersen, 1986,

$$R_f = 0.045 \tag{2}$$

When the above theory is applied to each layer in the Great Belt the following relation is obtained between the energy loss and the entrainment integrated over the total Belt Sea. The PROD can be related to the energy loss:

$$PROD = CQ\Delta H = CKQ^3 \qquad (3)$$

in which C is a constant. Combining Eqs 1, 2 and 3 the following expression for the entrainment is found.

$$Q_e = R_f CKQ^3/0.5\Delta\rho_o gh \qquad (4)$$

To keep the mixing (entrainment) unchanged requires not only that K is kept unchanged, but also that R_f must not be influenced by the link. Wind mixing is neglected as this mixing is not influenced by the link.

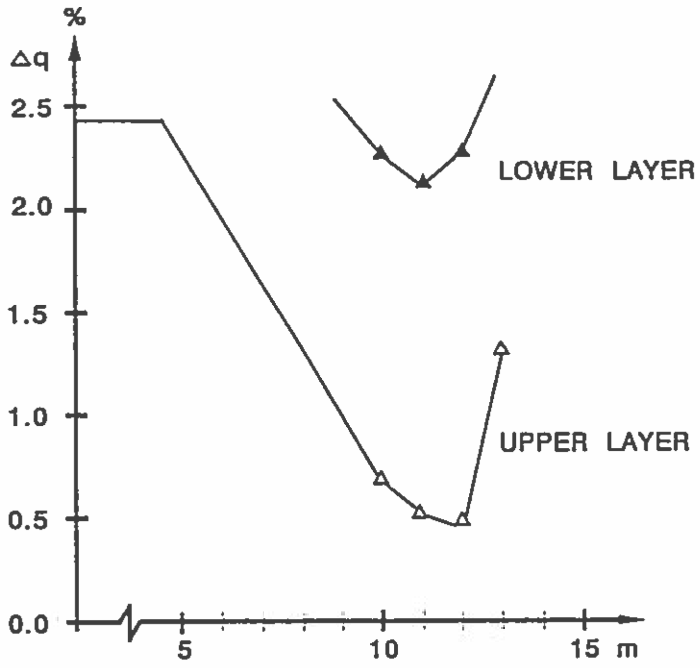

Figure 10. Minimizing discharge deviation for a selected link, see Fig. 4. The abcissa is dredging depth as indicated in Fig. 4 and the ordinate is the flow deviation. DHI/LIC (1988).

A priori one may expect R_f to increase due to the turbulence generated by the bridge piers placed on the sea bottom. Experimental tests, however, showed that the value for R_f is not significantly changed by the piers (DHI/LIC, 1987). Therefore it can be concluded that when the zero blocking solution is reached for the flow resistance then a zero solution is also reached with respect to the mixing between layers.

The above arguments are only correct if the interfacial area in the near field remains more or less the same. The compensation dredging could alter this relationship if it is extended too much. Generally, the compensation dredgings are placed somewhat above the interface, but local strong currents combined with a strong tilting of the interface may cause the pycnocline to rise above the dredging area. In order to keep track of this another criterion is added to the resistance criterion, namely that the production of turbulent energy over the interface should remain the same before and after the link. The total turbulent energy produced in the near field and the interface area, A is given by

$$PROD = \int_T \int_A prod\ dAdt \qquad (5)$$

in which prod is the local production of turbulent energy. Eq. 5 can be divided into production for the upper layer and for the lower layer:

Upper layer

$$PROD_1 = PROD_w + PROD_i + PROD_p + PROD_e \qquad (6)$$

Lower layer

$$PROD_o = PROD_i + PROD_b + PROD_p + PROD_e \qquad (7)$$

in which

$PROD_w$: Wind generated turbulence term
$PROD_i$: Interface friction term
$PROD_b$: Bottom friction tern
$PROD_p$: Pier term
$PROD_e$: Flow expansion term

Each of the terms $PROD_1$ and $PROD_o$ are evaluated separately by a subroutine of the numerical model, see Fig. 11. Once this is done deviation of the PROD term, Δp, is treated like deviation of discharge, Δq, in order to determine the zero solution dredging with regard to mixing.

MIXING, SUPERCRITICAL FLOW

The findings of Bo Pedersen (1986) show that the simple approach of a constant efficiency factor, R_f, for the mixing is not fulfilled for supercritical flow. When the flow becomes supercritical the momentum balance is used to assess the mixing, Wilkinson (1970).

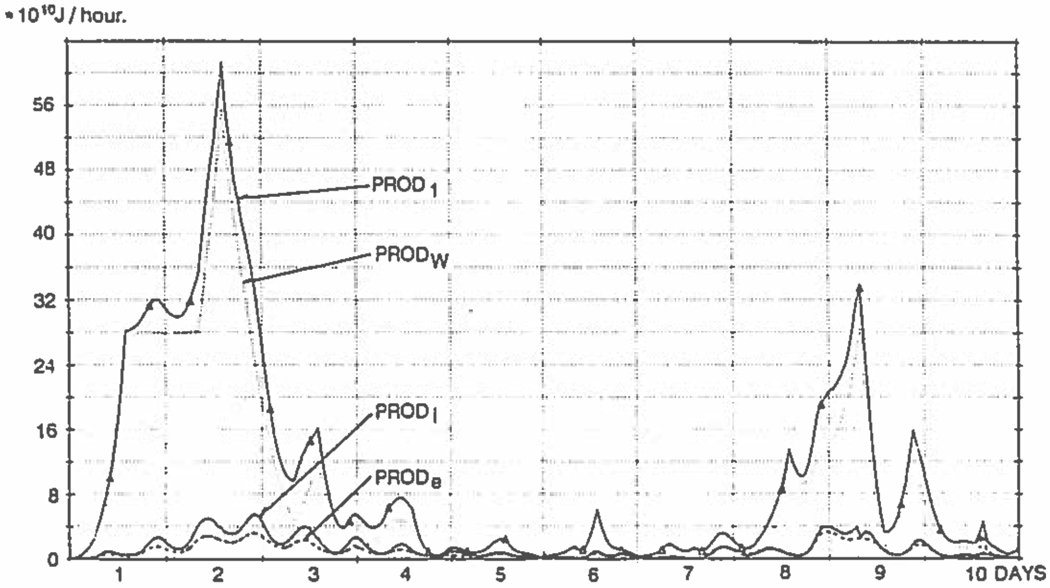

Figure 11. Example of calculated production of turbulent kinetic energy, PROD, for the design period. Integrated values for Great Belt ±10 km of the link. DHI/LIC (1989).

Expressing the momentum balance for the control volume shown in Fig. 12

$$I_o + P_o = F + I_D + P_D \tag{8}$$

where I and P are flow momentum and pressure integrated across the entire cross-section, index o is the southern boundary and D is the northern boundary of the near field, (Fig. 12). F is the combined resistance to the flow from the crossing and natural topography.

The individual terms in Eq. 8 are now examined. When the link is built a resistance is introduced due to the bridge-piers and the embankment which is compensated by dredging to keep F unchanged (to reach zero solution F will depend on the discharge and interface depth and be essentially independent of the redistribution of the mixing). I and P shall be unchanged for the zero solution. The supercritical flow situation is therefore characterized by having only one parameter which determines the mixing. This parameter is the total force F. When F is kept unchanged then the mixing is unchanged.

Applying this principle the flow through the link section means that the total force on Sprogø and the peninsulas of Knudshoved and Halsskov shall remain the same before and after the construction of the bridge.

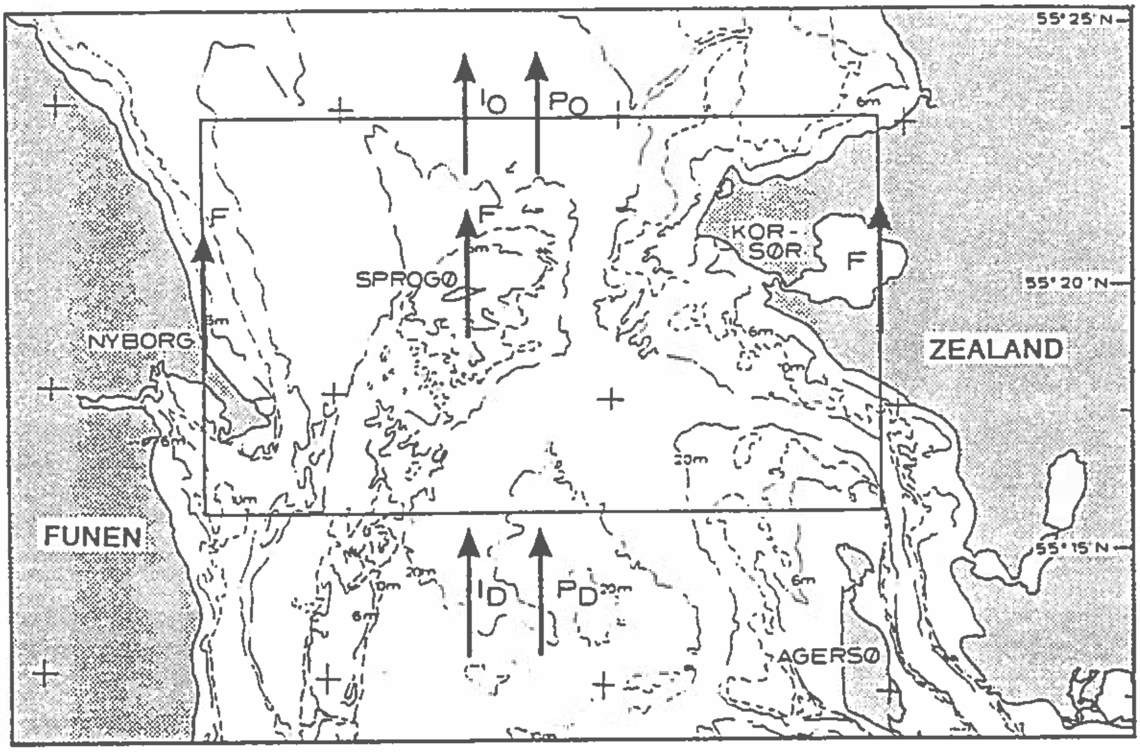

Figure 12. Control volume for Halsskov-Knudshoved narrows.

In practice this means that the reaction force on the northern and southern border shall remain the same before and after the construction of the crossing. This is automatically true when the resistance criterion is satisfied and therefore the zero solution criterion concerning supercritical flow is satisfied as well.

It is noted that the above method assumes that the foreseen redistribution in flow from Vesterrenden to Østerrenden does not dramatically change the shape of the stratification profile downstream of the flow control where the two flows merge. This assumption is basically a part of the two-layer approach and believed to be of minor importance with regard to the zero effect solution.

It is noted that the zero effect solution is aimed to ensure no changes in the integrated mixing over the near field. Also, when the flow is critical, the major part of the mixing will take place in the subcritical part of the flow thus decreasing the sensitivity of the zero solution to an incorrect representation of supercritical mixing. This point is further supported by the fact that the field observations suggest that the hydraulic jump in the Belt will in nearly all cases be of a weak gradually adjusting type (Farmer and Møller, 1990).

SENSITIVITY EVALUATION

Since both the design as described above and the construction of the compensation dredging naturally includes some uncertainty it is important to establish a measure of this uncertainty and to assess the resultant possible changes in the Baltic.

Uncertainty of design is assessed by investigating the effect on the dredging level of changes in the model calibration parameters (bottom friction coefficients, interfacial friction coefficients, wind friction coefficient, eddy viscosity, boundary conditions, interface level, density difference between layers, design period).

The result of a standard design period calculation is shown in Fig. 10. Similar calculations are performed with changes in model parameters and boundary conditions. In total 10 different sets of parameters and alternative design periods were investigated. The investigation showed that the dredging depths varied within 0.5 m, which is very satisfactory and shows the robustness of the concept. It is noted that 0.5 m corresponds to the practicable accuracy of the dredging operation.

Given the uncertainty of the dredging level it is possible to evaluate the maximum uncertainty of the zero effect solution in terms of maximum deviation from the zero effect criteria for the Baltic Sea. To assess the possible effect on the Baltic a steady-state model is set up. This model (LIC, 1984) is based on Bo Pedersen and Møller (1981). The Baltic model calculates changes in Baltic salinities and layer depths due to changed resistance in the Great Belt. If the zero solution is reached exactly then there is no change in resistance and hence no change in the Baltic. But when the uncertainty of the dredging and hence the resistance is introduced we can calculate the response in the Baltic. The calculation shows that the potential change in surface layer salinity of the Baltic is compensated 90-110% by the compensation dredging: 90% if maximum uncertainty causes undercompensation, 110% if uncertainty causes overcompensation.

The sensitivity evaluation shows that the method of determining the zero solution is efficient.

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[1] It is recognised that the internal reports referenced here are not widely available; this appears to be an inevitable consequence of a program that is part of a major engineering project. However, the open policy now adopted by the Great Belt Link Company means that the information contained in them is accessible and for this reason it has been considered useful to include the bibliographic references at this stage.

November 1989
1006-1/8911.ulb
CED/JSM

MEASUREMENTS AND MODELLING IN THE GREAT BELT: A UNIQUE OPPORTUNITY FOR MODEL VERIFICATION

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ABSTRACT. Environmental studies initiated in conjunction with construction of a bridge across the Great Belt will offer some remarkable opportunities for scientific investigations. In this paper we provide some background to the studies and outline the oceanographic aspects of the environmental plan and its implementation. The combination of a two-dimensional two-layer numerical model of the strait and a plan for comprehensive field measurements provides a unique chance for verifying the model, and thus deepening our understanding both of the modelling approach and of the fluid dynamics of the strait. In anticipation of the major field program some limited data were collected in a pilot study. Preliminary comparisons are encouraging.

1. Introduction

The Great Belt (Storebælt in Danish) is a channel approximately 18 km wide that divides Denmark into Jutland and Funen to the west and Zealand to the east. It is the largest of the three channels linking the Baltic to the Kattegat and North Sea (Figure 1.1). A major construction project (The Great Belt Link) is now underway to build a rail and road link across the strait and thus replace the busy cross-Belt ferry routes. The strategic location of the link and environmental concern about potential interference in the exchange of water between the Baltic and Kattegat have led to a comprehensive environmental plan.

A primary purpose of the present paper is to draw to the attention of the scientific community the scope of this project and the unique opportunity it presents for the study of stratified flows in straits. We outline the oceanographic aspects of the environmental plan and its implementation, including numerical modelling, oceanographic measurements in the strait and a comparison of model predictions with preliminary field observations. As background to the subsequent discussion a brief outline of the construction plan and of the overall hydrographic setting is presented in §2. A key concept in this plan is the 'zero solution' discussed by Ottesen-Hansen & Møller (1989). The basic approach to be taken with respect to compensating for blocking effects of the construction works is summarised in §3.

Both in concept and execution this study departs from traditional environmental programs associated with industrial developments. The concept of fully compensating any adjustments to the exchange flow due to engineering works is novel and places special demands on the understanding of stratified flow in the strait and on the required field measurement program. Scale estimates of the influence of the construction works on the mean flow show that even in the absence of compensation dredging the overall effect of the construction would be small: it would therefore be unrealistic to rely only on direct measurements of the flow,

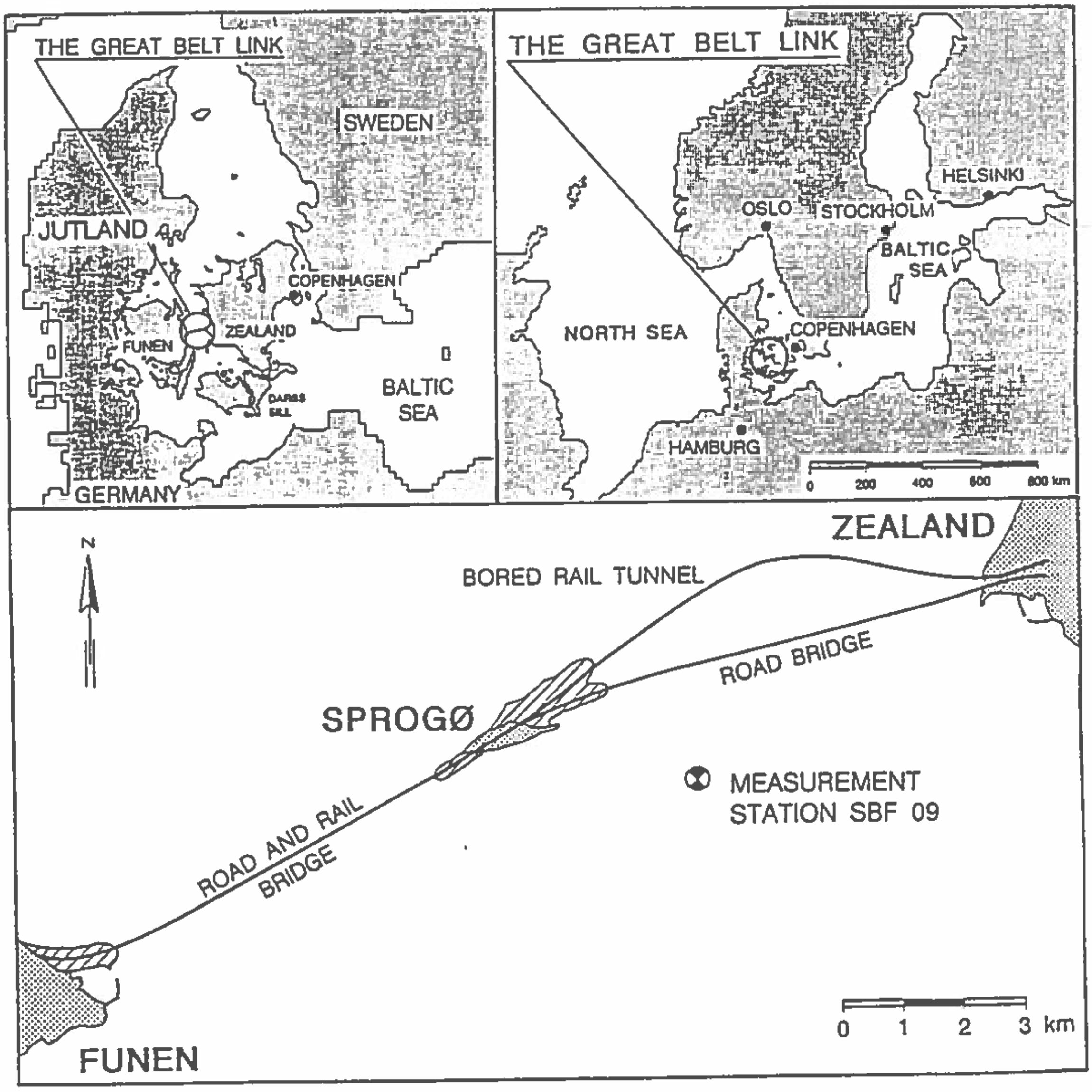


Figure 1.1. Chart showing the Great Belt Link.

either to identify such changes or to guide the required excavations, but of course the local effects in the immediate vicinity of construction will be quite large. For this reason our plan has been to use a numerical model and then to thoroughly test the model with measurements obtained in an intensive observational program. With the confidence gained from such tests the model may then be used to calculate the appropriate compensation adjustments.

It should be emphasised that no attempt is being made to model any long term changes in the Baltic that might arise from the blocking. The goal is to compensate the potential blocking with dredging calculated as accurately as possible with existing modelling technology. Thus, to within the accuracy of our calculations, there will be no change imposed on the water exchange, and therefore no change is predicted for the Baltic.

The proposed observational program which is discussed in §4, makes use of novel measurement approaches and is probably one of the most comprehensive that has ever been undertaken in a major strait. At the time of writing (June 1989) this program is just beginning; it will continue throughout the construction period (1989-1995).

The modelling effort represents a substantial undertaking. Together with analytical and laboratory investigations it is discussed in §5. Two-dimensional two-layer models have of course been used previously. The primary difficulty in applying such models to a topographically and hydrodynamically complex environment such as the Great Belt, is lack of knowledge of the boundary conditions. As discussed in §3, the application of the model to the 'zero solution' neatly circumvents the requirement for knowledge of precise and detailed boundary conditions, because a correct compensation for blocking of the flow by the bridge implies, by definition, that there will be no far-field influence; thus any reasonable boundary conditions outside of the immediate region of construction and compensation excavations may be used to test whether the compensation dredging is appropriate. But the validity of the model itself still needs to be tested and it is this need that has in part motivated the design of a comprehensive field measurement program.

A preliminary observational program was carried out in November 1987. The purpose here was to gain experience with different measurement approaches and to acquire an initial set of data with which to compare the model. In this pilot study the extent of data available is much less than that which will be obtained in the full measurement program. The data are nevertheless sufficient to carry out some preliminary tests of the model and these tests are also discussed in §5.

From an oceanographic point of view, a comparison of model output and observations constitutes an ambitious challenge to our ability to describe and understand the details of stratified flow in the Great Belt. A comprehensive analysis of the data over different seasons, and thus for various degrees of stratification, should lead to new insights on factors influencing exchange through this major strait.

2. The Great Belt Link Project and Its Hydrographic Setting

The project will consist of a combined road and rail bridge across the western Channel. At the island of Sprogø (see Figure 2.1) the traffic is divided into rail and road. The road link between Sjælland and Sprogø will consist of an elevated bridge while the rail link will consist of a bored tunnel.

The Great Belt is a broad and shallow strait separating the relatively saline North Sea from the fresher Baltic. It is the largest of the Danish straits and is estimated to account for 70% of the exchange between the Baltic and the open ocean, Jacobsen 1980. The exchange of water is of course of fundamental importance to the maintenance of water quality throughout the Baltic (Fonselius 1969 and 1988, Welander 1974, Pedersen 1978 and 1982, Pedersen and Møller 1981, Stigebrandt and Wulff 1987); it is this consideration that has led to the design of the 'zero solution' concept and has motivated the extensive hydrodynamic modelling and measurement program discussed below.

The hydrography of the Danish straits has been subject to study since the turn of the century (Knudsen 1899, Jacobsen 1910, 1913 and 1925). In this early period the basic features of the flow were revealed. Prior to the the comprehensive Danish Belt Project (1980a, 1980b,1981) several sporadic field investigations and theoretical works exist and attempts to model the exchange were made. (Würtki, (1954), Svansson (1972), Bertelsen and Warren (1977), Matthäus et al. (1983), Stigebrandt

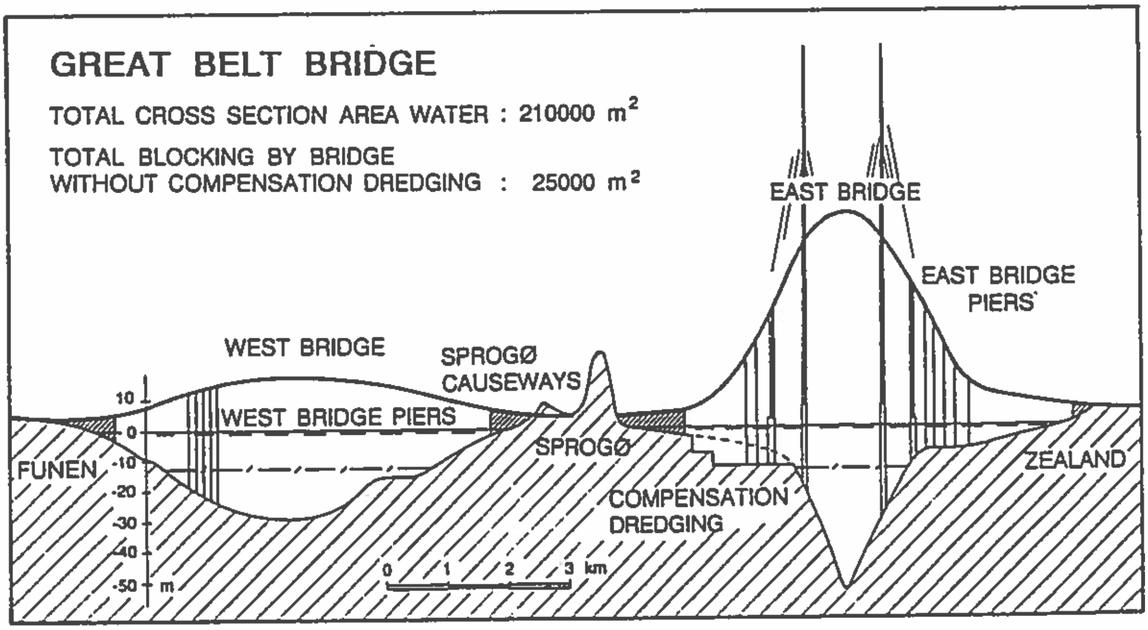


Figure. 2.1. Overall layout of the Great Belt Link. In addition to the bridge piers, substantial causeways in addition to an artificial island just north of Sprogø contribute to a blocking of the flow. Compensation dredging is planned in the eastern channel so to as offset this effect.

1983)). But with the Belt project a large and long term monitoring program was launched. Based on this wide material a brief summary of the hydrography of the Great Belt is given here.

For much of the year the strait is stratified. There is a background density driven flow in which the saline water flows southward toward the Baltic along the sea-floor, beneath a northward flowing fresher layer. This residual baroclinic flow is however strongly forced by a barotropic component which is driven by larger scale weather systems moving across Scandinavia so that both layers typically move together, but at different speeds, for a few days in one direction and then in the other. A modest tidal signal is superimposed on this meteorologically forced flow.

The Great Belt forms part of a large estuary comprising the Baltic Sea, Danish Straits and southern portion of the Kattegat. The outer boundary condition for the resulting estuarine circulation occurs in the form of fronts separating the fresher Baltic outflow from saline water moving in from the North Sea. The fronts are just the surface outcroppings of the interface dividing the two layers; they move back and forth through the Straits under the influence of the barotropic forcing (see Figure 2.2) and may be sites of significant mixing.

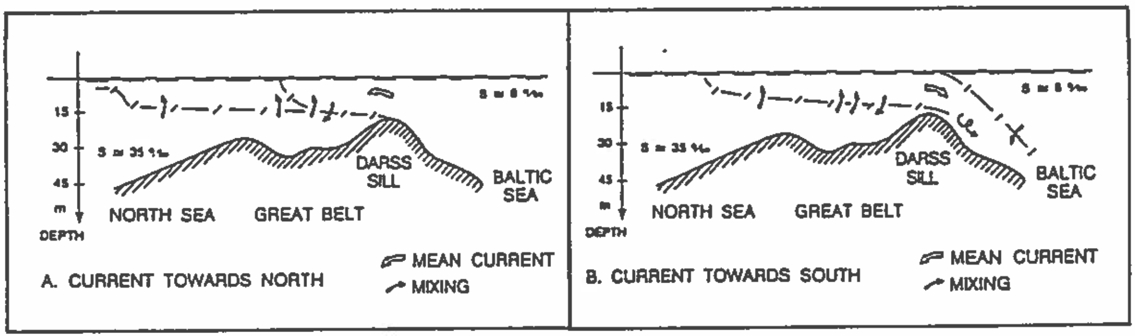

CURRENT CONDITION, GREAT BELT

Figure 2.2. Sketch of stratification in the Great Belt and neighbouring waters during outflow and inflow events.

Current measurements in the Strait illustrate the strongly correlated movements of upper and lower layers. However when the barotropic component is weak the baroclinic circulation can assert itself as a bi-directional flow with the fresh layer moving north above the southward flowing deeper layer. Figure 2.3 shows a scatter diagram in which current measurements at 7m in the surface layer are plotted against those at 30m in the deeper layer. While much of the data is consistent with a positive correlation, a significant fraction of the points lie in the second quadrant implying that for part of the time there is bidirectional flow corresponding to the estuarine circulation.

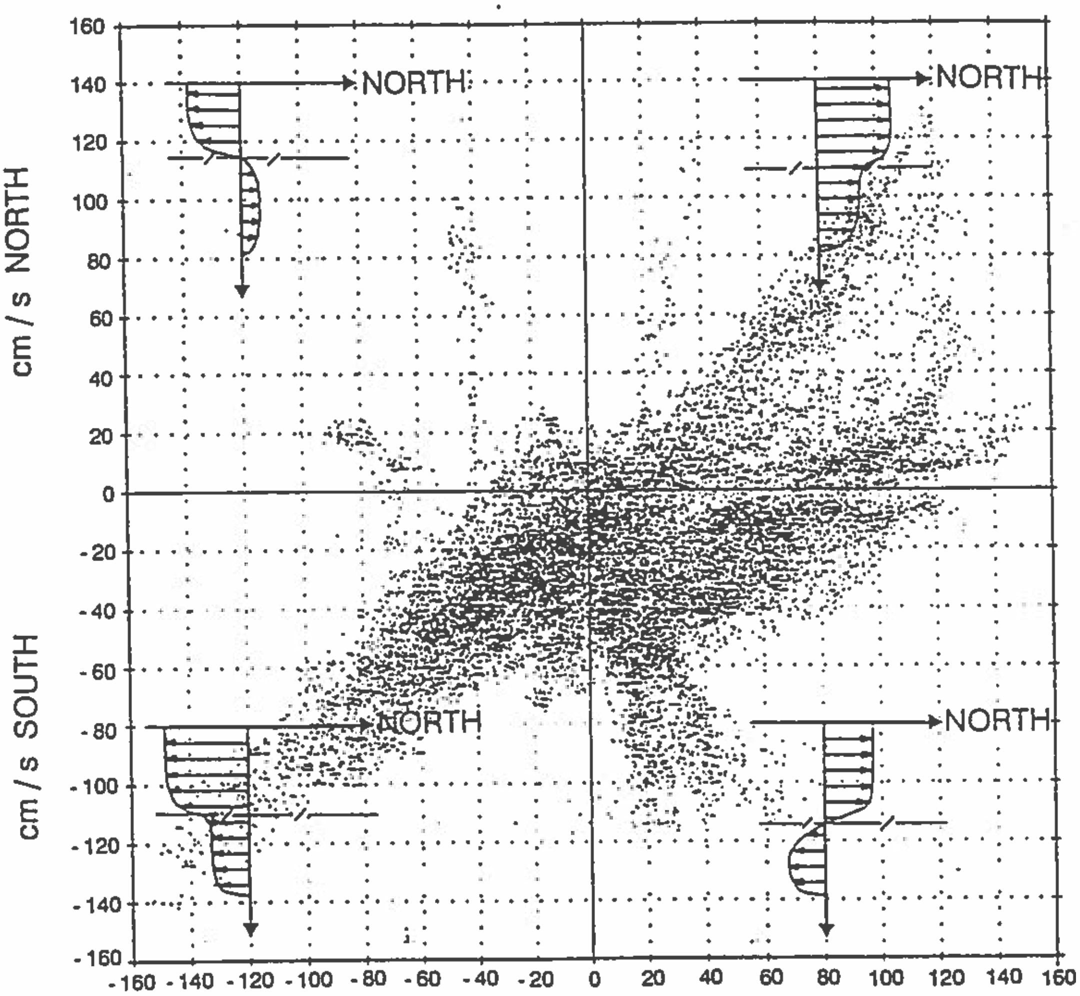


Figure 2.3. This scatter plot is derived from currents measured in the eastern channel at 7m depth in the upper layer and 30m in the lower layer. The currents are resolved into North-South components, with data from the deeper instrument scaled on the vertical axis and the upper layer instrument on the horizontal axis. Data are from the period 7 May - 2 June and 4 October - 1 November, 1977. Data from The Belt Project (1980a).

The density gradient is dominated by the salinity distribution. Maximum stratification occurs in June and July, with minimum values in the winter months (Figure 2.4). By combining available current measurements with the known variations in stratification, estimates of the internal Froude number can be made (Figure 2.5). It appears that for most of the year a subcritical two-layer flow is the rule. For about 15% of the time this two-layer flow is hydraulically controlled. The control however is not of the bidirectional sort, but arises from strong barotropic forcing on the two layers as they move through constricted areas of the Strait. For less than 1% of the time the flow is well mixed; this condition holds for extreme events, such as occasional inflows arising from winter storms.

A scale analysis of the momentum equation for each layer has been used to estimate the relative balance of forces. (DHI/LIC 1988). The sea surface slope typically provides the dominant driving force for the upper layer, except during transitional periods when wind stress and the horizontal density gradient become important. For the lower layer, the barotropic pressure gradient is also typically dominant, with interfacial stress contributing in the same direction as the surface layer current. This explains the fact that both layers tend to move in the same direction except during transitional periods. When the barotropic component is weak, the interfacial slope can dominate, driving the salty lower layer southward.

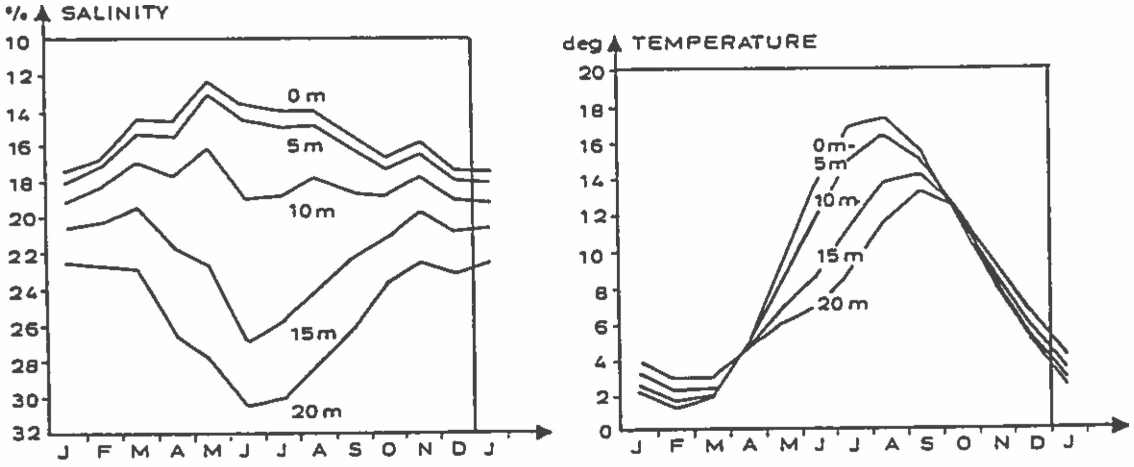


Figure 2.4. Seasonal variation in salinity and temperature. Monthly mean values are shown for different depths at the Halsskov Rev Lightship East of Sprogø for the period 1931-60. Strong mixing between the layers occurs during stormy periods in the autumn and winter. During summer there is less wind, reduced mixing and consequently stronger stratification. Data from The Belt Project 1980a.

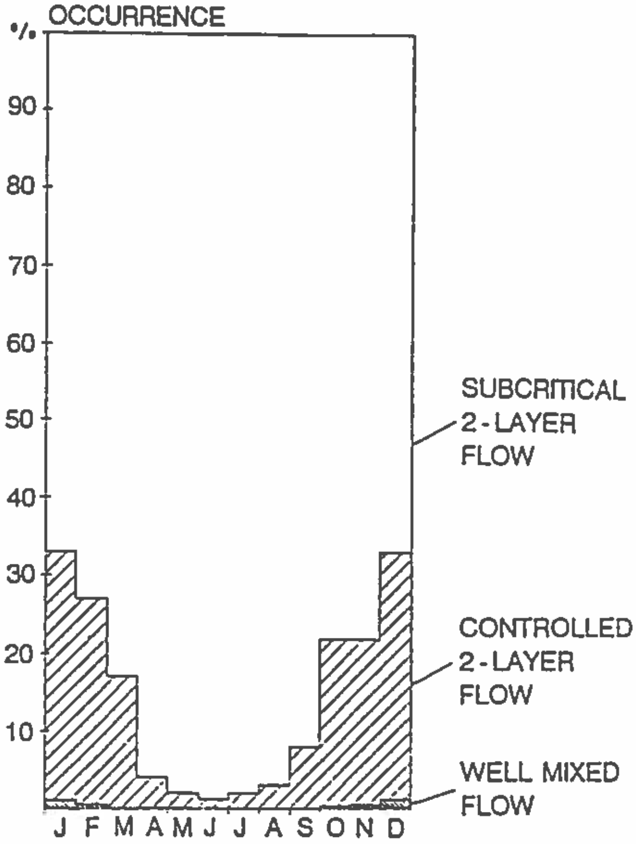


Figure 2.5. Estimated probability distribution for different hydraulic conditions in the Great Belt, including subcritical 2-layer flow, controlled 2-layer flow and well mixed flow. It must be emphasized that this estimated distribution may be substantially revised as data from the comprehensive environmental monitoring program become available.

3. Application of the Zero Solution Concept

The bridge is being constructed under the constraints, imposed by political agreement, that:

1. The discharge through the Belt remain unchanged by the crossing;

2. The salt balance for the Baltic remain unchanged by the crossing;

This political agreement requires a scientific interpretation. As discussed by Ottesen-Hansen and Møller (1989) and DHI/LIC (1988), the interpretation is based on the assumption that the stratification can be approximated by a 2-layer flow. With this approximation the requirement is that the deviation in discharge for each layer, and that the mixing between the two layers, remain unchanged. Note that it is not sufficient that just the discharge should remain unchanged. An alteration in mixing will alter the salinity of each layer, and indeed it has recently been estimated (Jürgensen, 1988 and 1990, and Jacobsen 1988) that mixing by ship traffic has resulted in a noticeable increase in the salinity of the Baltic.

The above interpretation depends upon an arbitrary choice for the 2-layer representation. Observations indicate that both a near surface zone and the deeper part of the water column are usually well mixed. On occasion there may be two pycnoclines, although usually only a single, well defined pycnocline occurs (Figure 3.1). The two-layer representation is found by choosing the depth at which the salinity is half-way between the surface and bottom values. This approximation breaks down as the stratification gets very weak in the winter, but in these conditions the flow is more appropriately considered to be single layer.

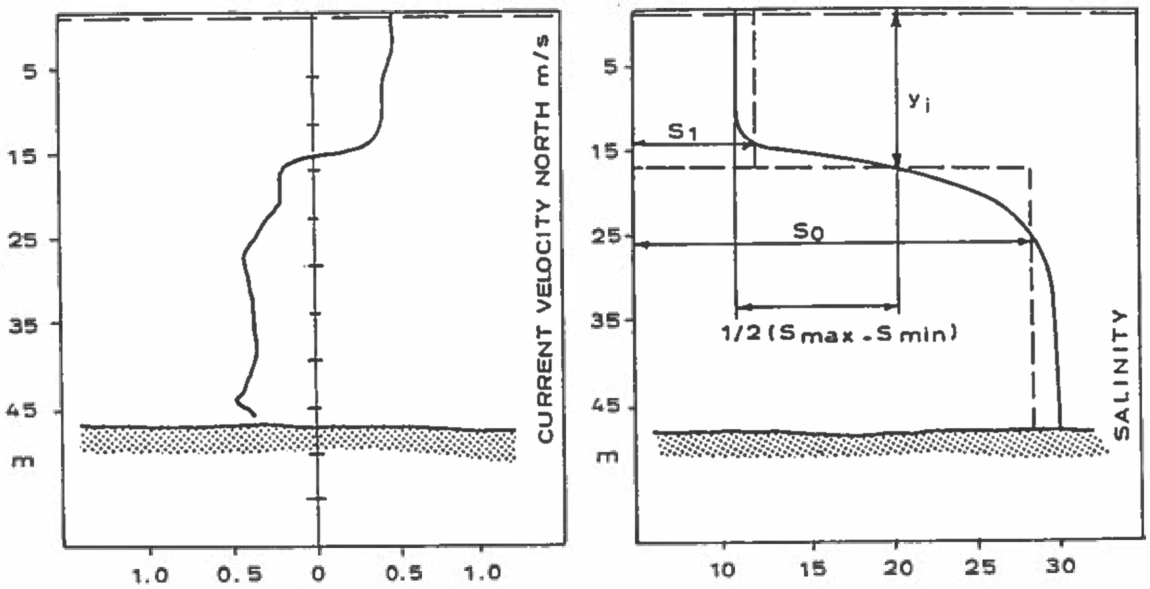


Figure 3.1. Example of current and salinity profiles. 30 October 1987. North East of Sprogø. Densities and velocities in each layer are determined as mean values within the layers defined by y_i (interface depth), where y_i is determined as the depth in which the salinity equals $S(y_i) = 0,5 (S_{max} + S_{min})$.

The intention is to avoid far-field hydrographic influence. Only in this way is it possible to avoid essentially unpredictable environmental effects (biological and hydrodynamic). Some near-field influences are of course inevitable. But the concept of a zero-solution discussed by Ottesen-Hansen and Møller (1989) involves compensating for the flow resistance introduced by ramps, bridge piers, etc. so that, to within the limits of our present ability to determine it, the two-layer exchange remains unaffected and thus the far field consequences are eliminated.

From the point of view of the present discussions, an important aspect of the application of this solution is that a prototype flow regime for a design period of 10 days is used against which to optimise an excavation plan. The model flow regime includes a typical meteorologically forced northward flow followed by a southward flow. The optimisation procedure consists of adjusting the modelled compensation excavations incrementally, running the model for the same boundary conditions and finding the deviation from the prototype flow.

The model calculations are not limited to a single 10-day prototype flow, and in fact tests have been carried out for a wide range of flow conditions. For example tests have been carried out for substantially different values of interface depth, barotropic pressure gradient and wind-stress. The 10-day period was chosen as being representative of stratified conditions including both subcritical and controlled regimes. Its relatively short duration makes it practicable to run a very large number of simulations, which is necessary for optimising the dredging calculation. Although the well-mixed flow is not represented in the design period separate calculations show that the dredging required for satisfactory compensation of a 2-layer flow is fully applicable for the well-mixed case. The final zero solution will be thoroughly checked for much longer period simulations.

An advantage of the chosen scheme is that since a 'zero solution' is sought, that is, a solution with minimal deviation from the prototype flow, the precise boundary conditions are not important. They only become important if the deviation from a 'zero solution' is significant. On the other hand it is critical to the success of the scheme that the model be a good representation of the physics. The extensive measurement program to be carried out in the strait will provide an opportunity for model verification.

4. Environmental Monitoring Program

A comprehensive monitoring program has been initiated in the Great Belt, with the following purposes:

(1) To establish additional reference data on flow in the strait prior to the bridge construction.

(2) To provide a comprehensive data set for verifying and if necessary, tuning the numerical model.

(3) To provide adequate data for running forecast models required in the day-to-day planning of sensitive aspects of the construction.

(4) Verification and control of the effects of compensation dredging.

(5) Verification of effects in the nearby waters of Langelandssund and nearfield impact studies.

The program includes both moored instrumentation and measurements from a vessel. Figure 4.1 shows the general layout. The overall design of the program is closely linked with the two-layer numerical model discussed below. In particular, measurements of the required boundary conditions (sea-surface height and interface height) are obtained at the northern and southern boundaries of that part of the strait included in the model. A total of 9 water level gauges is included. These water level measurements, along with observations from other selected sites, are communicated directly by radio, cable or public telephone link to a central data station in Sprogø. Real time measurement in this way is essential to provide up-to-date input for environmental forecasting.

Remote current profiling using acoustic Doppler instruments will take place both in the eastern and western channels (stations 7 and 9) with real time data link by cable. A novel technique will be used to measure the interface level at the northern and southern boundaries. In addition to temperature-conductivity chains (with sensors at 7, 10, 12, 14, 16 and 19m) an echo-sounder will be used. Prior tests from a ship have shown that a well defined maximum in the acoustic backscatter occurs at the interface. The acoustic technique is still under development but good results are achieved when the interface is sharp and not too close to the surface or bottom (within 10% of depth). Both internally recording (stations 3 and 12) and real time measurements (stations 2, 7, 9, 11 and 13) of the interface depth will be obtained.

Additional instrumentation will be used to measure meteorological parameters (at Sprogø), waves (stations 5 and 7) and dissolved oxygen and turbidity at 7 and 9m depth (stations 2, 7, 9, and 11). The vessel M/S PIP will be equipped with an acoustic Doppler current profiler, an electro-magnetic current profiler, CTD with dissolved oxygen and turbidity sensors, acoustic interface sensor and a conventional echo-sounder. The vessel uses a Syledis positioning system. Additional measurements of currents, temperature and salinity, oxygen and interface level will be obtained in the sound West of Langelandssund.

While the recording instruments and real time observations will continue throughout the construction phase, there will also be certain periods of intensive ship-based measurements during 1989, 1990 and 1991. During the measurement periods, comprehensive observations of the flow in the vicinity of construction and dredged areas will allow the calculations of compensation dredging to be updated.

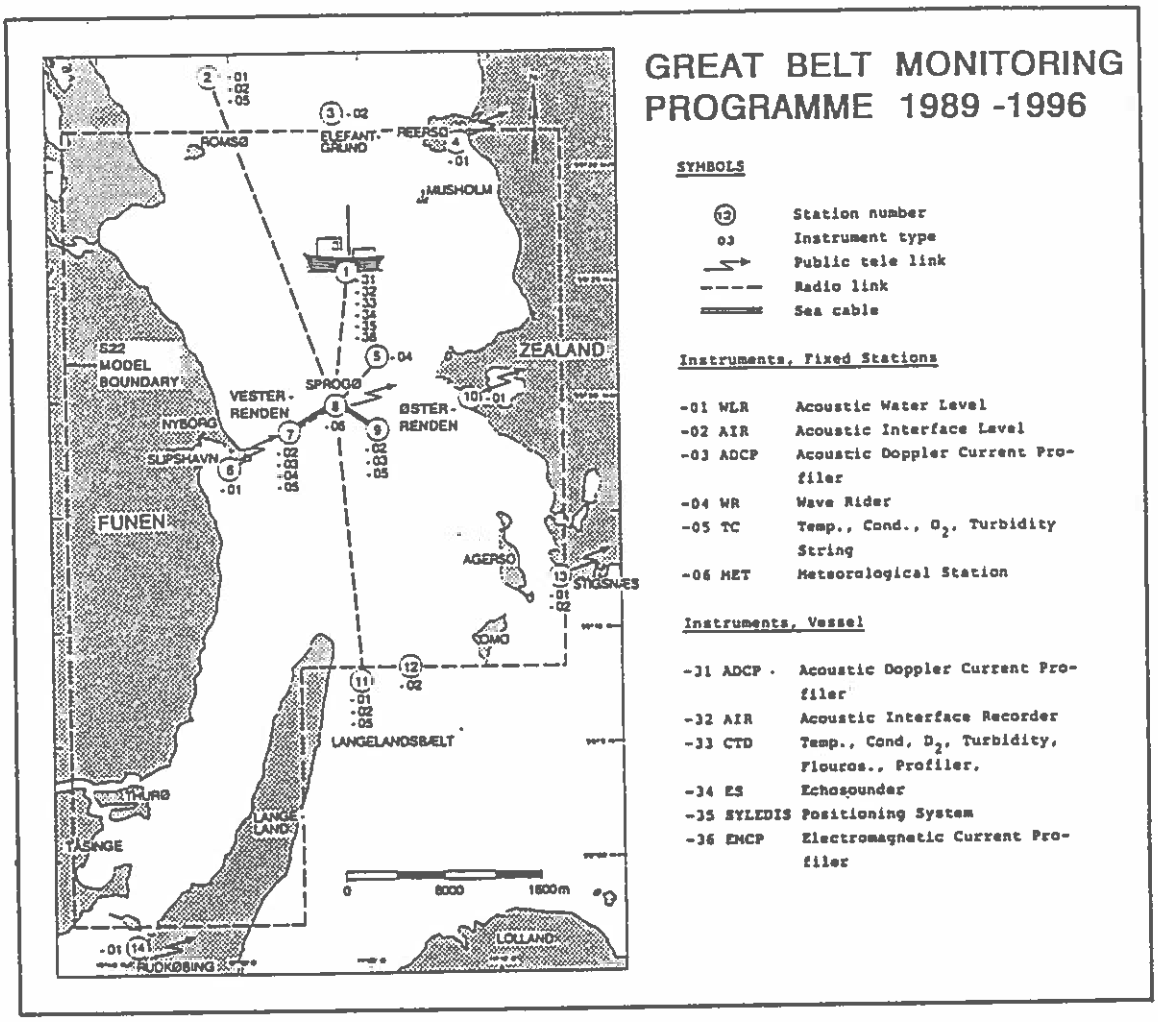


Figure 4.1. Sketch showing locations of different instrumentation included in the Master Plan for Environmental Monitoring. Much of the data will be relayed to a central station at Sprogø by cable, telephone and radio, allowing real-time analysis and environmental forecasting.

5. Modelling and Model Verification

Scale analyses and laboratory modelling

The primary tool for calculating the influence of the bridge on the flow, and for determining the necessary compensation dredging, is a two-layer, two-dimensional numerical model called System 22. Before this model was set up, a large number of analytical investigations as well as some laboratory studies were carried out (DHI/LIC 1988). The purpose of these was to identify the overall magnitude of various effects and to ensure that the subsequent modelling would provide a satisfactory representation of the fluid dynamics of the Great Belt.

The scale analysis was carried out for a representative bridge design (the final design was not fixed until later), along with representative flow parameters established during field studies. The analysis showed that resistance to flow through the Great Belt is dominated by a combination of friction and expansion loss, the latter occurring just downstream of the contraction formed by the narrow channels on either side of Sprogø. The bridge construction will have the effect of increasing the flow resistance in the western channel by about 4% while reducing it, after completion of compensation dredging, by about 5% in the eastern channel. The net effect will be a small transfer in discharge from the west to the east channel.

In order to ensure that the zero solution is achieved it is necessary to keep the mixing unchanged. Mixing between two layers in a subcritical flow is appropriately formulated in terms of a flux Richardson number. Following Bo Pederson (1980), the flux Richardson number depends upon the production of turbulent kinetic energy. For given flux Richardson number, R_f the resultant entrainment across the interface can be found. The turbulent kinetic energy production can be calculated by integration, for example over the sea-floor, interface and sea surface. The resultant mixing can then be found for a given value of the flux Richardson number. When correctly formulated in terms of the turbulent kinetic energy production, estimates of R_f both in laboratory and field studies suggest a value of about 0.05. However it was not clear that this value would also be appropriate for the case of bridge piers in the two-layer flow. Consequently laboratory studies were carried out; these demonstrated that even for this case a value of 0.05 was appropriate. This demonstrates that the mixing is maintained unchanged by transferring the energy loss of the flow (turbulence production) from 'natural' processes like bottom friction and expansion losses to 'artificial' processes like pier resistance, which precisely is the goal of the compensation dredging. Nevertheless, scale calculations of mixing due to the bridge showed that it is small relative to other factors. For example the turbulent kinetic energy production due to the bridge piers in the upper layer is about 5% of that due to typical wind effects on the area within 10 km North and South of the bridge.

A result of the scale analysis of two layer flow in the strait was the finding that for a significant fraction of the time (Figure 2.5) the flow was hydraulically controlled. The analysis showed however that under these circumstances the flow typically passes through a gradually adjusting internal hydraulic jump and only resembles a fully turbulent jump in a few cases if at all. The hydraulic analysis further showed that it is normally only flow in the eastern channel that is controlled, with flow in the western channel remaining subcritical but frictionally limited so as to match the downstream conditions.

An uncertainty remains with respect to mixing in the controlled flow. The flux Richardson number formulation could not be expected to apply in the rapidly varying flow associated with an internal hydraulic jump and laboratory studies were conducted to investigate this case also. (DHI/LIC 1988).

Numerical Model

Before the recent implementation of a two-layer numerical model in the strait, various theoretical models had been developed for the Great Belt and neighbouring seas (Figure 5.1). These include a local numerical model (DHI/VKI, 1985) in which only the surface layer was described using the DHI System 21 barotropic model. Model calculations were also performed for the Kattegat (LIC, 1985). A model was also developed to describe the mean current and mixing for long term equilibrium (~30 years). In this model, referred to as the Østersø model (LIC, 1984), the mean transport of salt to and from the Baltic, east of the Darss sill, was calculated.

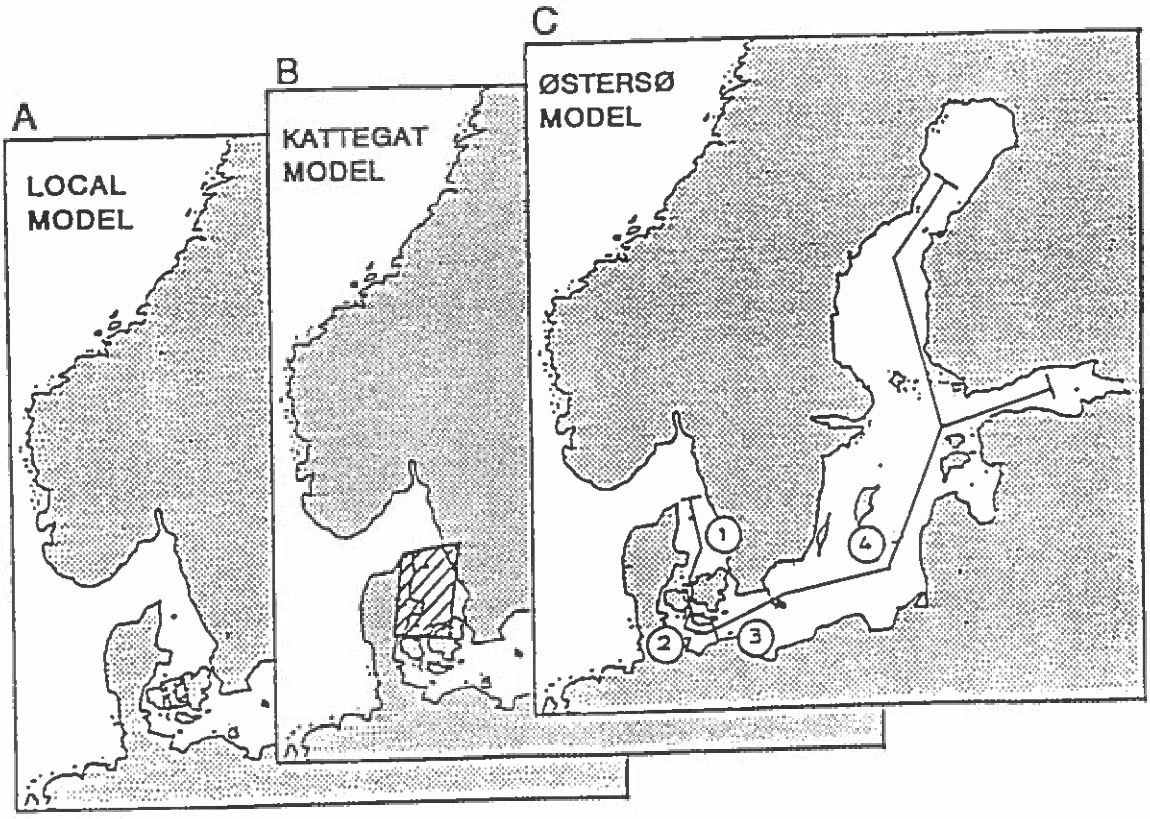


Figure 5.1. Areas included in previous model studies related to the Great Belt.

The primary numerical model used in this study is a fully 2-dimensional 2-layer mathematical model developed at DHI and referred to as System 22. (For full details of this model the reader is referred to Abbott (1979) and DHI (1987)). The system generates a model of a given area by entry of appropriate bathymetric data. It computes the surface, interface levels, and flows in both layers in a rectangular grid in response to specified forcing functions, boundary and initial conditions. The basic equations are the continuity, x-momentum and y-momentum equations for each layer. These include the non-linear convective and cross-momentum terms. The model includes effects of rotation, wind shear stress, bed shear stress, interfacial shear stress, mixing, turbulent momentum dispersion, barometric pressure gradients and horizontal density gradients and changes within each layer. Production of turbulent kinetic energy is computed from the modelled flows as an overlay to S22. The equations are solved by implicit finite difference techniques with variables defined on a space-staggered rectangular grid.

In the present implementation the grid size was chosen to be 500m (a 250m grid is chosen for final calculations). Since the bridge piers are of order 30m, their impact on the flow was modelled by calculating the current induced drag force due to each pier and representing it by an equivalent shear stress contribution compatible with the S22 model momentum formulation.

The model calculations were carried out over an area that includes the central portion of the Great Belt where the construction is taking place. In order to provide more realistic boundary conditions the two-layer S22 model is located within a larger area that is described using the single layer model (S21). Sea-surface levels at the S22 model boundaries are transferred from the single-layer to the two-layer model. The areas included in each model are shown in Figure 5.2.

A number of model verification tests were conducted using both laboratory results and analytical solutions. An extensive series of tests were carried out to verify that the model performed adequately in the presence of flow separation downstream of a contraction. In particular, flow separation is expected in the neighbourhood of headlands and islands. Provided that the modelled area includes all of the separated flow the model performs well. These comparisons provide confidence in the ability of the model to reproduce well defined flow regimes such as can be modelled analytically or in the laboratory. Nevertheless the model's primary use requires that it successfully describe the much more complex environment of the Great Belt. The only realistic way of verifying its performance in this environment is by direct comparison with appropriate field data.

There is one important limitation to the S22 model: the numerical technique is unstable in the presence of supercritical flow. This limitation may be overcome with an appropriate reformulation of the basic equations and appropriate procedures for achieving this have been proposed. However, implementation and testing of these procedures have not at this time been carried out and an alternative measure has been adopted. A dissipative interface is used to dampen the instability in supercritical flow. Although there is some theoretical basis for this

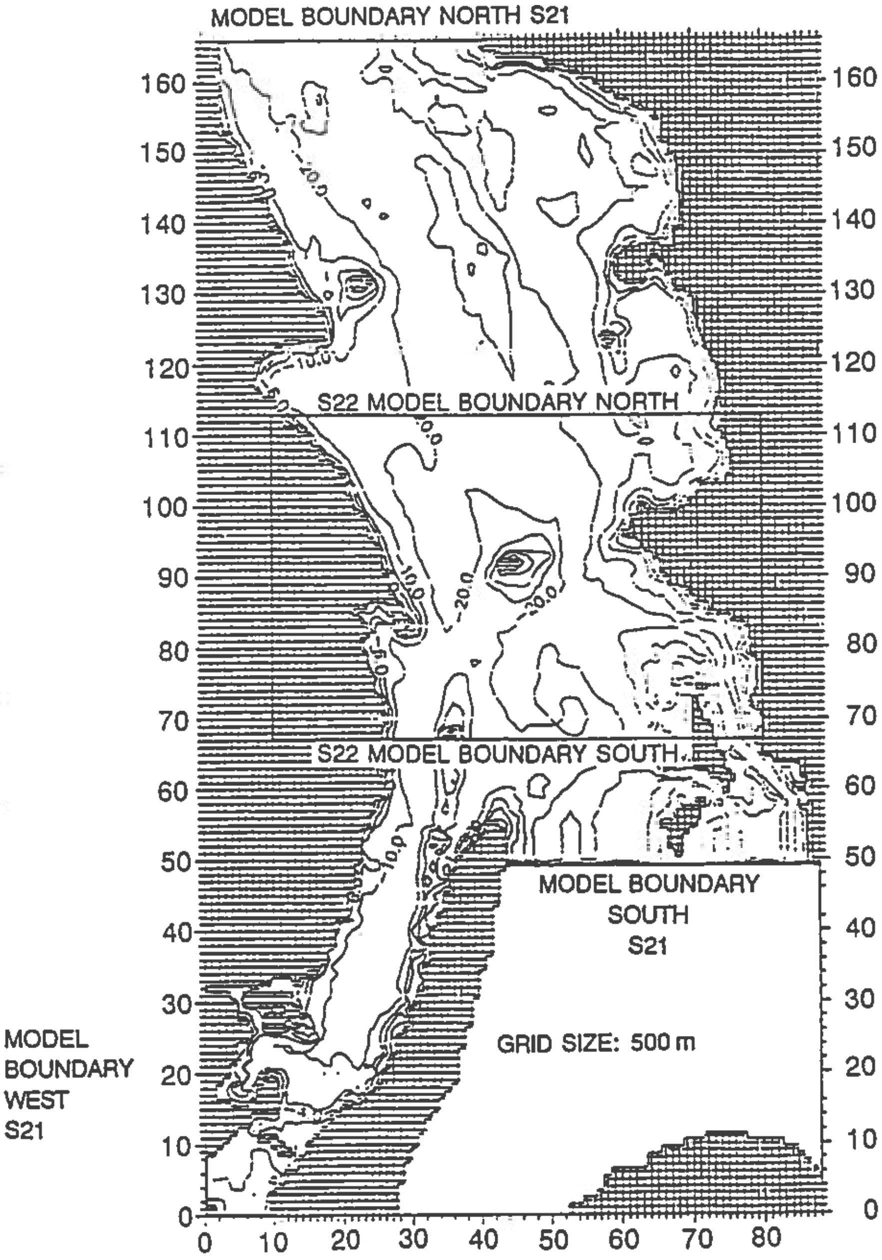
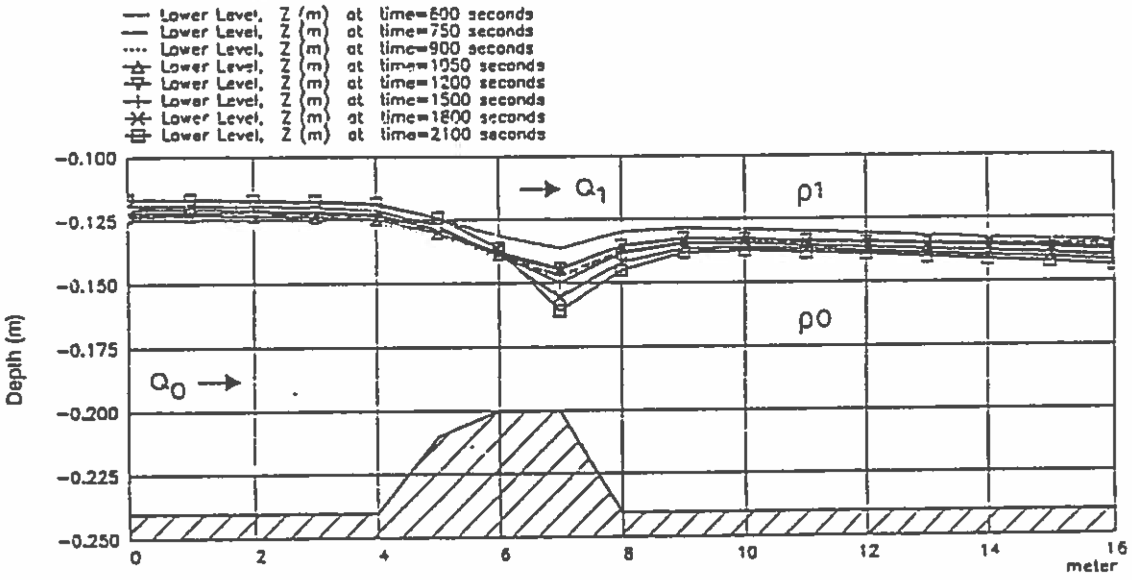


Figure 5.2 Areas included in the present model studies. The larger area is modelled by the single layer S21 sytem using available water level and meteorological data. This model is then used to derive water level boundary conditions for the 2-layer model S22, which encompasses the smaller area of primary interest. The grid element spacing is presently set at 500m, although finer resolution may be used if required.

approach (Abbott 1979), tests with comparisons with analytical solutions were carried out. The tests showed that the model behaves well, provided that the jump is weak. This is nearly always the case in the Great Belt, so the dissipative solution is considered satisfactory in lieu of an appropriate adaptation of the numerical scheme.

An example of using the dissipative interface for flow over a sill is shown in Figure 5.3. The boundary condition is a steadily increasing discharge Q_0 and Q_1 and a steadily decreasing interface level at the down stream end of the flume.



WATER DEPTH 25m

$Q_0 = 3.5 \cdot 10^{-3} \cdot \frac{3 \cdot t \cdot 10^{-3}}{5400s}$ m^3/s, $Q_1 = 0.1\ Q_0$

$\Delta = (\rho 1 - \rho 0)/\rho 0 = 0,01$

t = TIME (SECONDS)

Figure 5.3. Numerical simulation of flow over a sill.

In Figure 5.4 is shown a time series of the interface depth upstream and at the sill. After an initial wave (t < 600 sec.) the interface stabilises. On the figure is shown the quasi-steady analytical solution for the critical depth over the sill and the upstream interface level.

It is seen that the numerical solution breaks down at approximately t = 2300 sec. But it is interesting to note that for moderate flow (850 s < t < 2300 s) the flow is critical and the upstream interface depth is calculated correctly. This will be the typical situation in Storebælt where only weak jumps have been observed.

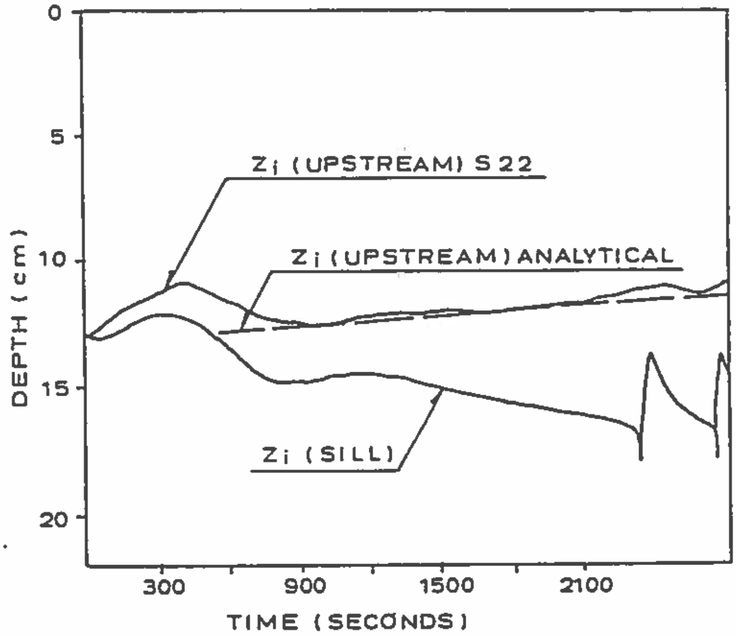


Figure 5.4. Numerical simulation of flow over a sill. Time series of interface level upstream of sill and at sill. Analytical solution is quasi-steady.

In §5 an example of critical flow observed in Storebælt is shown together with the simulated flow.

Model Verification with Field Data

A preliminary field study was carried out in November 1987. It had originally been planned that the initial period (November 1-4) be used to tune the model, but comparisons indicated reasonable agreement between model and data, so model calibration was omitted and the full data set used for verification by direct uncalibrated comparison with measurements. Thus, the parameters originally chosen, for example for the shear stream formulation, were retained unchanged. Comprehensive boundary data, such as will be collected under the new environmental monitoring program, were not available. Nevertheless there was sufficient information to allow an initial comparison of data and model output. Figure 5.5 shows the general plan; current meters were installed at Stations A, B, C and D and there were a total of 6 water level recorders.

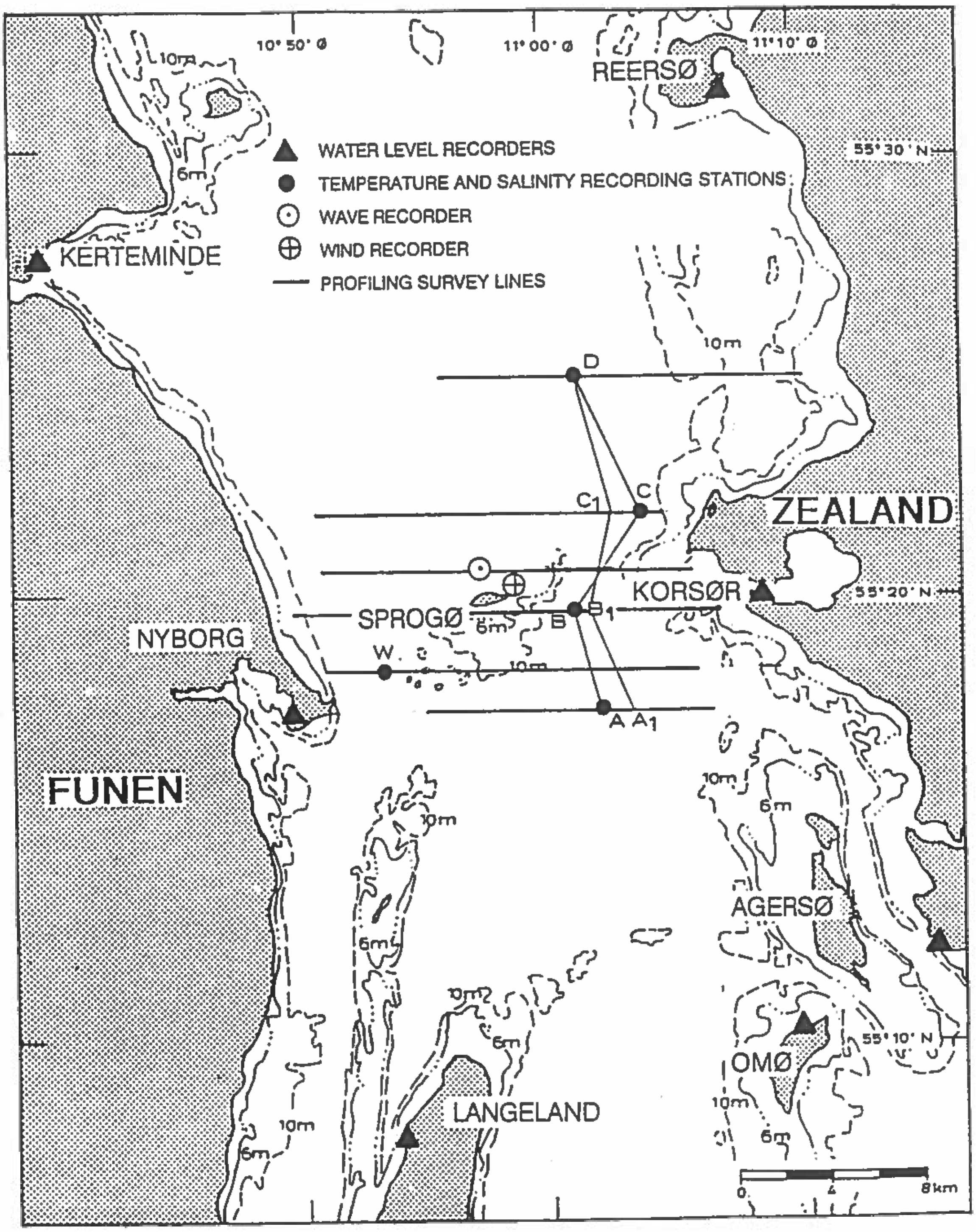


Figure 5.5. Location of instrumentation used in the November 1987 pilot study. Current meter records were obtained at Stations A, B, C, D and W.

Care is required in the definition of interface depth and layer properties, given the continuous nature of the observed profiles, see Figure 3.1. Even for the quite limited period of available observations, the amount of data and model calculations is enormous and only a small representative sample can be shown here. We have attempted to develop means of presenting the data in such a way that the comparison between model and observations is most readily discerned.

Sea-level fluctuations were calculated with the barotropic model S21. Its effectiveness may be judged from Figure 5.6 where the height <u>difference</u> across the mid-point of the Great Belt (i.e. Korsør-Sliphavn) is shown during a short period of strong flow towards the north. Typical variability in sea level difference is 15-20 cm; the difference between modelled and observed sea-level difference is of order 1-2 cm.

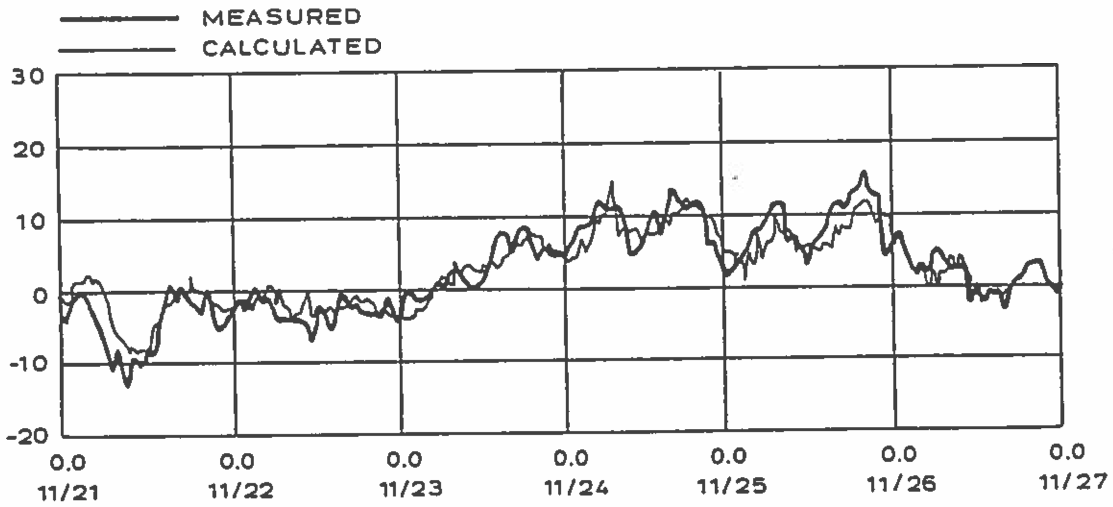


Figure 5.6. Water level difference across the Great belt. Measured and calculated. Note that comparing measured and calculated water level difference is a more sensitive measure of model performance than comparison of water levels.

From the observations of meteorological and hydrographic parameters, 21-27 Nov. 1987, the two-layer model S22 was used to calculate the driving forces. For the chosen period, the north-south sea-surface slope produces the dominant term in the momentum balance (Figure 5.7).

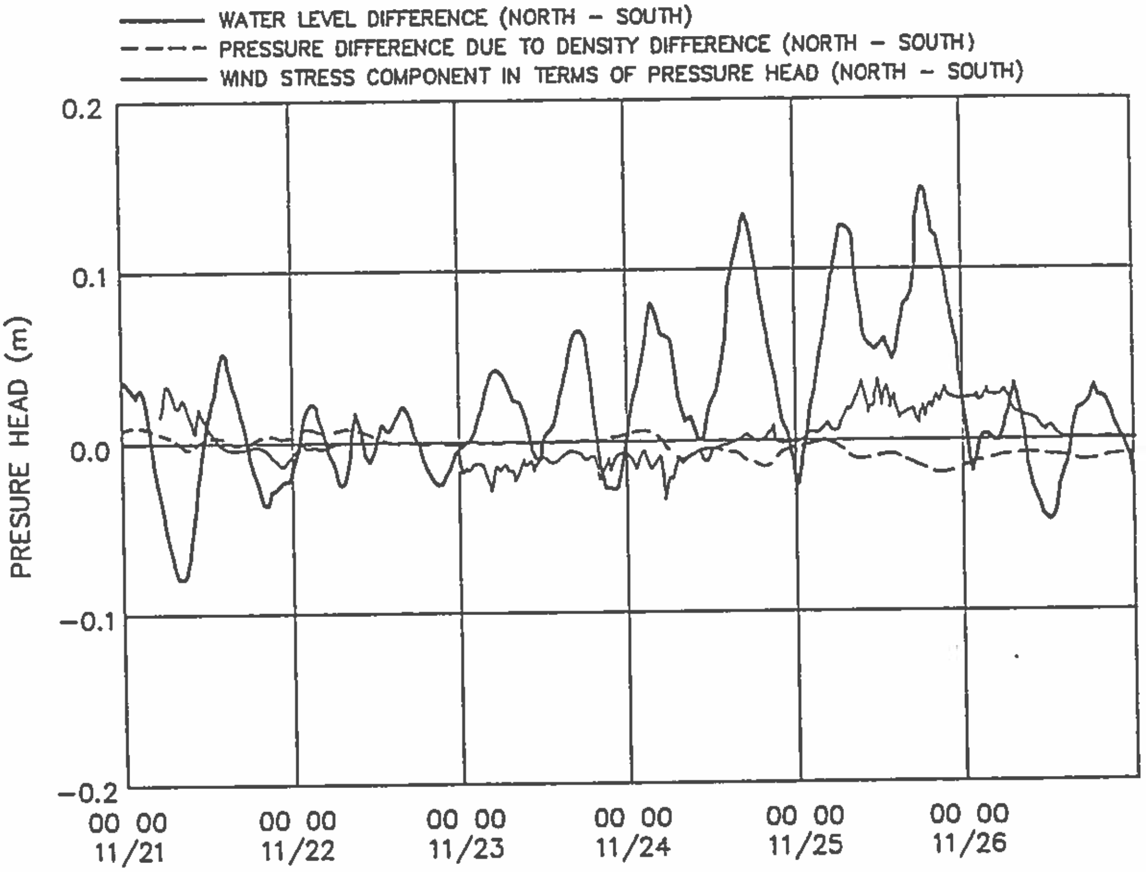


Figure 5.7. Relative magnitude of terms driving the two layer flow, calculated using observations obtained during the 6 day period 21-27 November, 1987. The sea-surface slope is generally the dominant term.

Observed and calculated layer velocities are shown in Figure 5.8 for both upper and lower layers. Except for a brief extreme overestimate on November 24, the upper layer is modelled fairly well. In the lower layer there is a tendency to underestimate the flow speed. The modelled depth to the interface at Station B is compared with depths obtained with the CTD in Figure 5.9; agreement is good. However it should be noted that attempts to derive the interface depth by interpolation of conductivity and temperature at the four discrete depths of the moored current meters are of limited accuracy.

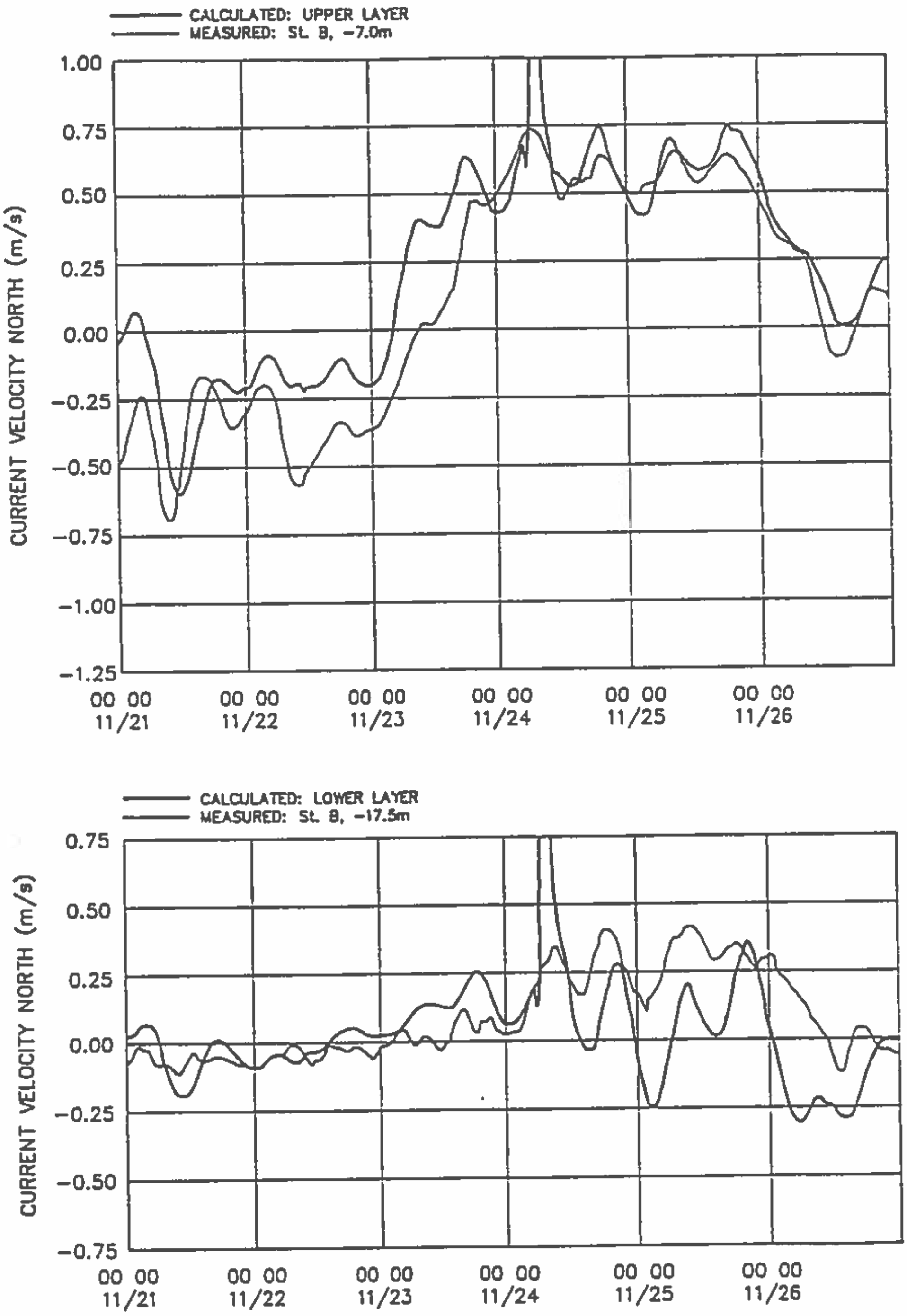


Figure 5.8. Calculated (solid line) and observed (broken lines) currents at Station B for the upper and lower layer respectively during the period 21-26 November, 1987. Apart from a brief extreme discrepancy on 24 November, the calculated flow speeds are in reasonable accord with the observations, although somewhat biasing the current towards the south in the lower layer.

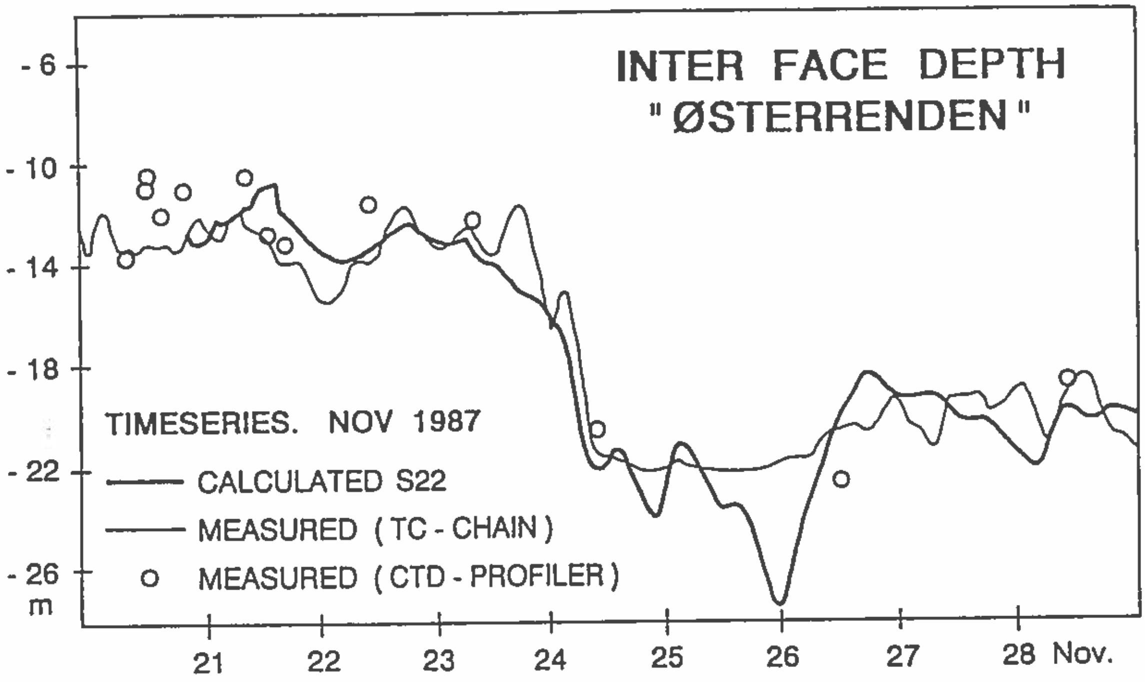


Figure 5.9. Measured and calculated interface depth for Station B. Nov. 1987.

Measurements of the interface depth and current were also obtained from the M/S PIP as transects and sections across and along portions of the strait. The quality of the echo-sounding estimates of interface depth depends upon the strength and consistency of the target and the procedure for processing the signal. Normally a fairly clear indication is obtained but occasionally the results are somewhat scattered. Figure 5.10 shows a transect on 6 November when there was supercritical flow towards the south. The interface estimates are somewhat scattered in this example, although not inconsistent with the CTD interface depths, shown as '*' in the figure. Further developments of the acoustic technique have increased the resolution. Model interface depth is also shown as a dashed line connecting small open circles. It is interesting to note that the modelled and observed interface depth appear to be in good agreement for this case of hydraulic control.

Finally in Figure 5.10 an example of a spatial plot of current vectors for the upper layer is compared with corresponding vectors obtained from the Doppler profiler on M/S PIP as it traverses the channel on 6 November. The upper layer model velocities appear to be in close agreement with the observations.

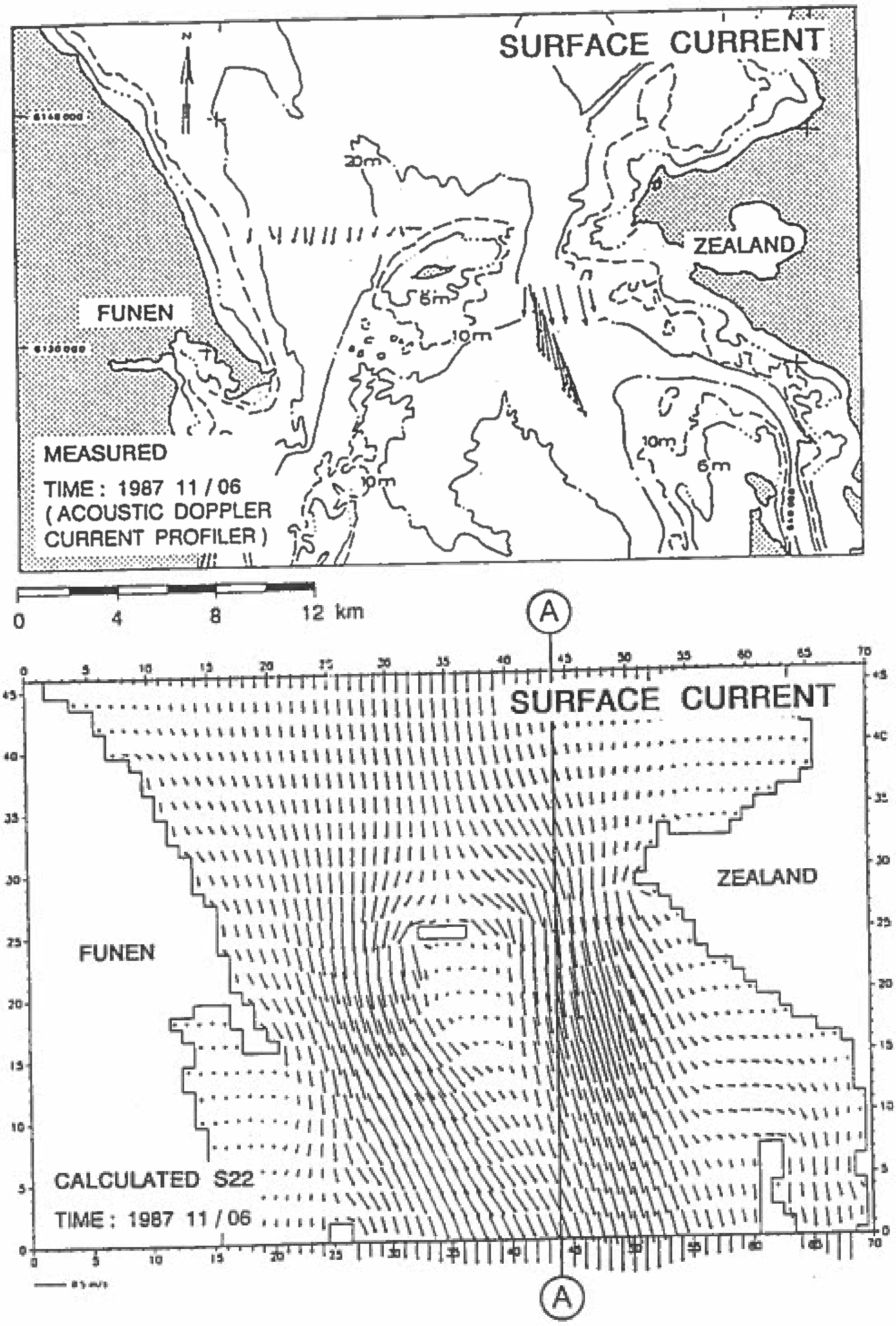


Figure 5.10. (to be continued).

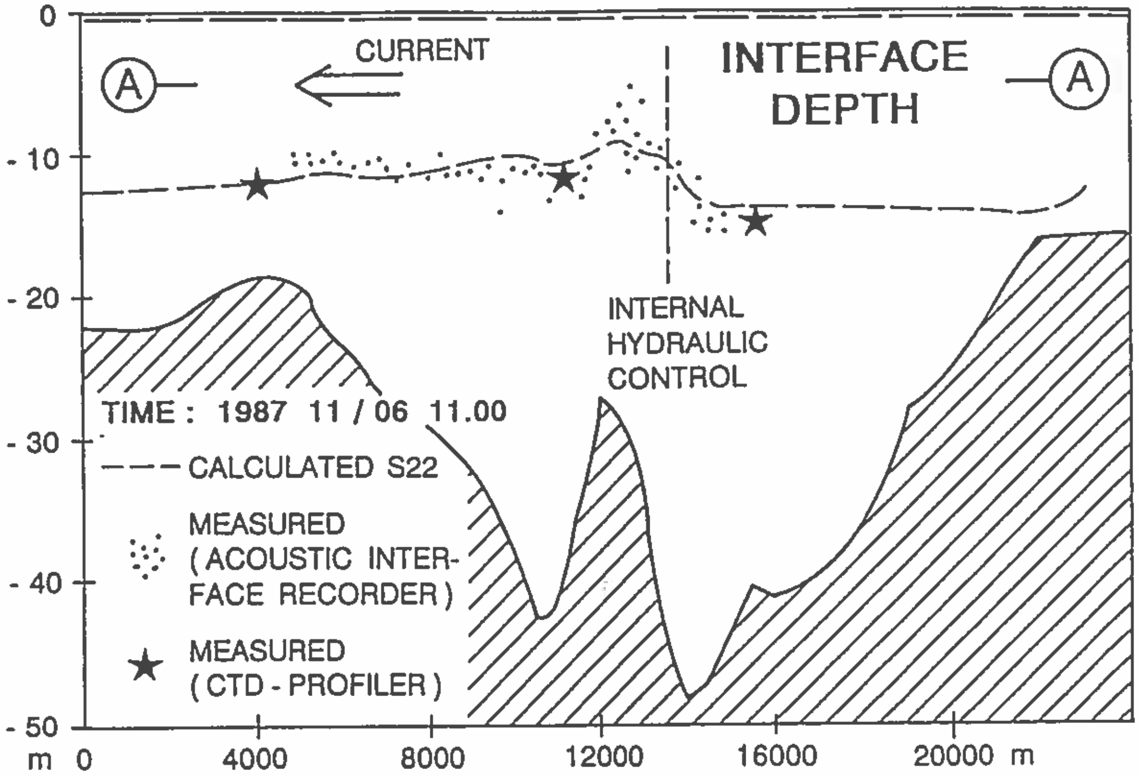


Figure 5.10. Examples of measured and modelled flow parameters. A full documentation of model-field data comparisons is given in DHI/LIC 1988. Further reports will describe results of the full model verification program 1989-91.

6. Concluding Remarks

The initial comparisons of model predictions and observations are in reasonable accord, and are probably as good as can be expected given the limited boundary data available. Together with the laboratory model and analytical verifications, this gives us reasonable confidence that the S22 model is a suitable tool for calculating the required compensation dredging. We emphasise that the zero solution calculation is insensitive to the choice of boundary conditions, but the accuracy of the model used to calculate the zero solution can only be verified by field observation, and such verification depends upon accurate measurements of boundary conditions.

The new monitoring plan will provide a much more comprehensive data base with which to examine model performance. Indeed the quality and extent of the monitoring program provide a truly unique opportunity for testing two-dimensional stratified models. The Great Belt Link Company has declared an open policy with respect to the observations, so the resulting data set will provide a bench-mark for future studies and model comparisons of stratified flow in straits. Moreover the duration of the program (1989-1996) will make the data invaluable for studies of the exchange between the Baltic and the Kattegat.

However it should be noted that the comparison between measured and computed data given above is of a qualitive nature. This is a serious drawback especially when it comes to use of the present complete monitoring program. Two questions arise, the first being scientific, the second of a technical nature; namely, how do we quantitatively compare the two types of data and express the error bounds of modelled and measured data, and how do we evaluate the uncertainty of the method with regard to reaching the zero solution ? The first question involves data assimilation procedures not yet developed. The second involves knowledge of the sensitivity of the Baltic to changes in the Great Belt. A preliminary approach is given in Jürgensen (1988) and Ottesen Hansen and Møller (1989).

Over the coming years, the full potential of the monitoring program will be used to test the two-layer model S22. The limitations of the present model must be better understood and, if possible, overcome. Also a barotropic forecast model covering the entire North Sea and Baltic (DHI S21) will be run interactively with the monitoring to allow a forecast capability which will be of great practical value to the construction program. It is expected that the program will lead to a number of scientific studies. Of particular interest is the behaviour of the flow when it is hydraulically controlled.

Acknowledgement

The environmental studies presented here were sponsored by Storebæltforbindelsen under the administration of Mr. Christian Tolstrup.

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January 1990

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CED/JSM

AS Storebæltsforbindelsen

Environmental Investigations
Status Report no.2

- Biological Mapping
- Impact Assessment

Main Report

June 1988

PRELIMINARY

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This report has been prepared by COWIconsult at the request of A/S Storebæltsforbindelsen.

Marine Identification Agency has been subcontractor on bottom fauna and macrophyte identification. The investigations of herring spawning areas were performed by the Danish Institute of Fisheries and Marine Research. A/S Dykkerteknik and Køge Bådmandscompagni have performed the diving operations.

COWIconsult's project team comprises M.Sc. Anders Randløv (Project Leader), M.Sc. Erling Poulsen and M.Sc. Margot Nielsen. Deputy Executive Director, Ph.D. Henning Therkelsen has been overall responsible.

Job no. 16825

Lyngby, 5 June 1988

Preface

This status report no. 2 is an update of status report no. 1 (in Danish) from December 1987.

The report is based on available data from previous investigations and of the following activities:

- Field survey in October/November 1987 comprising
  - Video survey of bottom conditions in the nearby environment of the link alignment.
  - Collection of sediment samples.
  - Collection of bottom fauna samples.
  - Sampling of Macrophyte vegetation on stone reefs at Sprogø and Halsskov.

- Field survey in April 1988
  - Video survey of complementary areas south of Sprogø with stone reefs and gravel.
  - Detailed video survey of the distribution of mussels.
  - Investigation of occurence af herring spawning around Sprogø.

- Laboratory analyses of sediment and bottom fauna and vegetation samples collected in October-November 1987.

Furthermore, the impact assessment has been elaboratored based on new detailed information on the project designs.

List of contents

List of Appendices

(found in a separate volume)

1. Summary

1.1 Purpose

The investigations have two main purposes:

- to make a biological mapping of areas of the Great Belt that will be directly or indirectly affected by civil works related to the proposed Great Belt link.
- to make a preliminary environmental impact assessment of the implementation of the Great Belt link.

The investigation will serve as a part of the basis for a decision on planning of dredging, dumping and reclamation activities and also as basis for future investigations of possible effects in the Great Belt.

1.2 The Work

The work has comprised the following items:

Survey of literature

Available material regarding the ecological conditions in the Great Belt has been compiled and studied.

Existing knowledge has been supplemented with field investigations in areas planned for dredging, dumping and reclamation.

Stone reefs

The composition of macrophyte vegetation and epifauna on the stone reefs at Sprogø and Halsskov has been mapped by video recordings. To obtain more detailed informations on the composition of macrophyte vegetation on the stone reefs the video recordings were supplemented with sampling of vegetation.

Mussel beds	A detailed mapping of the occurrence of mussel beds *(Mytilus edulis)* at Sprogø and Halsskov Reef has been performed by means of video recordings.
Sediments and bottom fauna	The composition of the sediment and the bottom fauna in soft bottom sediments in areas without stone reefs has been investigated by sampling at 80 stations in the Great Belt.
Herring spawning	The occurence of spring-spawning herring around Sprogø was investigated.

1.3 Biological Conditions

Figure 1.1 shows areas with biological conditions of high priority.

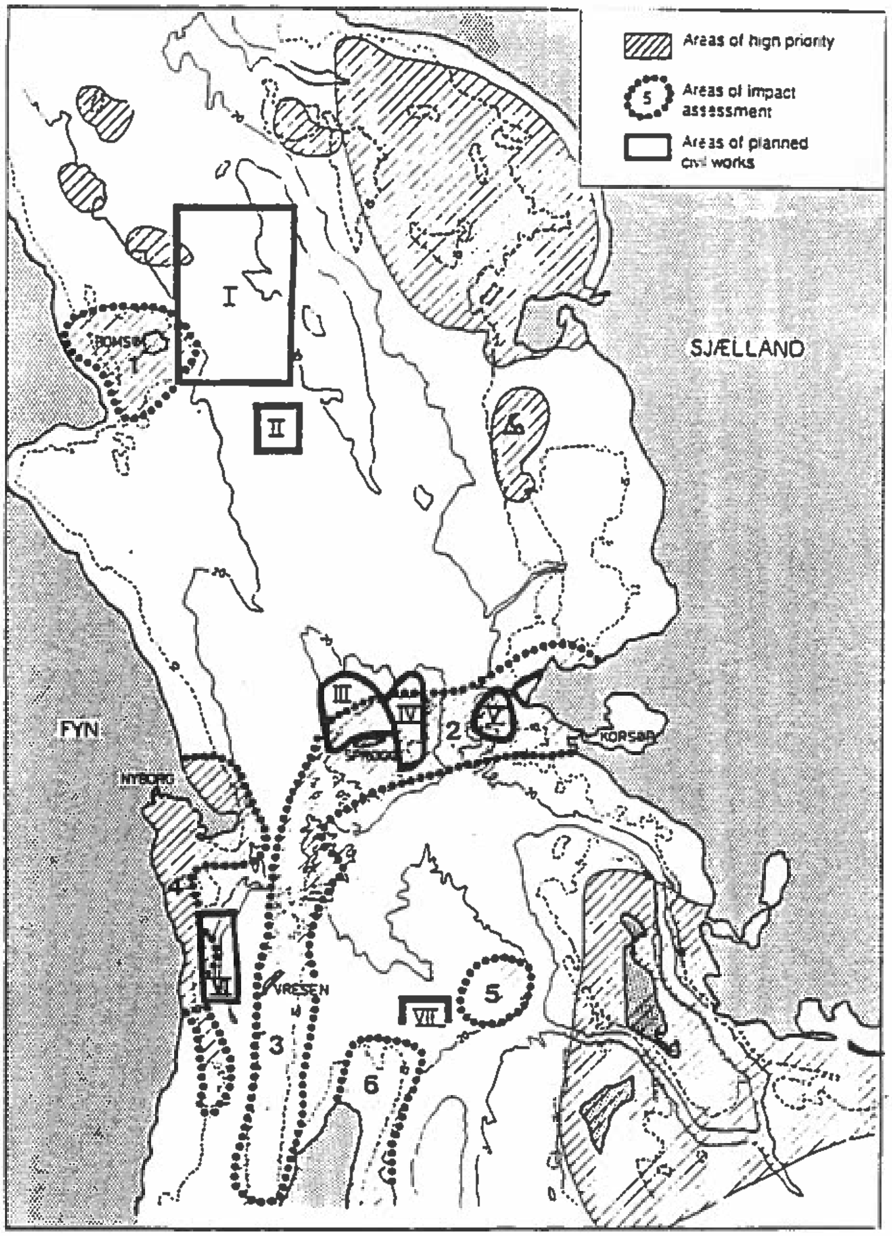


Figure 1.1 - Areas in the Great Belt with biological conditions of high priority (hatched). Areas without hatching have mainly sandy or muddy bottom. Areas planned for dredging, dumping or reclamation are also shown.

Eider and other diving ducks

In the Great Belt diving ducks accumulate during the summer moulting period as well as during the winter. The importance of the Great Belt as a refuge area for diving ducks is due to good foraging possibilities on the reefs, especially on the mussel beds.

Several of the areas are of international importance as haunt and wintering places for diving ducks, especially eiders. This applies to the following areas:

- the area around Romsø
- the area around Sprogø and Halsskov Reef
- the area around Vresen
- the area around Agersø and Omø.

The above areas are protected under the EEC Bird Directive. Further, the area around Agersø and Omø are also included in the Ramsar Convention on protection of wet lands.

Spawning ground for herrings

Spawning grounds for herring are found at several places in the Great Belt where the bottom consists of coarse sand, gravel or stones. This applies to the following areas:

- Vresen
- along the coast north and south of Nyborg
- along the coast east and west of Langeland
- northeast of Langeland and
- around Sprogø

Reef

Stone reefs are found in several places in the Great Belt. Stone reefs have a rich flora and fauna, and it is spawning, nursery and refuge area for a number of fish species of economic value, for instance cod, lumpsucker and garfish. Stone reefs are particularly found in

- Jammerland Bugt
- around Romsø
- around Reersø and Musholm
- from Langeland via Vresen to the waters around Sprogø
- Halsskov Reef, and
- around Agersø and Omø.

The remaining parts of the Great Belt

In the remaining parts of the Great Belt the bottom mainly consists of sand or sand mixed with mud, (soft bottom) with low protection value.

Vegetation and fauna on stone reefs

The vegetation and the fauna have been classified in seven types of biotopes, each named after the most conspicuous and characteristic species:

- Pebble gravel (no visible vegetation and fauna)
- Mussel beds (at depths down to 10 m)
- Eel grass/*Polysiphonia* biotope (at depths of less than 5 m)
- *Delesseria*/*Halichondria* biotope (at depths from 5 to 10 m)
- *Laminaria*/*Delesseria* biotope (at depths of 10 to 15 m or 5 to 10 m)
- *Delesseria*/*Leucosolenia*/*Metridium* biotope (at depths from 15 to 20 m), and
- *Leucosolenia*/*Metridium* biotope (at depths of more than 20 m).

The depth limit for vegetation in the area seems to be approximately 20 m.

Fauna on soft bottom

In the field investigations five communities on soft bottom were identified:

- *Macoma baltica* community on sand bottom
- *Abra alba* community on sand bottom
- *Ciona* community on muddy sand bottom
- *Abra alba* community on sandy mud or mud bottom
- *Haploops* community on mud or sandy mud bottom.

1.4 Consequences

Figure 1.1 shows the biological condition of high priority and the planned areas of work on the bottom of the sea.

Presently, about forty alternative project designs are being studied.

In chapter 6 the environmental impact of a selection of these are discussed to demonstrate the spectrum of impact from minimum to maximum. The following points must be emphasized:

Nearby environment of the alignment

The dredging, dumping and reclamation activities in the nearby environment of the alignment will have the following **direct impact** on biological conditions of high priority.

- 0.6-3.4 km² of mussel beds which serves as feeding ground for diving ducks will be ruined; the area corresponds to 4-23 % of the mussel beds around Sprogø and at Halsskov reef which have status of EEC bird protection area. Some of these mussel beds may, however, be reestablished.

- 0.9-2.6 km² of herring spawning grounds will be ruined corresponding to 1-2 % of the herring spawning grounds in the Great Belt.

Indirect effects related from the sedimentation of sediments from the dredging, dumping and reclamation activities are difficult to estimate. It is anticipated that the estimated sedimentation around Sprogø of an estimated 2 mm of silt and clay might affect the herring spawning grounds.

Investigations of effects related to the release of nutrients and oxygen consuming substances have not been completed yet.

Other areas of the Great Belt

The impact of dredging and dumping activities outside the nearby environment cannot be fully assesed yet as these activities have not been planned in detail.

However, of the potential locations for these activities it is estimated that only activities in the area between Vresen and Fyn (area No VI, fig. 1.1) and the area north of Langland (area VII, fig. 1.1) may have an impact on biological conditions of high priority (herring spawning grounds and stone reefs) due to spreading of sediments. A more detailed inpact assessment can be performed when the volume of material to be shifted and areas for dredging are known.

2. Introduction

2.1 Background

In connection with the construction of the Great Belt link, a number of construction works are planned to be carried out, i.e.

- the reclamation of embankments
- the reclamation of an artificial island just north of Sprogø
- compensation dredgings in Østerrenden
- dredging for construction materials; and
- dumping of surplus material.

Figure 2.1 shows the areas for these activities. Areas for dredging and dumping are not finally decided. Fig. 2.2 show the location of places mentioned in this report.

2.2 Purpose of Investigations

The investigation only includes the local effects of the dredging, dumping and reclamation activities.

The investigation has two main purposes:

- to perform a biological investigation of the local areas of the Great Belt that will be directly or indirectly affected by dredging, dumping and reclamation activities;

- to perform an environmental impact assessment of these dredging, dumping and reclamation activities with respect to the fauna and flora in the areas in question.

The investigation will serve two purposes:

- to obtain necessary ecological information in order to minimize environmental impact
- to function as a reference of possible future investigations of long-time effects of the of the Great Belt Link.

2.3 Status and Content of the Report

Status

This report is a status report on the work carried out up to now.

Contents

The report is dividied into three parts:

- The first part (Chapter 3) surveys the *a priori* knowledge of ecological effects of dredging, dumping and reclamation activities in general. This knowledge has served as a basis for designing the field survey.
- The second part (Chapters 4 and 5) give a description of the biological conditions in the Great Belt based on the field surveys and the literature.
- The third part (Chapter 6) is an environmental impact assessment.

A separate volume contains the following Appendices:

Appendix I :	Analyses of Surface Sediment Samples from the Great Belt.
Appendix II :	Mapping of Stone Reefs by Video Recordings.
Appendix III:	Investivation of Macrophyte Vegetation North of Sprogø and at Halsskov Reef.

Appendix IV :	Mapping of Mussel Beds Around Sprogø and at Halsskov.
Appendix V :	Investigation of Bottom Fauna in Soft Bottom Sediments.
Appendix VI :	Spawning of Spring-spawning Herring Around Sprogø.
Appendix VII:	List of Received Material.

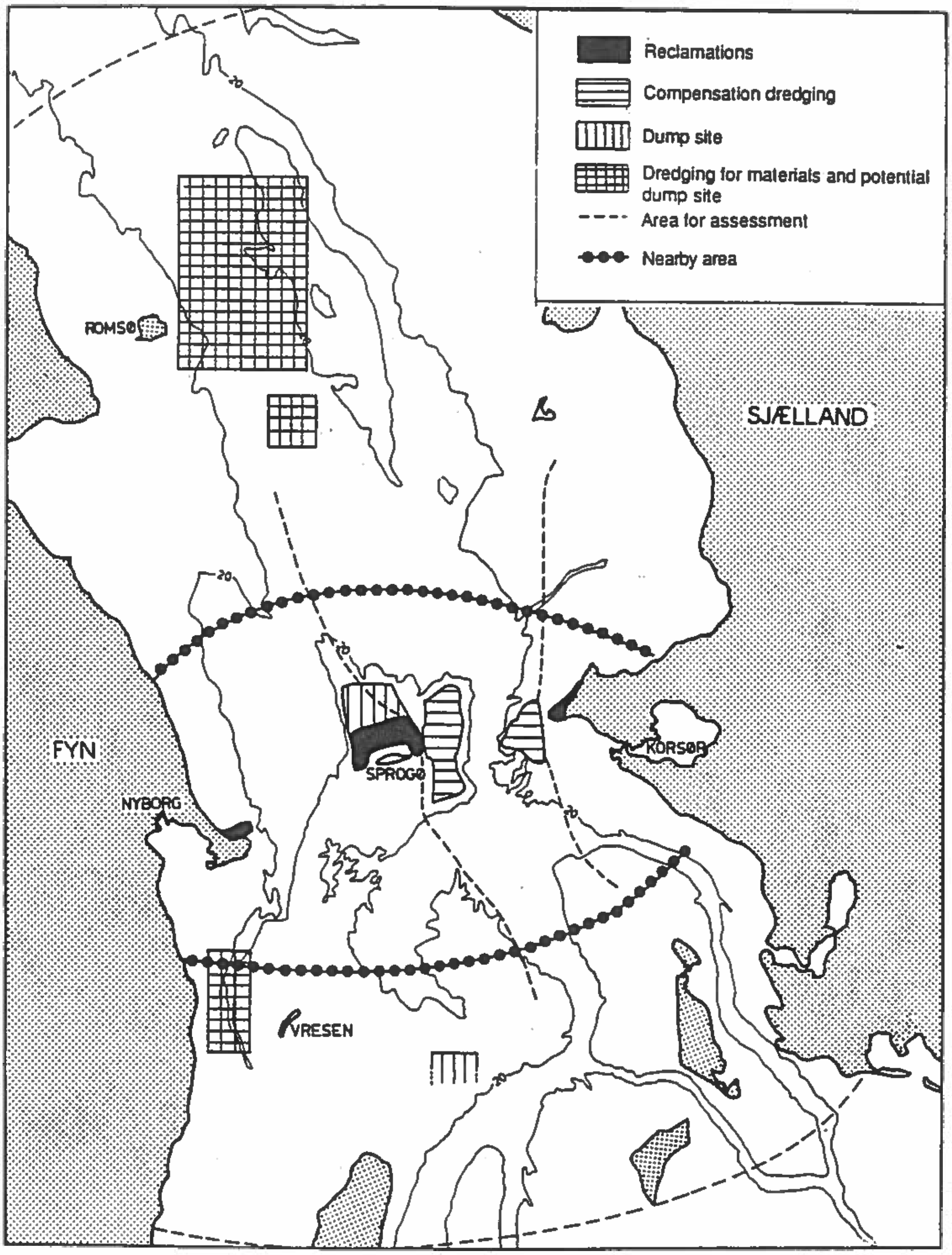


Figure 2 - Survey of areas, of dredging, dumping or reclamation.

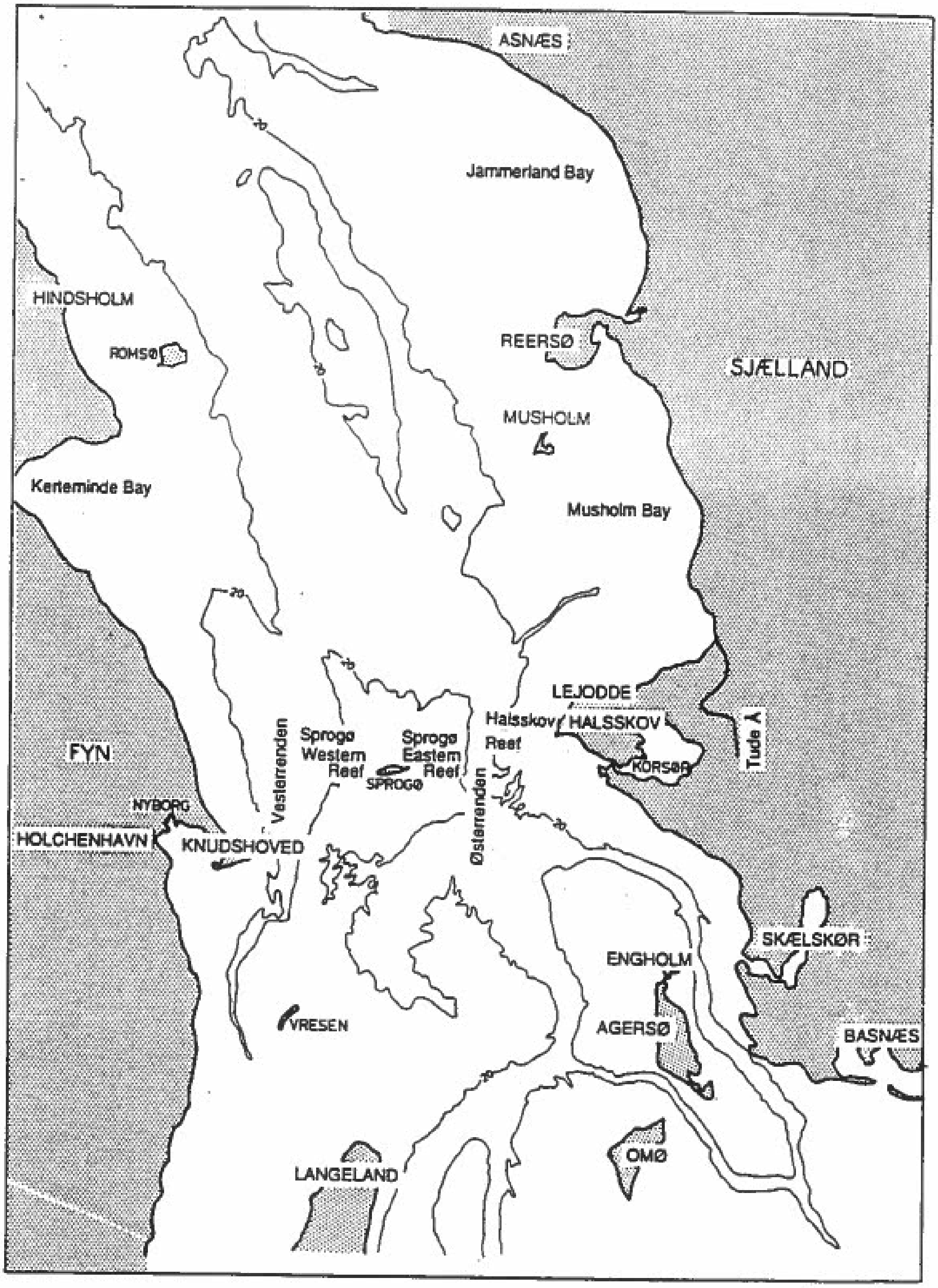


Figure 3 - The Great Belt. Location of places mentioned in this report.

3. Possible Environmental Impact of Dredging, Dumping and Reclamation Activities

A certain impact on the biological conditions in the nearby environment as a consequence of dredging, dumping and reclamation activities cannot be totally avoided. The issue is, however, to which extent the essential values concerning nature and economic important resources deteriorate, and in that case whether the work can be organized in a way to minimize ecological damage.

The possible ecological effects of dredging, dumping and reclamation activities are stated in general terms in the following, either as a direct effect of removal, dredging, dumping or reclamation or as a consequence of spreading of sediments in connection with the activities (Ref. 1,4,5,18,19):

- Damage to spawning grounds for bottom spawning fish.
- Damage to nursery areas for fish fry.
- Damage of refuge areas for fish living at the bottom of the sea (including damage to the food basis of the fish).
- Damage to other habitats of high priority for being protected, for instance reef which has a unique and rich fauna and flora because of the special ecological conditions.
- Damage to feeding areas of waterfowls.
- Reclamation and dredging may create adverse oxygen conditions as a result of the deeper anaerobe strata of the sediment being laid bare. Reduced compounds, e.g. H_2S or metal sulphides may be released. In the water column the metal sulphides and the hydrogen sulphides will be oxidized using oxygen. Furthermore, nutrients may be released.

- Dredging may result in holes with stagnant anoxic water; especially in sediment areas with a stratification of the water volumes.

The descriptions and evaluations of the report are founded on biological conditions which according to this lists of effects may be affected by dredging, dumping and reclamation activities in the Great Belt.

4. Methods

4.1 Previous Investigations

In connection with collection of information on previous investigations the following authorities have been contacted:

- Skov- og Naturstyrelsen
- Miljøstyrelsens Havforureningslaboatorium
- Danmarks Fiskeri- og Havundersøgelser
- Fyns amt; and
- Vestsjællands amt

The received material from these authorities was supplemented with material from A/S Storebæltsforbindelsen and information from the literature (published Danish report and scientific literature).

A list of the received material is given in Appendix VII.

On reviewing the existing knowledge of the ecology in the Great Belt the following has been particularly considered:

- the composition of surface sediments
- flora and fauna on stone reefs
- flora and fauna at other types of bottoms
- spawning grounds for bottom spawning fish
- nursery areas for fish
- the occurrence of sea birds; and
- the occurrence of oxygen depletion.

4.2 Field Investigations

The information on the ecology in the Great Belt obtained by reviewing the literature was supplemented with information obtained by field investigations. In the following these investigations will be described briefly. A detailed description of these investigations is given in Appendices I-VI.

4.2.1 Mapping of Stone Reefs by Video Recordings

The composition of the macrophyte vegetation and epifauna on the stone reefs at Sprogø and Halsskov has been mapped by means of video recordings along 23 transects (Figure 4.1). The procedure is described in Appendix II.

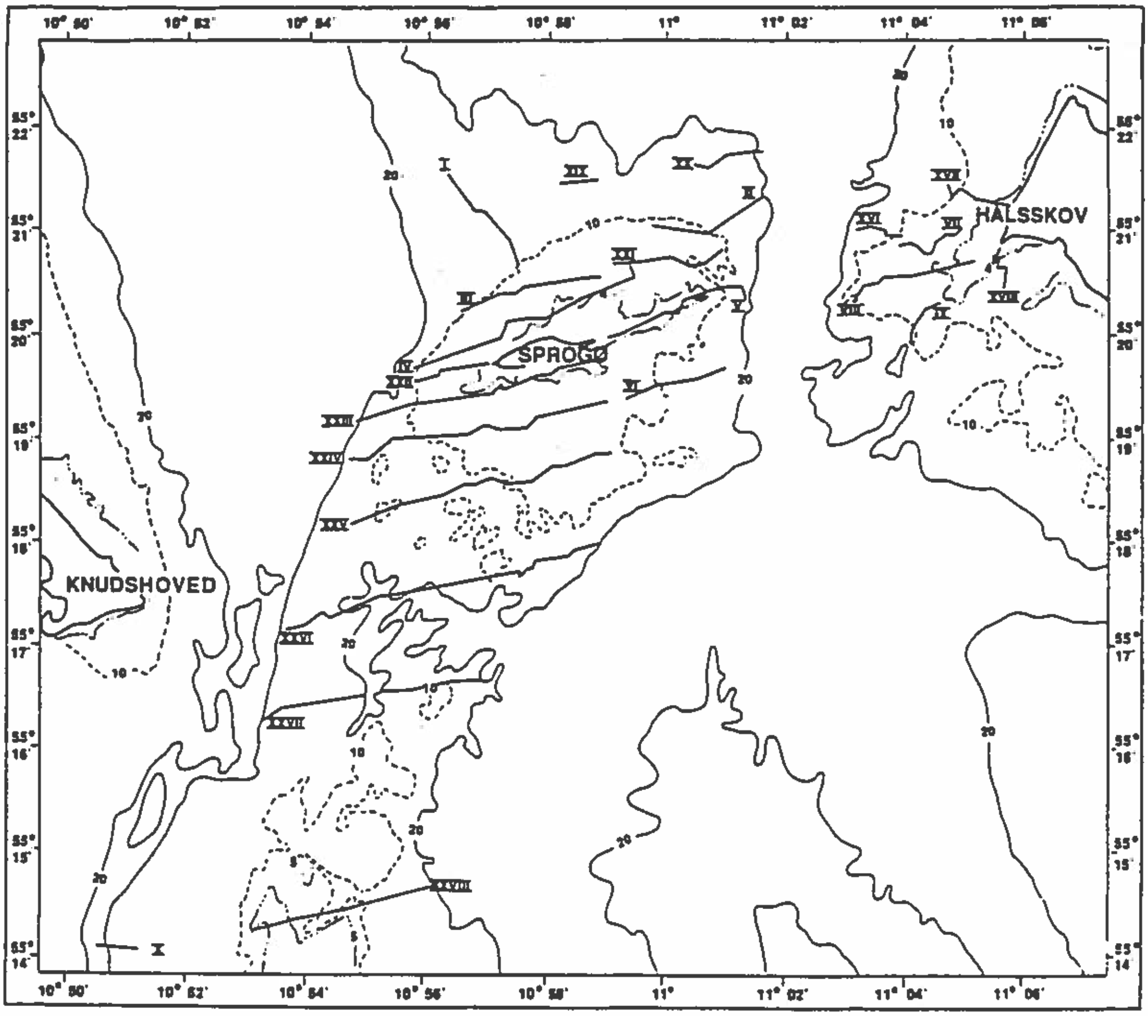


Figure 4.1 - Video recordings. Location of transects (Note: transects XI-XV do not exist).

4.2.2 Investigation of Vegetation

To obtain a more detailed assessment of the composition of the macrophyte vegetation on the stone reefs at Sprogø and Halsskov the video recordings were supplemented with sampling of vegetation at the locations shown in Figure 4.2. The procedure is described in Appendix III.

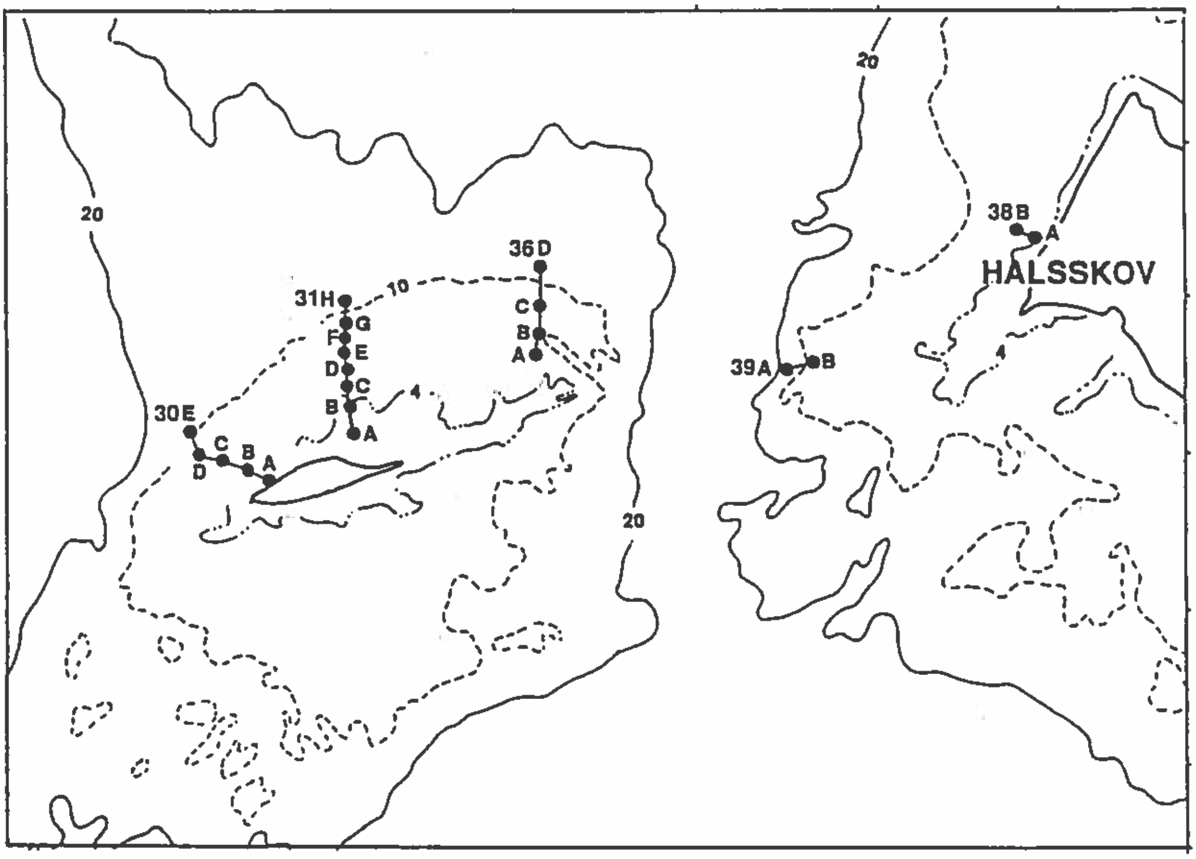


Figure 4.2 - Sampling locations, macrophyte vegetation.

4.2.3 Mapping of Mussel Beds

A detailed mapping of the occurrence of mussel beds at Sprogø and Halsskov Reef has been performed by means of video recordings along a number of transects in the area (Figure 4.3). The procedure is described in detail in Appendix IV.

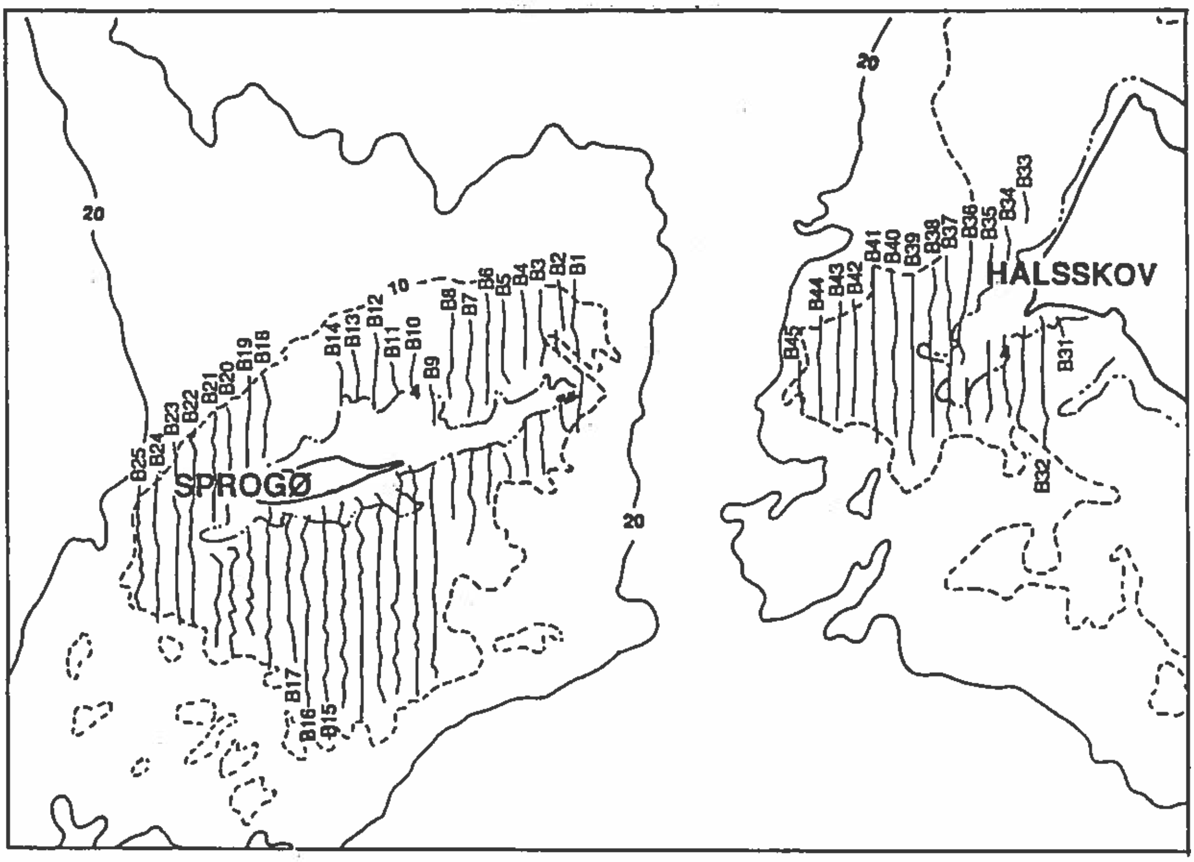


Figure 4.3 - Mapping of mussel beds by means of video recordings. Location of transects. (Note: transects 26-30 do not exist).

4.2.4 Investigations of Sediment and Bottom Fauna

The composition of the sediment and the bottom fauna in soft bottom sediments in areas without stone reefs has been investigated by sampling at 80 stations (Figure 4.4).

The procedure is described in Appendix I (sediment) and Appendix V (bottom fauna).

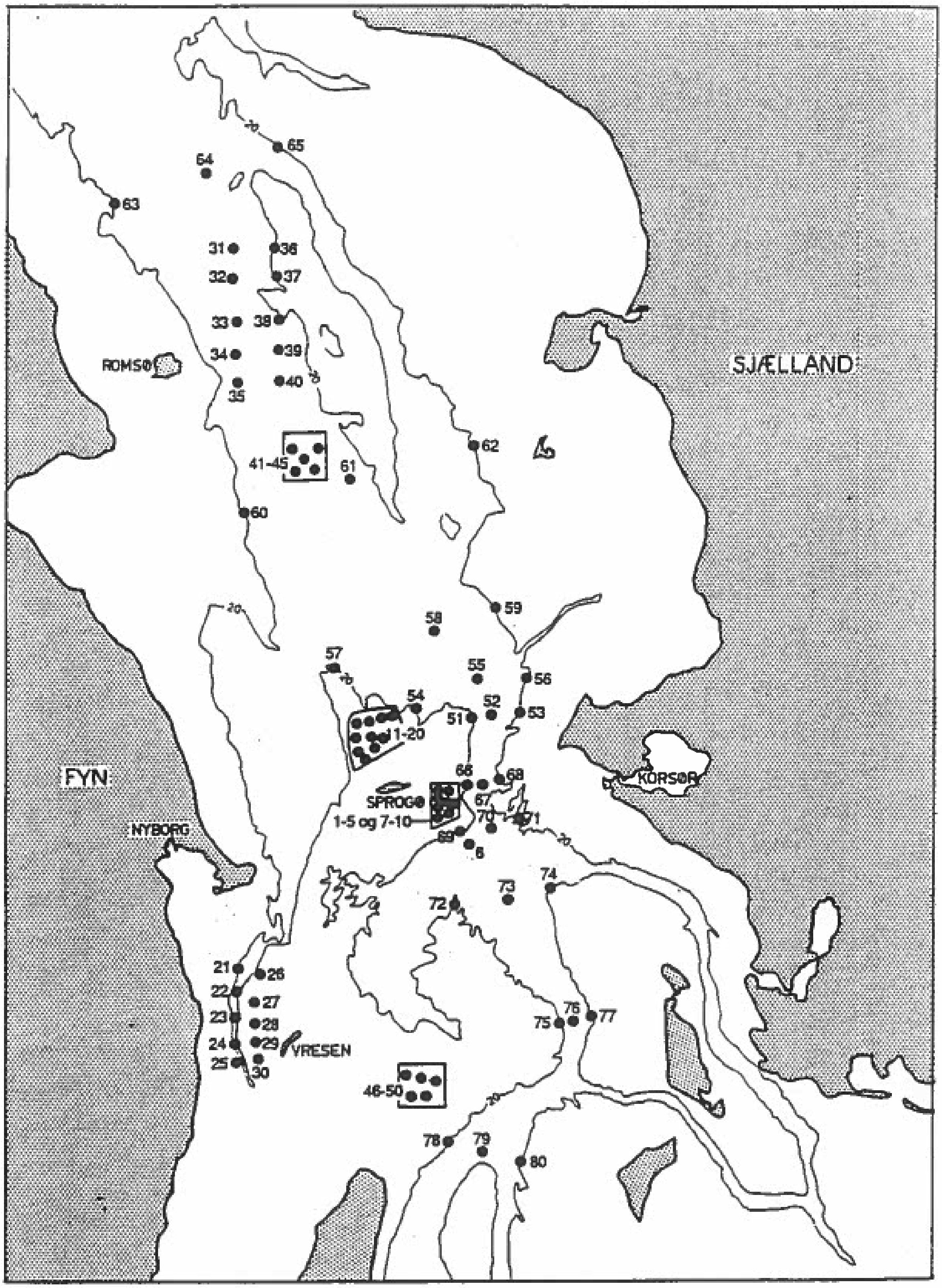


Figure 4.4 - Stations where samples of bottom fauna and sediment were taken.

4.2.5 Investigation of the Occurrence of Herring Spawning Grounds around Sprogø

An investigation of the occurrence of spring-spawning herring around Sprogø was performed. Herring were caught in herring nets on the locations shown in Figure 4.5, and the occurrence of spawning individuals and eggs on the nets investigated. The procedure is described in detail in Appendix VI.

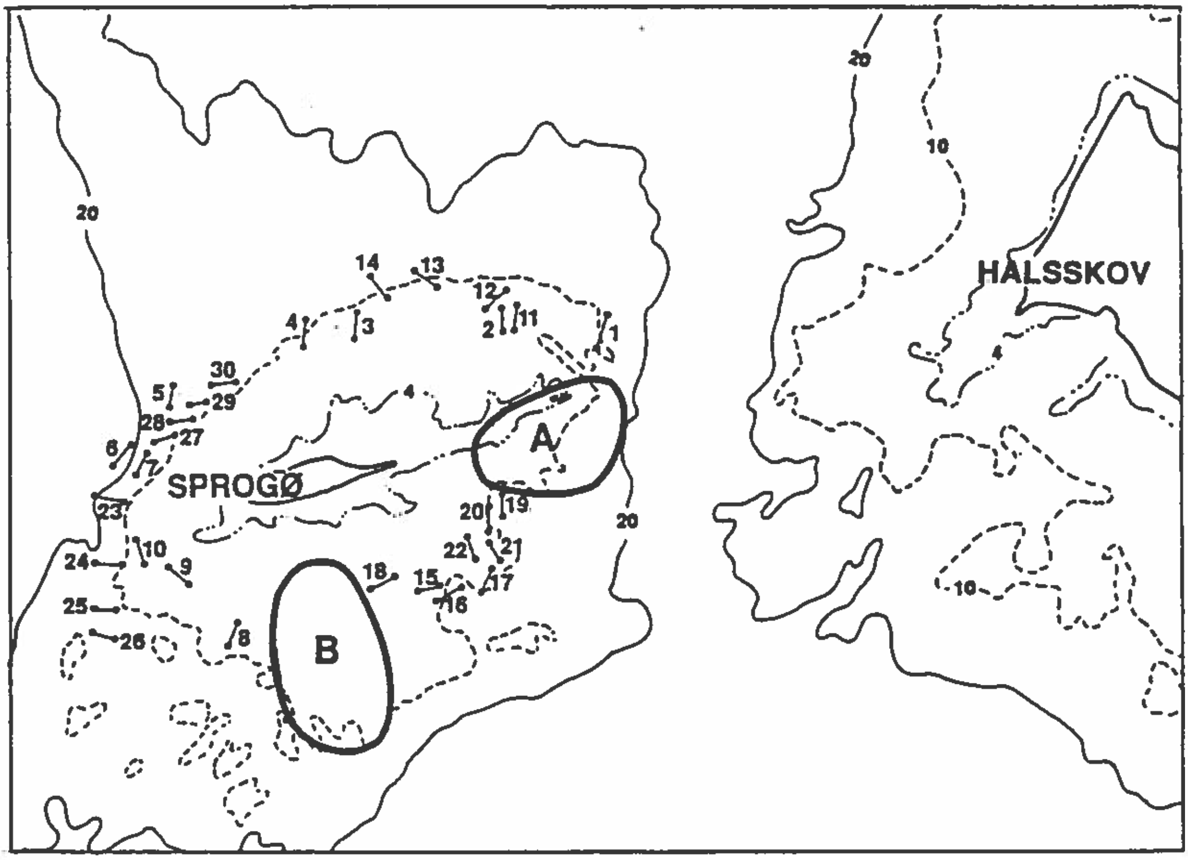


Figure 4.5 - Positions where herring were caught to assess the occurrence of spawning. Herring nets could not be applied in area A and area B.

5. Results

5.1 Surface Sediments in the Great Belt

Figure 5.1 shows the composition of the surface sediments in the Great Belt. The map has been made on the basis of own investigations and refs. 16 and 17. Results of own investigations of 80 surface sediment samples taken in November 1987 are given in Appendix I.

Own investigations showed considerable agreement with the information from ref. 16 and ref. 17. Exceptions were areas with mud bottom which earlier were characterized as sandy mud. Furthermore, our measurements in areas which earlier were characterized as sand bottom showed that the bottom here rather consisted of muddy sand and in some cases sandy mud.

As will be seen from the map, patchy distributions of sand, gravel and stone (reefs included) are present in the following areas:

- off Hindsholm
- around Romsø
- on low water north of Knudshoved
- at the area from Reersø to Musholm
- from Langeland via Vresen to the waters around Sprogø
- Halsskov Reef
- to the north of Langeland; and
- the waters around Omø/Agersø.

Muddy sand and sandy mud are found in major areas immediately north of and south of Sprogø and in the Jammerland Bay.

Mud bottom is found in some areas to the north and to the south of Sprogø.

Apparently, the remaining areas of the Great Belt are characterized by clean sand bottom.

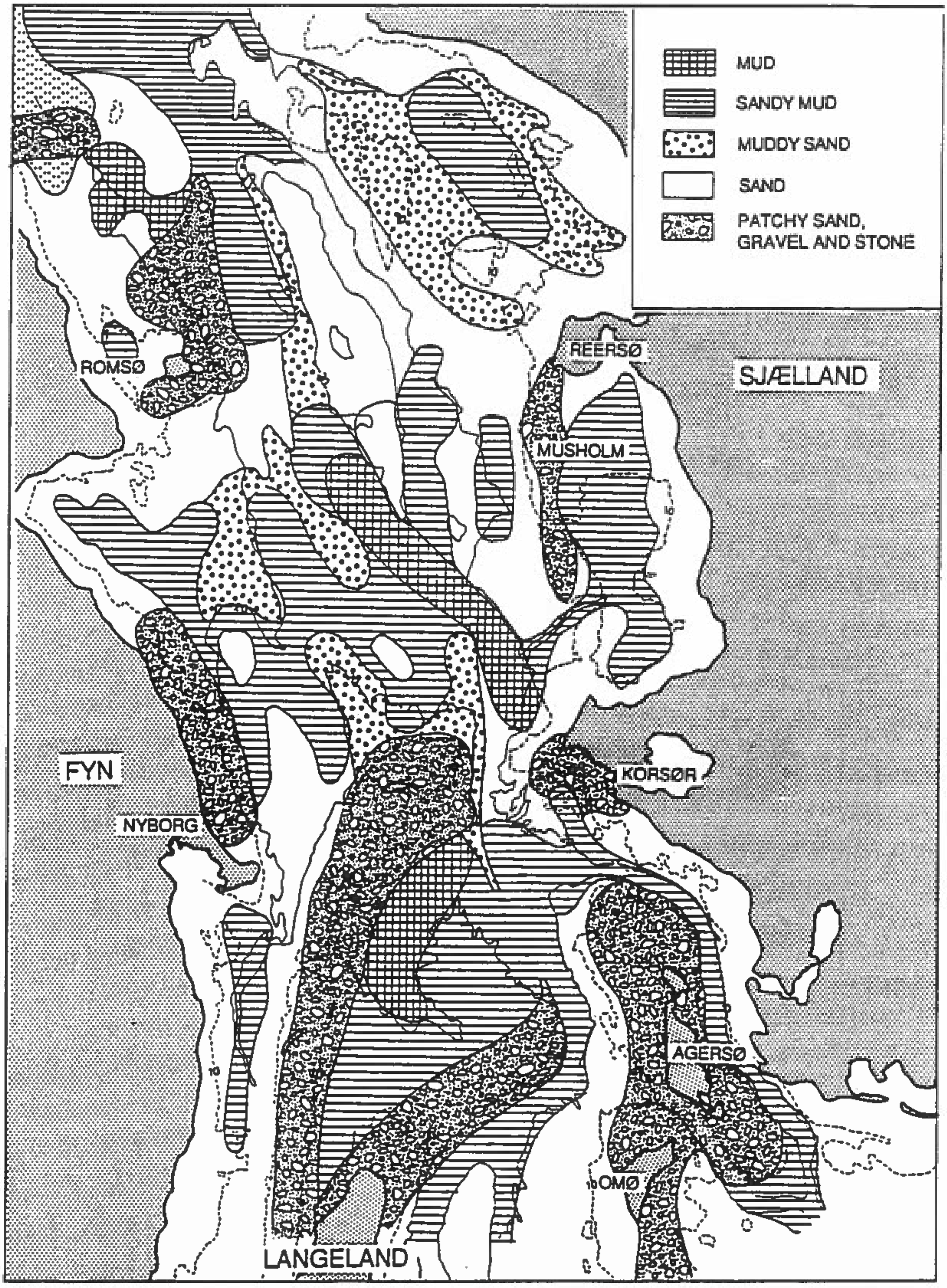


Figure 5.1 - Surface sediments in the Great Belt (refs. 16,17 and own investigations).

5.2 Fauna and Vegetation in the Great Belt

Different areas on the sea bottom support characteristic associations of bottom fauna and vegetation. The composition of vegetation and bottom fauna at one location is determined by a complicated interaction of environmental factors and biological interactions. Two factors exert a dominant influence on the distribution of organisms, i.e.:

- composition of sediments, and
- depth.

In areas without stones most of the fauna lives within the sediment (infauna), the composition of species being determined by the sediment type to a great extent.

In areas with stones, rich and diverse fauna and vegetation associations are found. The stones provide substrate for a wide variety of algal species and sessile animals (epifauna). In addition, infauna is found in the sediment between the stones.

5.2.1 Fauna and Vegetation on the Stone Reefs around Sprogø and at Halsskov

Figure 5.2 shows the composition of macrophyte vegetation and epifauna on the stone reefs at Sprogø and Halsskov. The map is based on the video surveys and the investigation of macrophyte vegetation in the area. A detailed description of the results of these investigations is given in Appendices II and III, respectively.

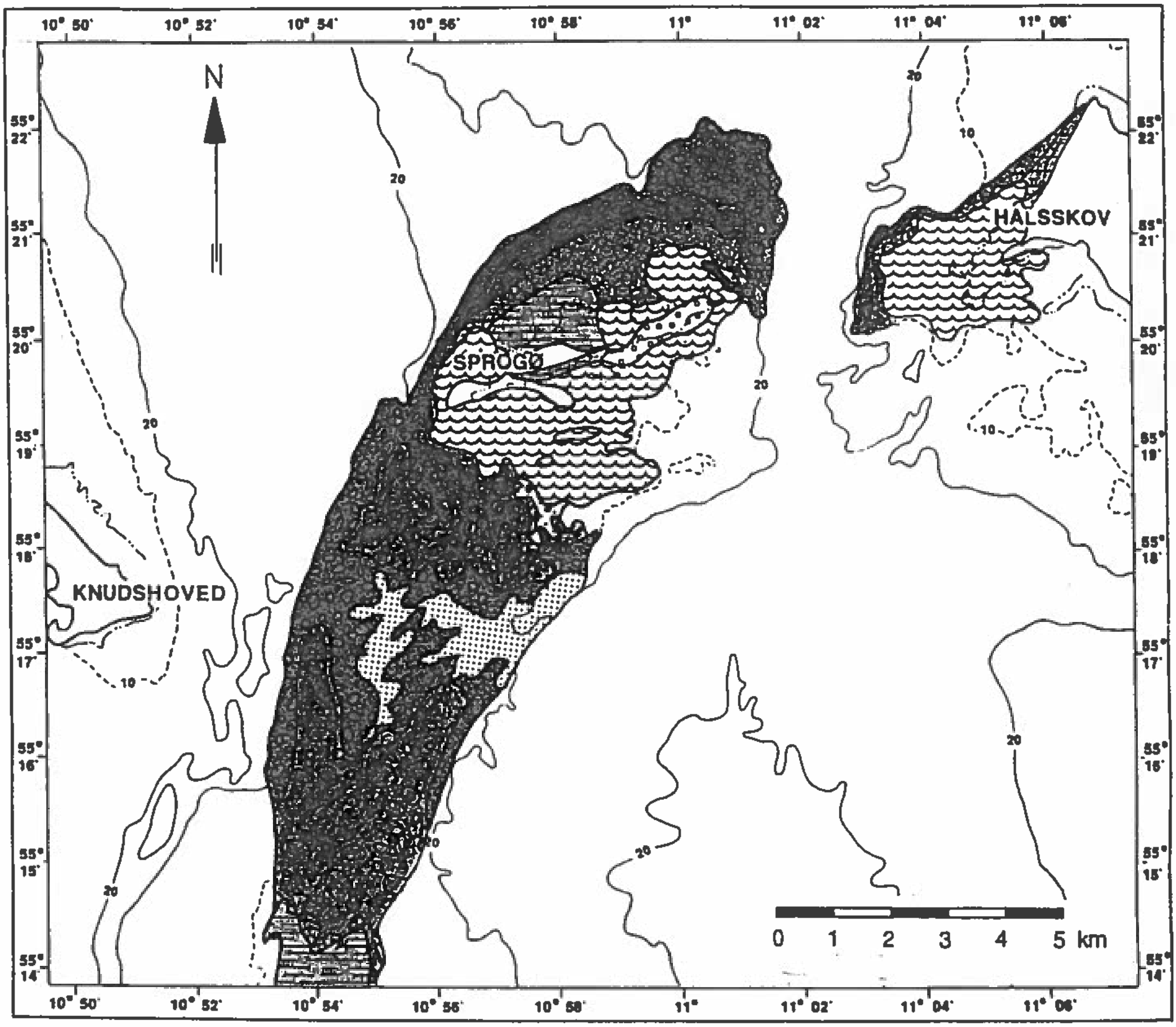


Figure 5.2 Macrophyte vegetation and epifauna on the stone reefs at Sprogø and Halsskov

- ⁘ Pebble gravel
- ≈ Mussel beds
- ▤ Eelgrass/Polysiphonia biotope
- ▩ Delesseria/Halichondria-biotope
- ■ Laminaria/Delesseria-biotope
- ▦ Delesseria/Leucosolenia/Metridium-biotope
- ░ Leucosolenia/Metridium-biotope

The composition of vegetation and fauna changes with depth to a great extent, and the depth limit for vegetation in the area seems to be approximately 20 m. The vegetation and the fauna have been classified in seven types of biotopes, each named after the most conspicuous and characteristic species:

- Pebble gravel (no visible vegetation and fauna)
- Mussel beds (at depths down to 10 m)
- Eel grass/*Polysiphonia* biotope (at depths of less than 5 m)
- *Delesseria/Halichondria* biotope (at depths from 5 to 10 m)
- Laminaria/Delesseria biotope (at depths of 10 to 15 m or 5 to 10 m)
- *Delesseria/Leucosolenia/Metridium* biotope (at depths from 15 to 20 m), and
- *Leucosolenia/Metridium* biotope (at depths of more than 20 m.

In the following each of these biotopes will be described.

Pebble gravel

In shallow water on the inner part of Sprogø Eastern Reef the surface sediment consists of pebble gravel with no visible vegetation and fauna (PL IV). Pebble gravel on Sprogø Eastern Reef covers an area of approximately 0.8 km².

Mussel beds

Mussel beds (*Mytilus edulis*) are found around Sprogø and at Halsskov Reef at depths down to approximately 10 m (PL I). Figure 5.3 shows the density of mussels and the extension of mussel beds in the area. The map is based on the video recordings along transects in the area (cf. Figure 4.3). The density of mussels (i.e. the percentage of the bottom covered by mussels) is grouped in five categories:

- 0%; no mussels present
- <20%; scattered occurrence of mussels. Usually on stones. Less than 20% of the bottom covered by mussels.
- 20-50%.; mussel beds proper. 20%-50% of the bottom covered by mussels.
- 50-90%; mussel beds proper. 50-90% of the bottom covered by mussels.
- 90-100%; mussel beds proper. 90-100% of the bottom covered by mussels.

As will appear from figure 5.3 dense mussel beds (density >20%) are found west, south and east of Sprogø and at Halsskov Reef, covering an area of approximately 15 km².

Apparently, the density is correlated with depth, 5-7 m being the optimum depth and 10 m the depth limit for mussels in the area.

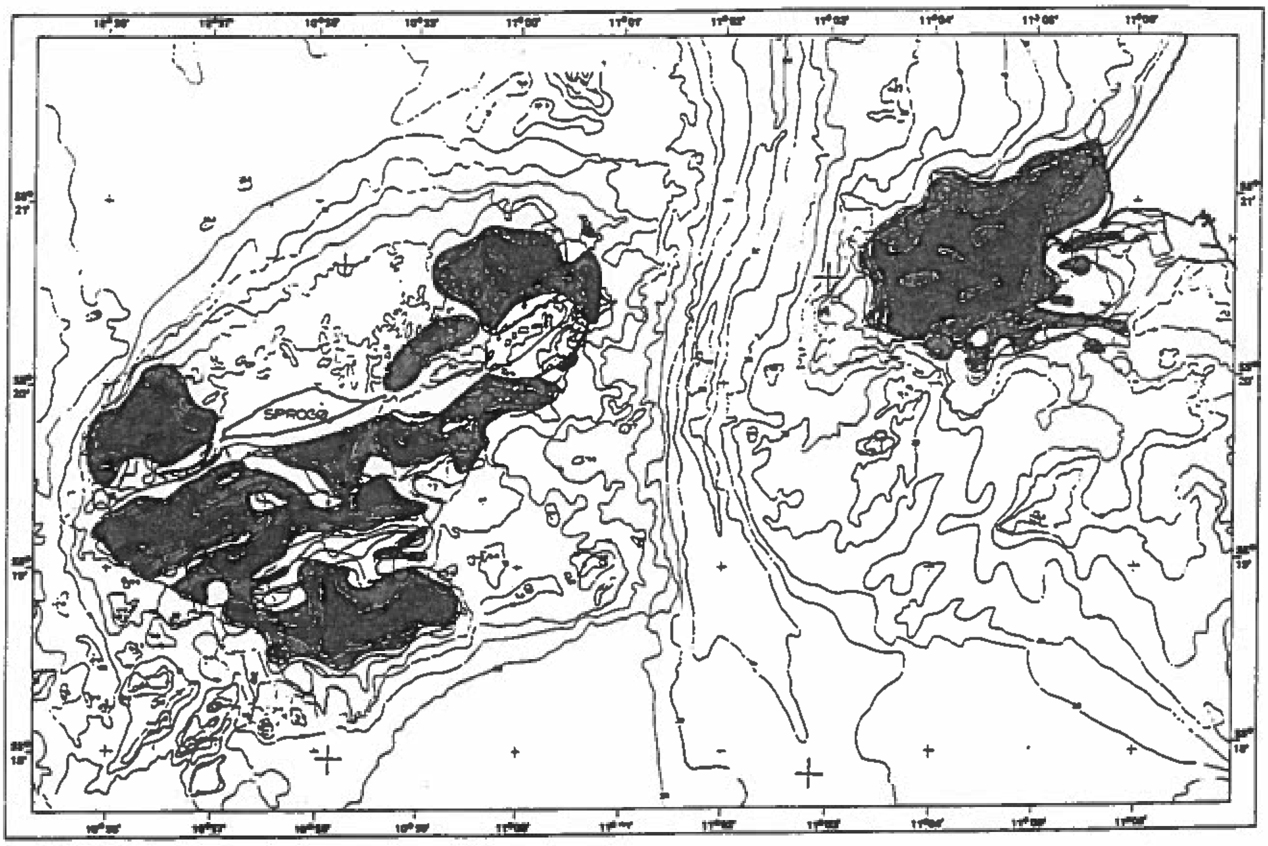


Figure 5.3 Mussel beds. Density of mussels around Sprogø and at Halsskov reef

Density

☐ 0%

☐ < 20%

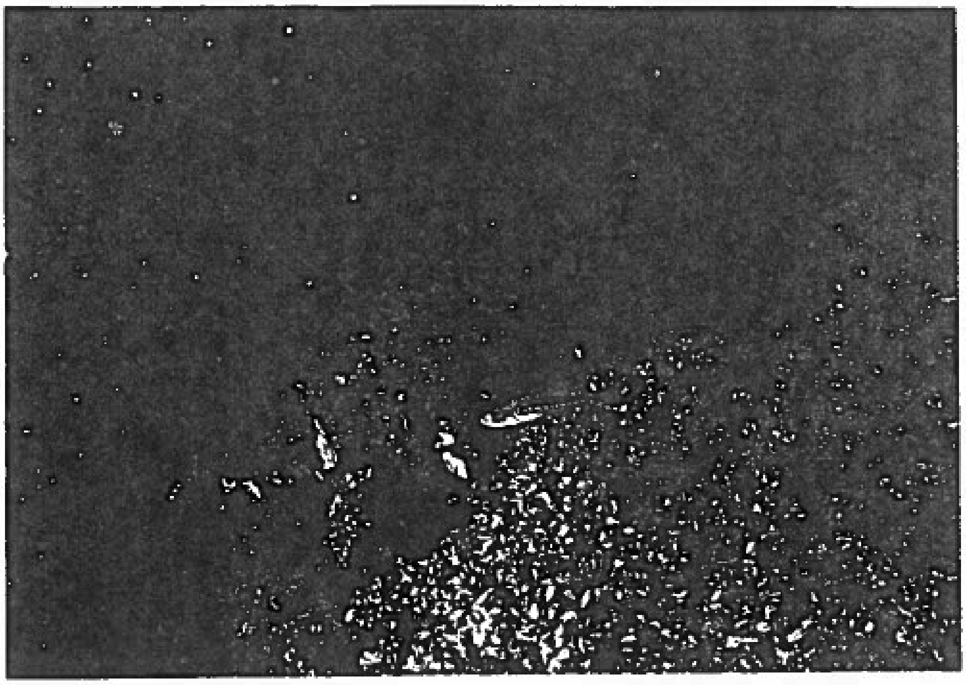
▨ 20-50%

▨ 50-90%

■ 90-100%

PL I Mussel beds

Mussel bed at Halsskov reef



Northeast of Sprogø. Stone covered by juvenile mussels.
Two-spotted goby *(Coryopnopterus flavescens)*

Eel grass/*Polysiphonia* biotope

Dense vegetation of eel grass (*Zostera marina*) was found north of Sprogø, at Halsskov and north of Vresen from the shore to a depth of approximately 5 m. This type of biotope covers an area of approximately 4 km².

The surface sediment is sand with large stones.

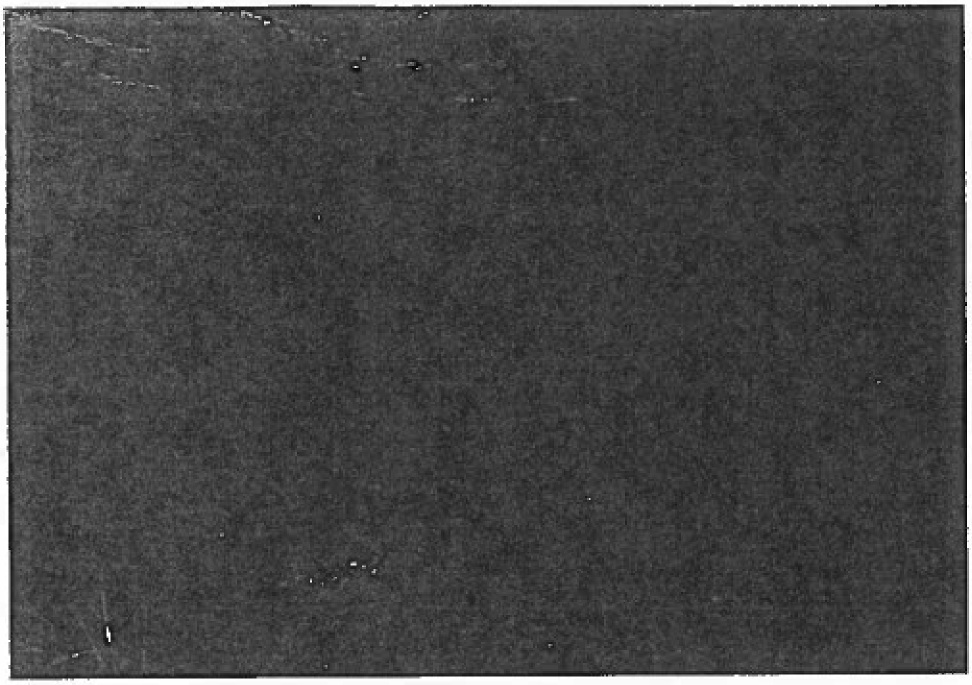
Generally, the sand and the stones were almost completely covered by vegetation (PL II, PL III). Among the stones eel grass was growing, generally covering the bottom almost entirely. However, the density gradually declined with depth. At a depth of approximately 6 m the eel grass had disappeared.

The stones were overgrown with a large variety of algae (PL III). 26 species were found, the following being dominant:

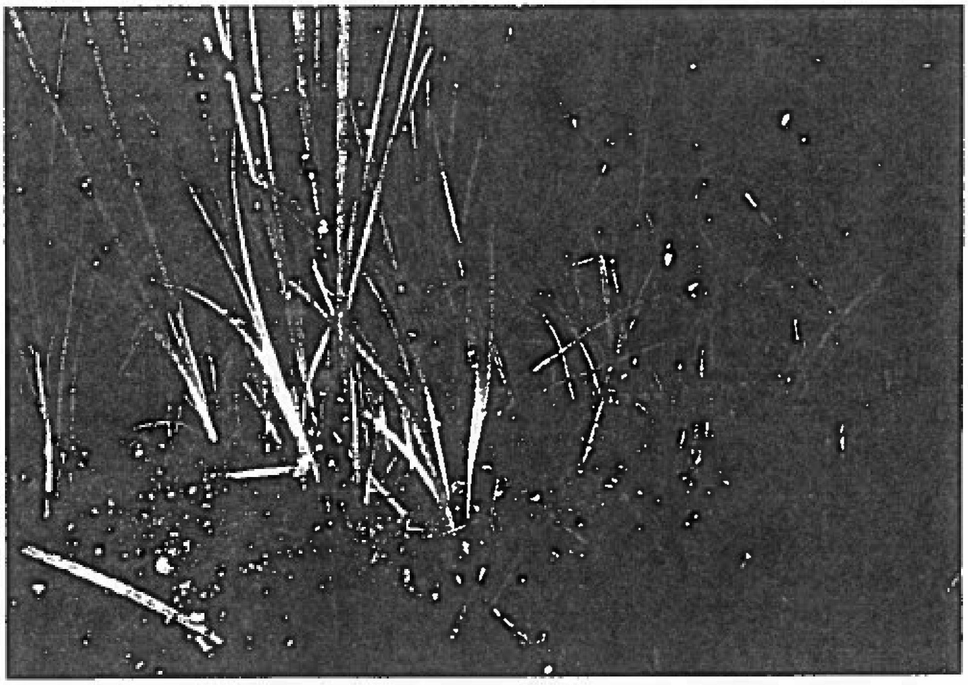
- *Polysiphonia elongata*
- *Polysiphonia nigrescens*
- *Delesseria sanguinea*
- *Rhodomela confervoides*
- *Ceramium rubrum*
- *Phycodrys rubens*
- *Membranoptera alata*
- *Phyllophora truncata*, and
- *Hildenbrandia sp.*

Small snails (*Rissoa*) were found in large amounts on the eel grass (PL II). The snails rasp of the dimatoms covering the eel grass. Moreover, many juvenile starfish (*Asterias rubens*) feeding on the Rissoan snails were found. On the stones breadcrumb sponge (*Halichondria panicea*) was conspiquous. Mysids were also a conspiquous element of the fauna. The fish fauna was dominated by two-spotted goby (*Coryophopterus flavescens*) (PL II) and fifteen spined stickleback (*Spinachia spinachia*). Furthermore, scattered occurrence of mussels (*Mytilus edulis*) on the stones was observed.

PL II Eel-grass/Polysiphonia-biotope

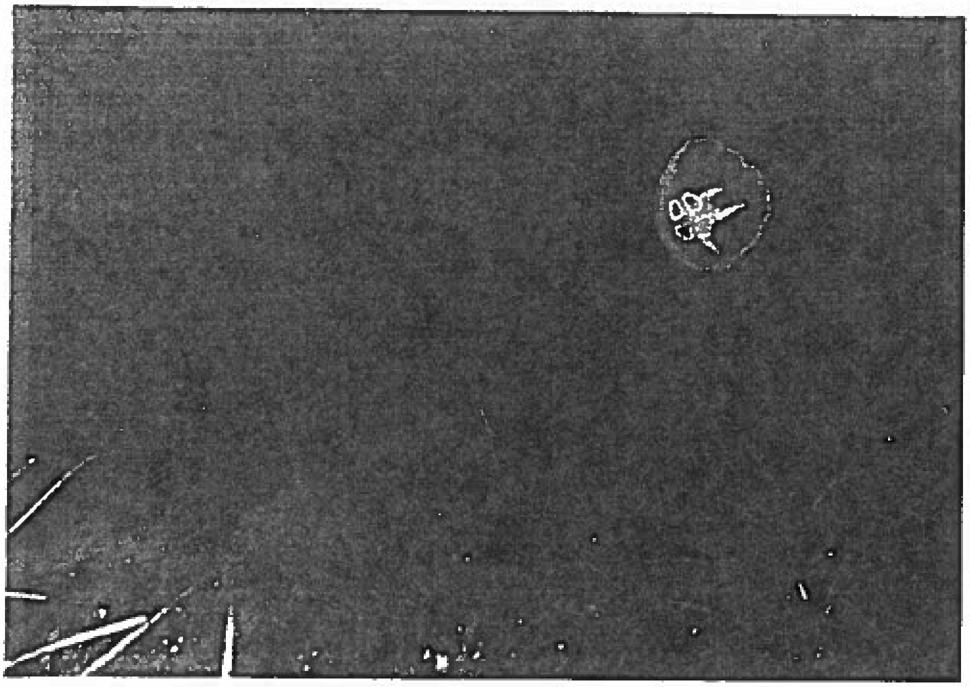


North of Sprogø. Depth 3,5m
Eel-grass *(Zostera marina)* and stones overgrown with red-algae *(mainly Polysiphonia sp.)* Shoal of two-spotted goby *(Coryopnopterus flavescens)*

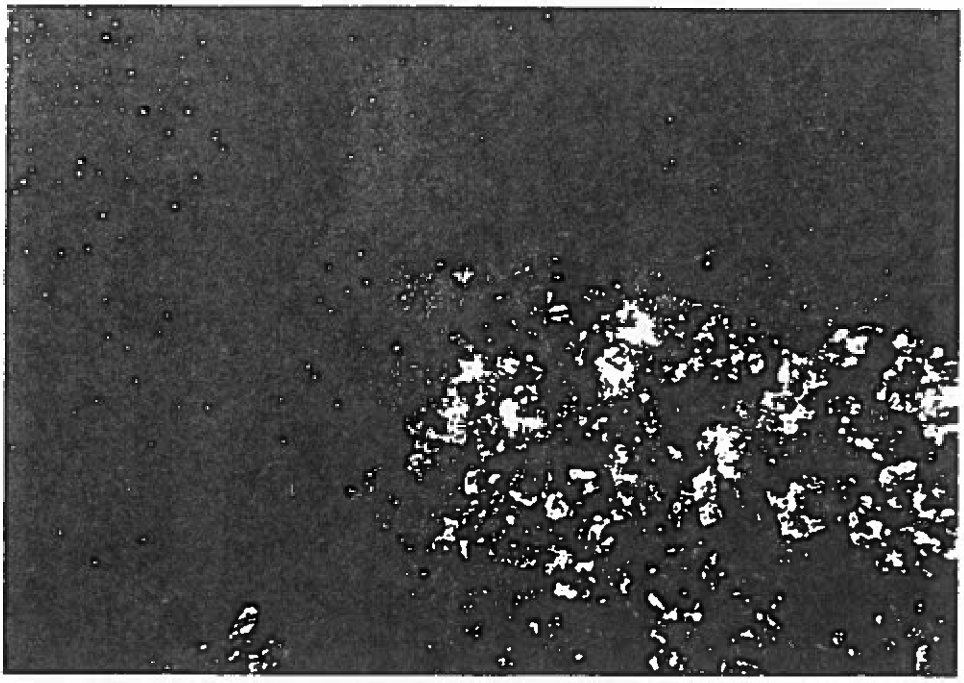


North of Sprogø. Depth 3.5m.
Eel-grass *(Zostera marina)* Rissoan-snails on the eel grass.

PL III Eel-grass/Polysiphonia-biotope



North of Sprogø. Depth 3.5m.
Eel-grass *(Zostera marina)*
and stones overgrown with red algae (mainly Polysiphonia)

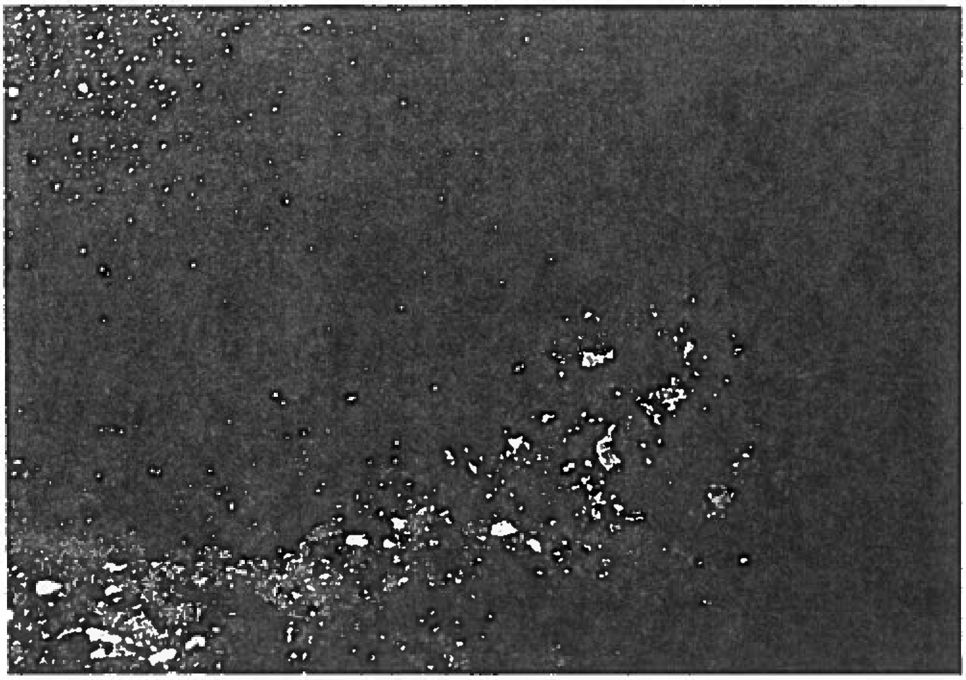


North of Sprogø. Depth 4m.
Stone overgrown with red algae (mainly Polysiphonia), crusty red algae (Hildenbrandia) and breadcrumb sponge *(Halichondria panicea)*

PL IV Pebble gravel

Pebble gravel on Sprogø eastern reef

PL V Delesseria/Halichondria-biotope



North of Sprogø. Depth 6m.
Stones overgrown with red algae *(mainly Delesseria sanguinea)* and breadcrumb sponge *(Halichondria panicea)*

Delesseria/Halichondria biotope

At depths of 5-10 m north of Sprogø and at Halsskov a biotope named *Delesseria/Halichondria* biotope was found (Figure 5.2). This type of biotope covers an area of approximately 4 km².

The surface sediment is sand with large stones. Generally, approximately 50% of the bottom was covered by algae attached to the stones (PL V). At some places only 10-25% of the bottom was covered by vegetation, at other places the density was 50-90%. 23 species of algae were found. *Delesseria sanguinea* was dominant. However, *Phycodrys rubens*, *Membranoptera alata* and *Phyllophora truncata* were also found in large amounts.

The stones were overgrown with breadcrumb sponge (*Halichondria panicea*) (PL V). Furthermore, scattered occurence of mussels (*Mytilus edulis*) on the stones was observed. Many starfish (*Asterias rubens*) were found as well as the following fish species:

- two-spotted goby (*Coryopnopterus flavescens*),
- sand goby (*Pomatoschistus minutus*), and
- goldsinny (*Ctenolabrus rupestris*)

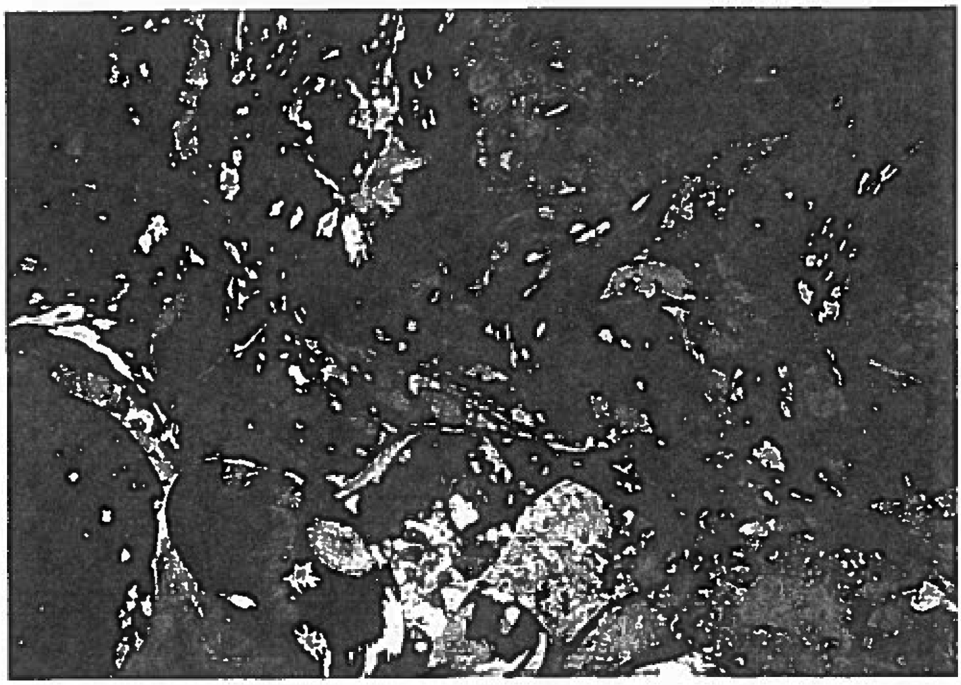
A few cod and flatfish were also observed.

Laminaria/Delesseria biotope

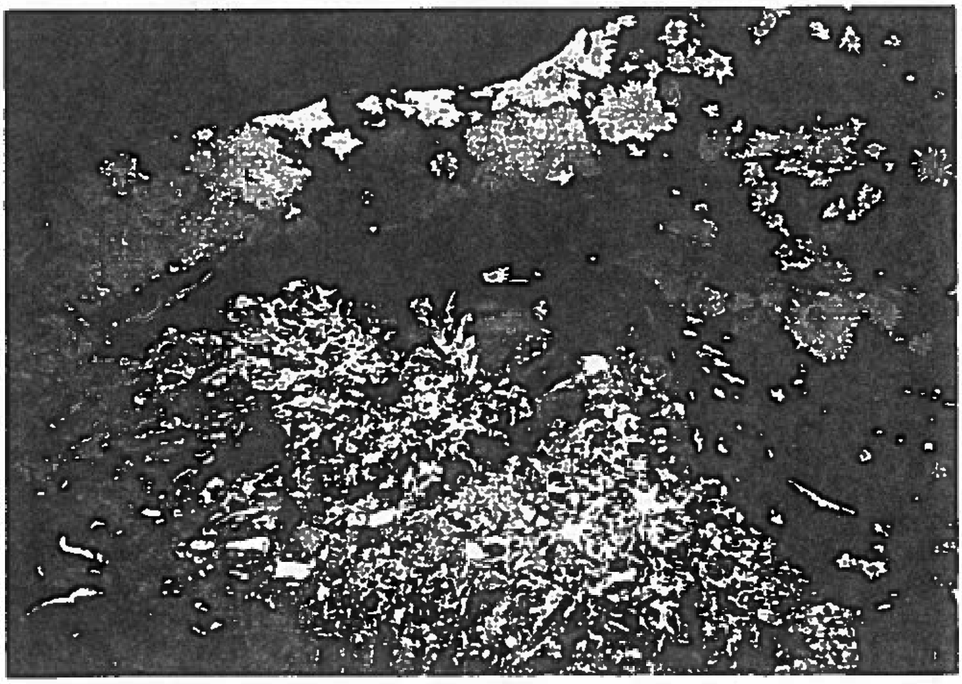
At depths of 10-15 m around sprogø and Halsskov and at depths of 5-10 m north of Vresen a dense vegetation of *Laminaria* was found (Figure 5.2, PL VI). This type of biotope, which has been named *Laminaria/Delesseria* biotope, covers an area of approximately 22 km².

The surface sediment is sand (and pebble gravel at several places) with large stones.

PL VI Laminaria/Delesseria-biotope



At Halsskov reef. Depth 15m.
Laminaria overgrown with bryozoans. Two goldshinny *(Ctenolabrus rupestris)*



At Halsskov reef. Depth 15m.
Laminaria overgrown with bryozoans.
Red algae *(Delesseria* sanguinea) Goldshinny *(Ctenolabrus rupestris)*

Generally, 50-90% of the bottom was covered by algae, some places 20-70%. *Laminaria* species and *Delesseria sanguinea* were dominant. The *Laminaria* species were: *Laminaria digitata*, *Laminaria saccharina* and *Laminaria hyperborea*. *Membranoptera alata*, *Phyllophora pseudoceranoides sp.* and *Hildenbrandia* were also conspiquous. 28 species of algae were found.

The *Laminaria* species were overgrown with bryozoans (PL VI) (especially *Membranoptera*) and *Spirorbis borealis*. Breadcrumb sponge (*Halichondria panicea*), starfish (*Asterias rubens*) and mysids have been observed in relatively large numbers.

The typical stone reef fish goldsinny (*Ctenolabrus rupestris*) and two-spotted goby (*Corypnopterus flavescens*) seem to be very common on the biotope. Furthermore, large cod have been observed and in April. Lumpsuckers (*Cyclopterus lumpus*) spawning in the area, were observed.

Delesseria/Lecosolenia/ Metridium biotope

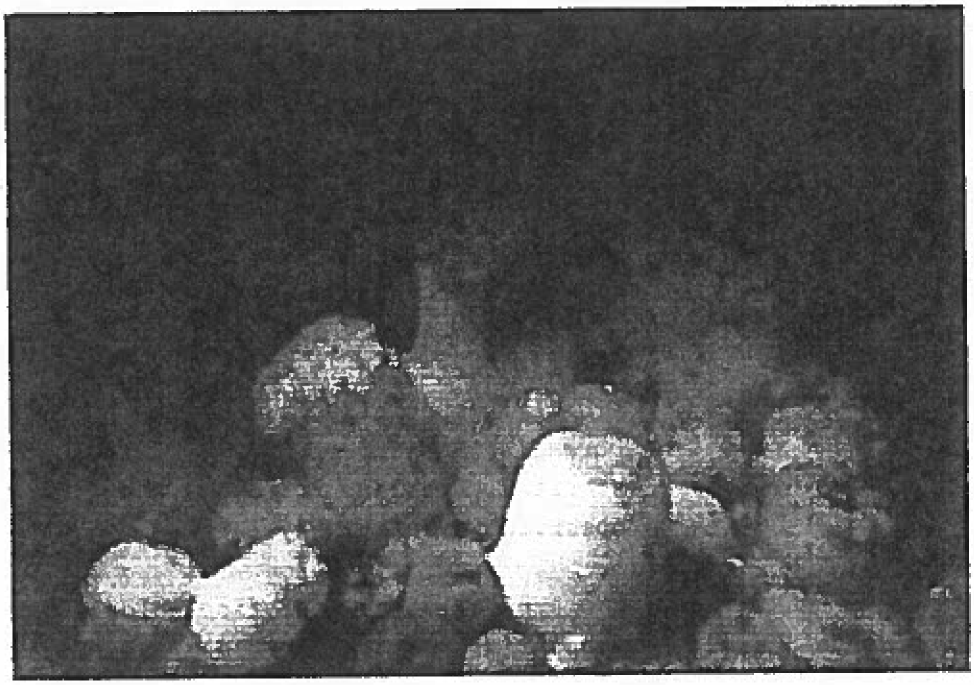
At depths of 15 to 20 m the *Laminaria/delesseria* biotope is replaced by a biotope type named *Delesseria/Leucosolenia/Metridium* biotope (Figure 5.2). This type of biotope covers and area of approximately 14 km².

The surface sediment is muddy sand with stones.

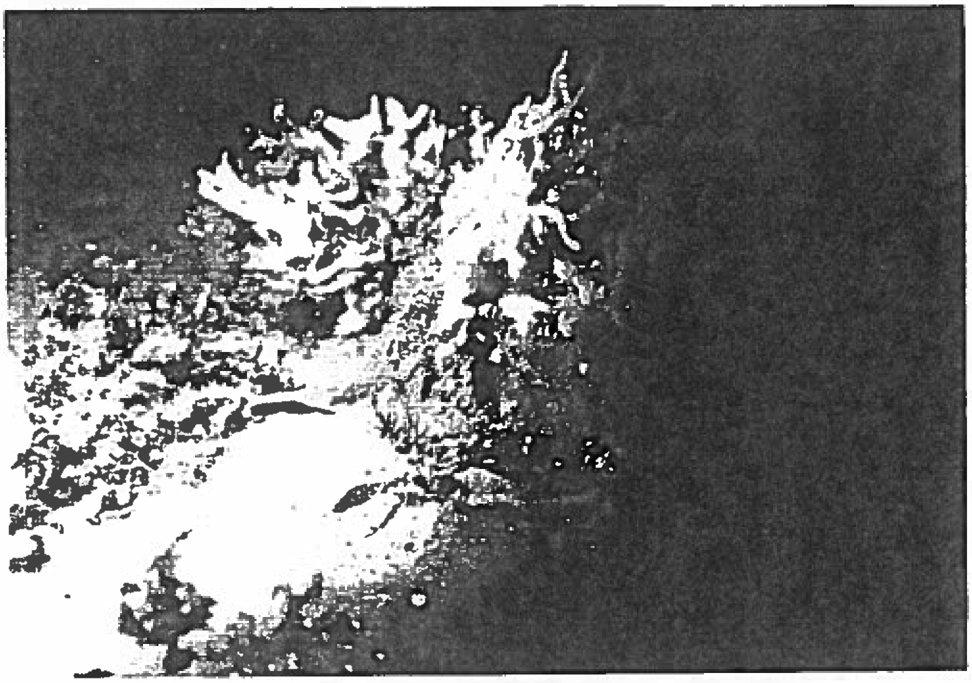
Generally, 40-80% of the bottom was covered by vegetation. However, some places down to 25-30%. *Delesseria sanguinea* was dominant.

The biotope was characterized by the occurence of many sponge colonies (*Leucosolenia complicata*) and several spots with dense populations of sea-anemones (*Metridium dianthus*) (PL VII). Futhermore, hydroids, sunstars (*Crossaster papposus*), brittle stars (*Ophiura*) and red whelk (*Neptunea antiqua*) were characteristic for the biotope.

PL VII Delesseria/Leucosolenia/Metridium-biotope



South of Sprogø. Depth 18m.
Sea-anemones *(Metridium dianthus)*



Northeast of Sprogø.
Sponge colonies *(Leucosolenia complicata)*

The following fish species were observed:

- cod
- dab
- plaice, and
- lumpsucker

Leucosolenia/Metridium biotope

At depths of 20-22 m south of Sprogø, a biotope looking like the above was found (*Leucosolenia/-Metridium* biotope). However, the vegetation has disappeared and the biotope was characterized by the occurrence of *Leucosolenia complicata* (density approximately 10%) and spots with dense populations of *Metridium dianthus*.

5.2.2 Bottom Fauna in Areas without Stones

At the beginning of this century, Petersen investigated grab samples of soft deposits in shallow waters off the Danish coast. He found that different areas supported characteristic associations of animals and he distinguished nine communities, naming each after the most conspicuous species. In the field investigations performed in November three of these communities were identified, i.e.:

- the *Macoma baltica* community
- the *Abra alba* community, and
- the *Haploops* community

Furthermore, a community characterized by many ascidians, not described by Petersen, was found. Figure 5.4 shows the location of these communites. <u>It must be emphasized that the map is only preliminary</u>, because all the sampled material has not yet been worked up. The bottom fauna investigations are described in more detail in Appendix V.

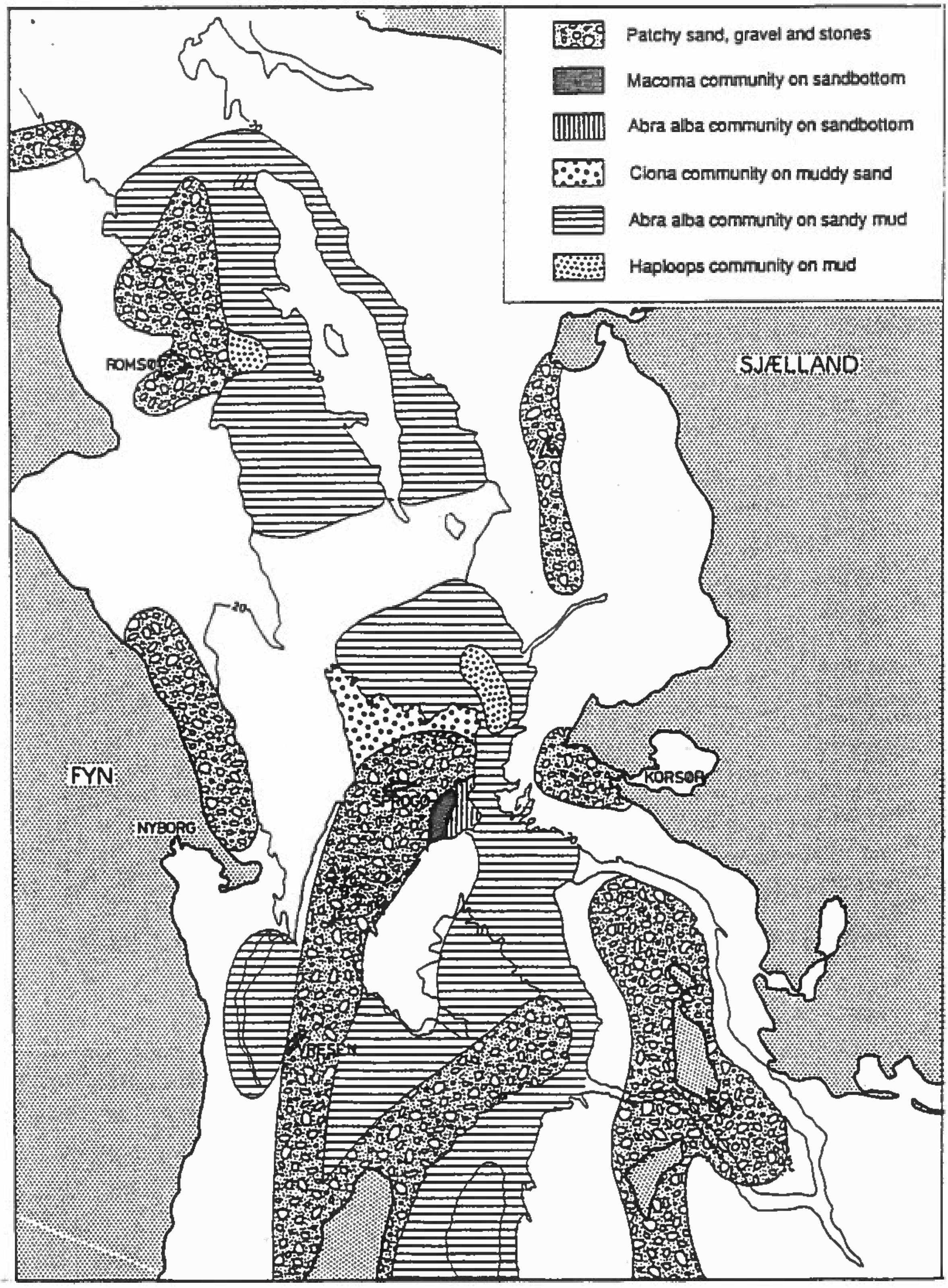


Figure 5.4 - Soft bottom communities found in the Great Belt in November 1987 (cf. Appendix V). The vegetation on stone reefs is described in Section 5.2.1, cf. Figure 5.2.

'*Macoma* community' on sand bottom

At a depth of 10-13 metres southeast of Sprogø the sea bottom consists of sand (PL X). The fauna can be characterized as a *Macoma* community the following types of animals being typical:

- *Macoma baltica*
- *Mya arenaria*
- *Arenicola marina*
- *Hydrobia* sp.
- *Cerastoderma edule*, and
- *Pygospio elegans*

Moreover, there are many *Lagis koreni*, *Scoloplos armiger* and starfish (*Asterias rubens*). (Cf. Appendix V).

'*Abra-alba* community' on sand bottom

At depths of 14-24 metres east and southeast of Sprogø the sea bottom consists of sand as well (Figure 5.1).

The fauna is characterized by species which are type animals for the *Abra alba* community, i.e.:

- *Abra alba*
- *Corbula gibba*
- *Macoma calcarea*
- *Astarte* sp.
- *Lagis koreni*
- *Nephtys (caeca* and *hombergii*), and
- Diastylis rathrei.

There are also comparatively many *Scoloplos armiger*, *Trochochaeta multisetosa*, *Myriochele oculata* and *Cyprina islandica*.

Ciona community on muddy sand

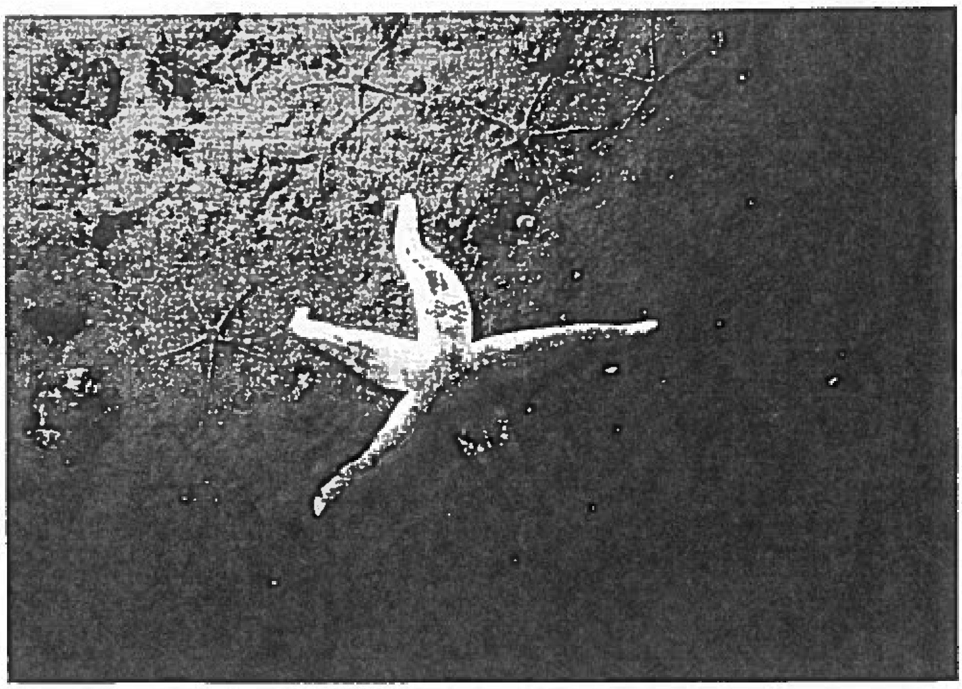
At a depth of 16-18 metres north of Sprogø on muddy sand, a community not described by Petersen was found, it has been named '*ciona* community' after the most conspicuous species, the ascidian *Ciona intestinalis* (PL VIII, Figure 5.4).

Approximately 50% of the bottom is covered by vegetation.

PL VIII Muddy sand

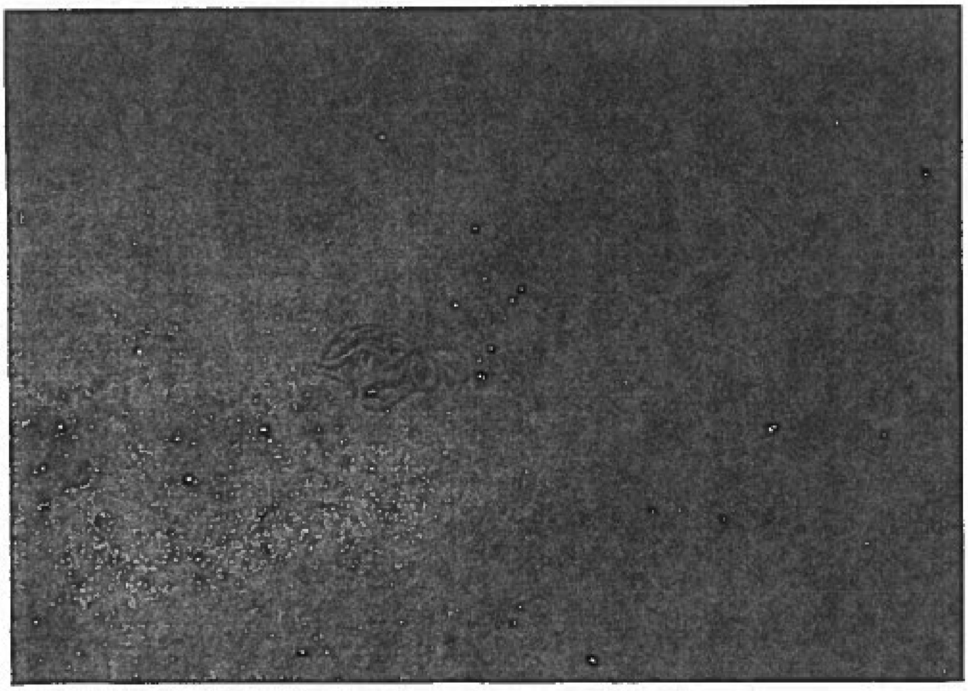
North of Sprogø. Depth 16-18m.
Algae and Ascidians *(Ciona intestinalis)*

PL IX Sandy mud



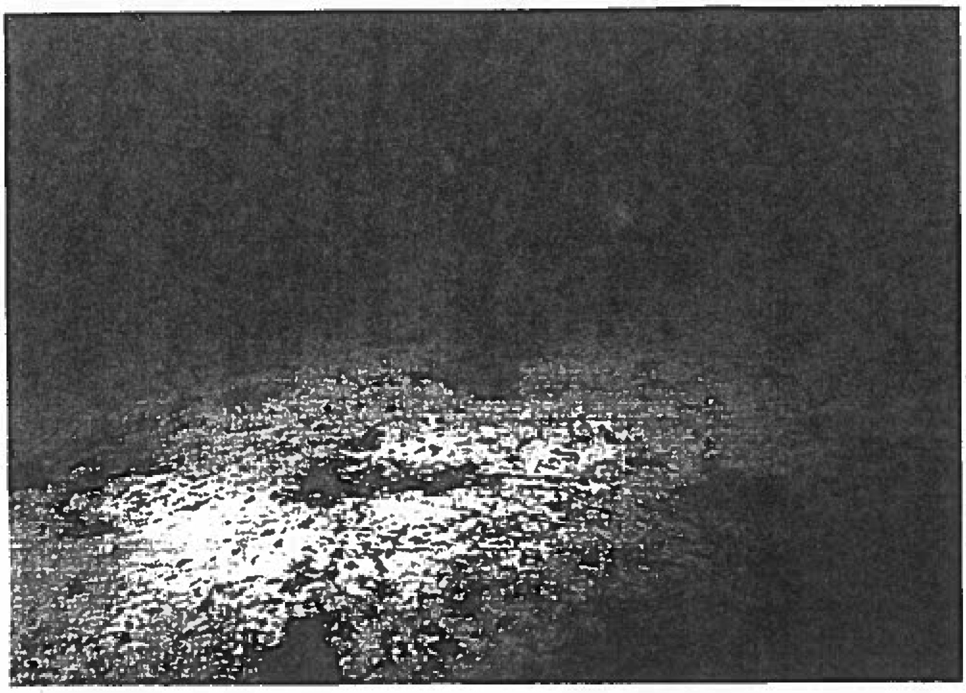
Between Vresen and Fyn. Depth 20m.
Starfish *(Asterias rubens)* and brittle stars *(Ophiura sp.)*

PL X Sand



Sandbottom south east of Sprogø. Depth 10m

PL XI Area with oxygen defficiency



White sulphur-bacteria on a depth of 15m southwest of Halsskov reef

Moreover, at the bottom surface there were relatively many *Ophiura, albida* and *Ophiura robusta.*

The infauna is characterized by the following species (cf. Appendix V):

- *Astarte* sp.
- *Nephtys* sp.; and
- *Terebellides stroemi*
- *Harmothoe* sp.
- *Rhodine gracilior*
- *Scoloplos armiger*
- *cerastoderma edule*
- *Macoma calcaria*
- *Microdeutopus gryllotalpa*, and
- *Ophiura ralbida*

'*Abra alba* community' on sandy mud or mud

At deep waters (out of the 20 metres curve) the bottom generally consists of sandy mud or mud (Figure 5.1), i.e. in the northern and southern parts of the Great Belt, in Østerrenden, in the waters betwen Vresen and Fyn and in the waters northeast of Langeland. The fauna can be characterized as an *Abra alba* community but with a sligthly different kind of species than the *Abra alba* community at the sea bottom with sand (PL IX). The fauna is characterized by the following species:

- *Abra alba*
- *Nephtys sp.*
- *Scoloplos armiger*
- *Cyprina islandica*
- *Terebellidae* sp.
- *Terebellides stroemi*
- *Astarte* sp.
- *Ophiura sp.;*

The distribution of these species in the different areas varies. A quantitative analysis of these differences will be available when the material has been finally analysed (cf. Appendix V).

'*Haploops* Community' on mud or sandy mud

At a depth of 32 metres out of Romsø and at a of 32-54 metres north of "Østerrenden" the bottom consists of mud or sandy mud. Here one will find an animal community that can be characterized as a *Haploops* community (Figure 5.4) characterized by the genus *Haploops*.

5.3 Spawning Areas for Bottom Spawning Fish in the Great Belt

5.3.1 Introduction

The vast majority of the fish species in Danish waters have pelagic eggs. There are, however, a few species that deposit the eggs on the seabottom or on the bottom vegetation.

Bottom spawning fish

This applies to

- herring
- lumpsucker
- garfish; and
- sand eel

Dredging, reclamation or disposal of dredge material are all threats to these species as the suitability of the sea bottom as a spawning ground can be destroyed either by a removal or covering of substrate or as a result of the gradual change of the composition of the sediment as a consequence of increased sedimentation.

Economic importance of bottom spawning fish

Herring is the commercially most important of the bottom-spawning fish, while garfish and lumpfish are of less importance. In the Great Belt sand eel is of no ecomic value. The sand eel is, however, important as feed for other commercial species (among others cod and turbot). This also applies to herring (Ref. 1).

5.3.2 Herring

Bottom substrate

The herring deposits its eggs on the bottom in comparatively shallow waters. If the eggs are to develop it is necessary that the bottom substrate consists of sand, gravel or stone. Moreover the water current on the seabottom must be relatively strong. The eggs are round with a diameter of 1-1.5 mm. They are adhesive and are deposited in more or less densely "mats" on the bottom substrate or the bottom vegetation (Refs. 1,5,6).

There are spring-spawning and autumn-spawning herrings in the Belt Sea (Ref. 3):

- The spring-spawning herrings spawn in shallow waters (usually down to a depth of 10-15 metres) in March, April and May.

- The autumn-spawning herrings spawn in September, October and November. This herring may spawn in deeper waters than the spring spawners (down to 15-20 metres).

In the Baltic Sea and the Belt Sea the population of autumn-spawning herring has decreased in recent years (Ref. 2). Thus in 1987 the Danish Institute for Fishery and Marine Research has not observed mature autumn-spawning herring in Danish waters (Ref. 7). The population of spring-spawning herring has, however, increased.

Spawning grounds for herring in the Great Belt

Two investigations illustrate the extent of the spawning areas for herring in the Great Belt:

- At the end of the 1940s and at the beginning of the 1950s the Danish Institute for Fishery and Marine Research mapped the spawning areas for herring in the Danish waters (Ref.s 2,4).

- In 1983 the Danish Institute for Fishery and Marine Research made an interview with the fishermen, using pound nets at Fyn in order to map the spawning areas of the herring in the Great Belt (Ref. 7).

According to the investigations from the 1940s and 1950s there are spawning grounds for both autumn and spring-spawning herring in the Great Belt in the areas shown in Figures 5.5 and 5.6.

The investigation from 1983 has not confirmed the existence of spawning grounds for autumn-spawning herrings. This is due to the fact that either the herring does not spawn in the area any more, or it could be that it spawns on deeper waters where pound nets are not applied. As to the spring-spawning herring the old and the new data correspond very well (Figure 5.7). Contrary to previous investigations the new ones show the presence of spawning grounds on the western and the eastern side of Langeland and in an area northeast of Langeland. The investigation from 1983 has not been able to point out that there are spawning grounds for spring-spawning herring around Sprogø.

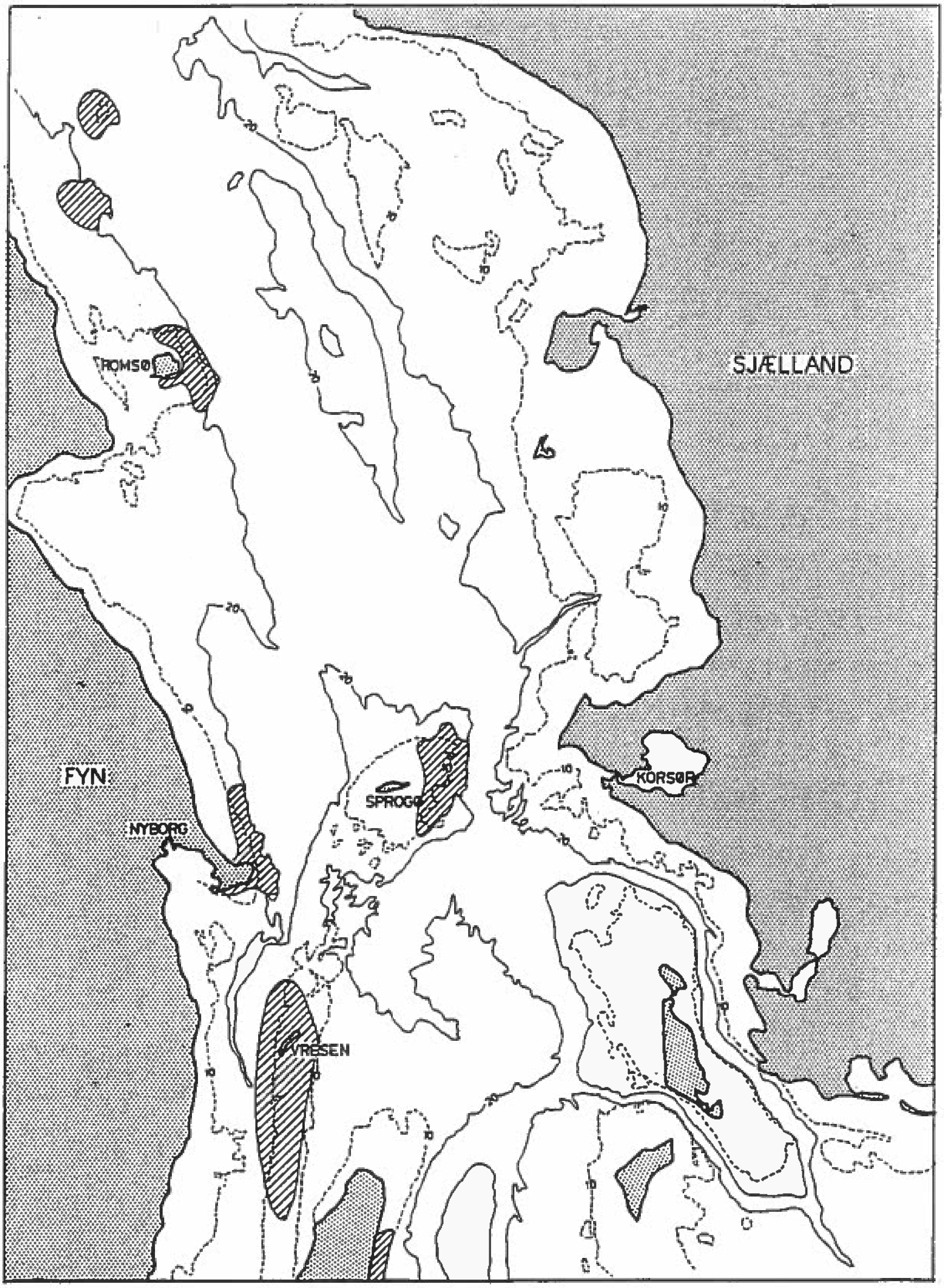


Figure 5.5 - Spawning grounds for autumn-spawning herring in the Great Belt, according to investigations performed in the 1940s and 1950s (Ref. 4).

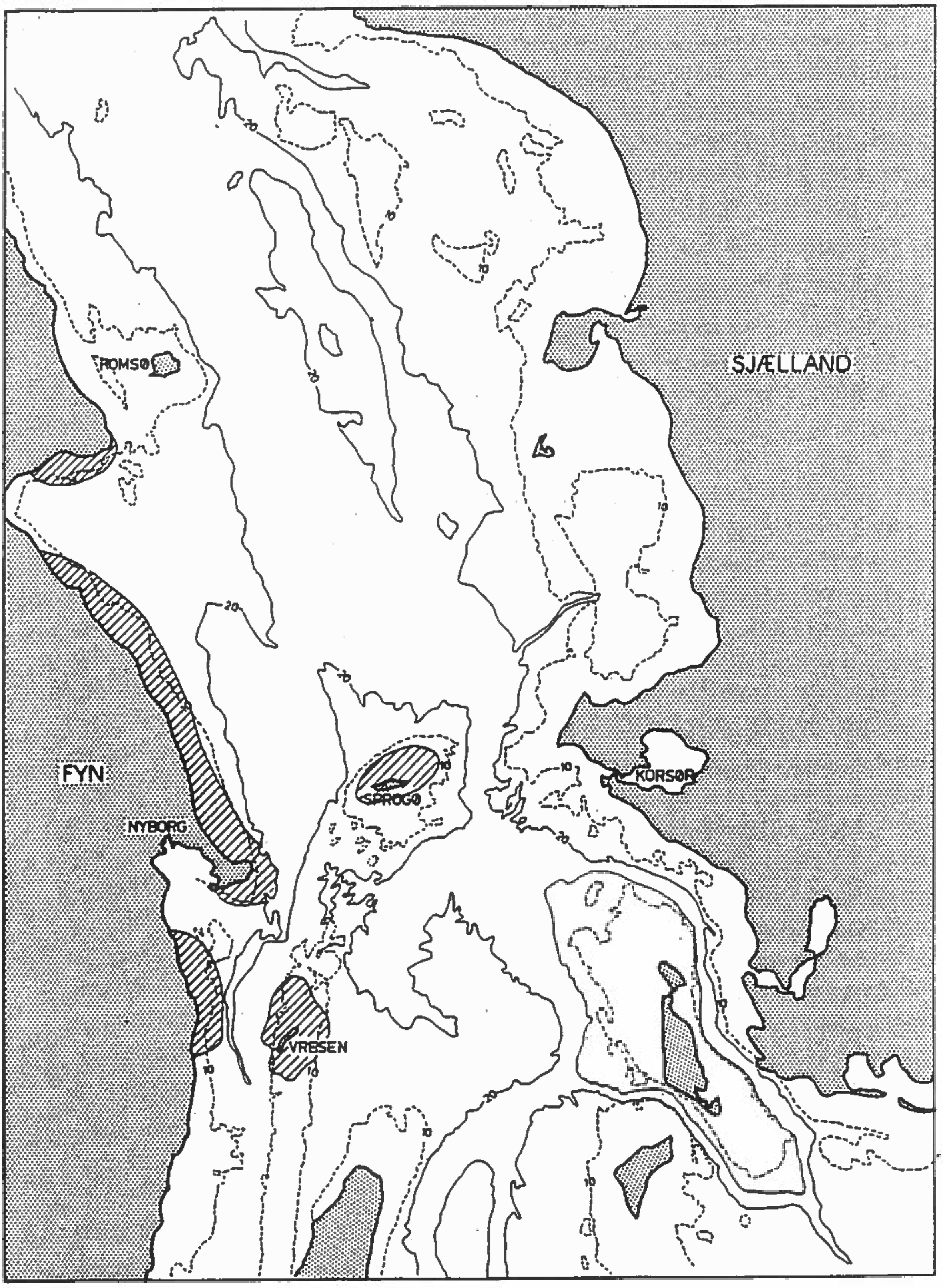


Figure 5.6 - Spawning grounds for spring-spawning herring in the Great Belt, according to investigations performed in the 1940s and 1950s.

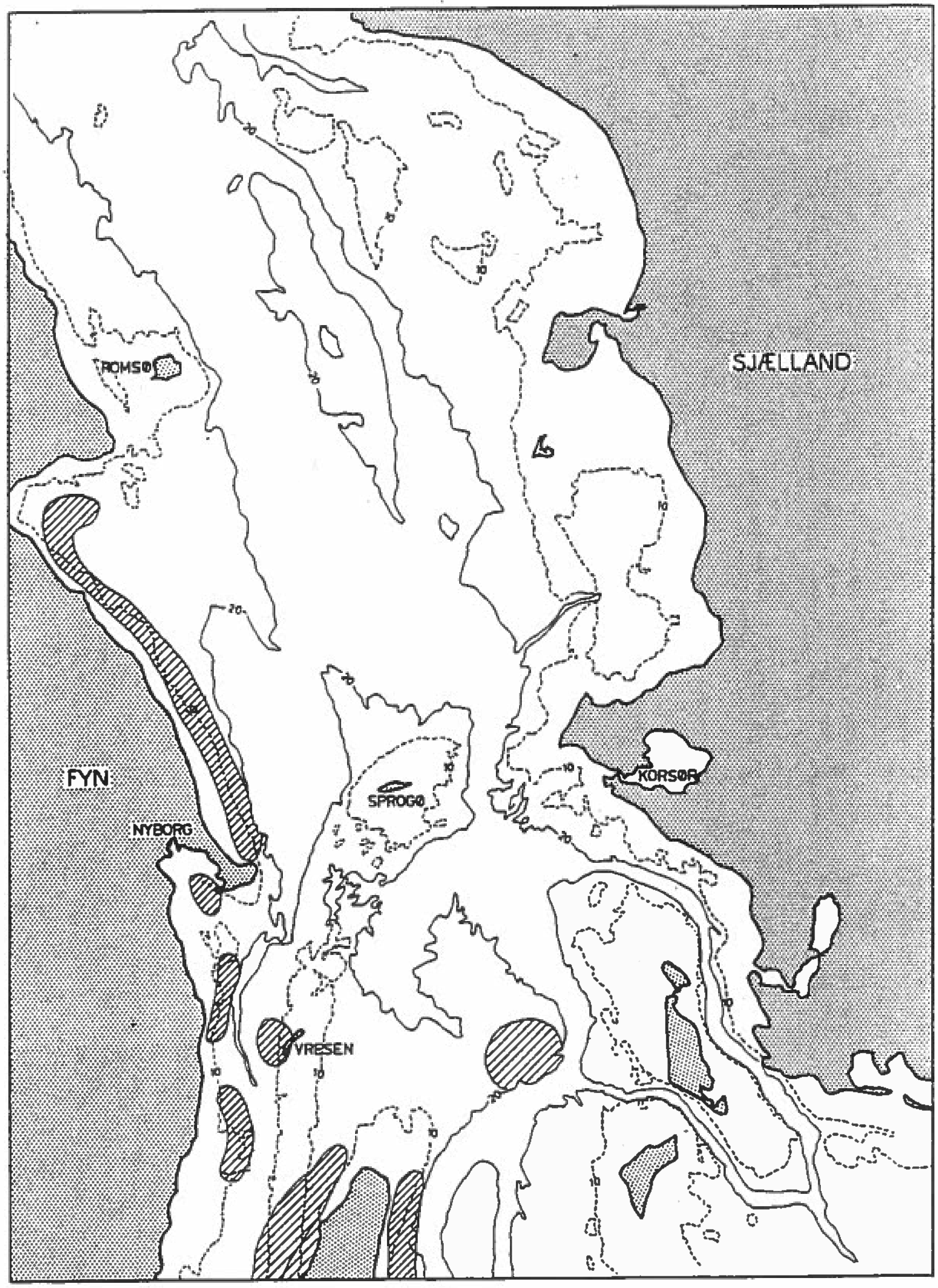


Figure 5.7 - Spawning grounds for spring-spawning herring in the Great Belt, according to investigations performed in 1983 (Ref. 7).

To verify if the spawning grounds for spring-spawning herring around Sprogø found in the 1940s and 1950s still exist, an investigation on the occurrence of spawning herring in the area was performed. Herring were caught in herring nets from 15 April to 28 April 1988 on the locations shown in Figure 5.8 and the occurrence of spawning herrings and eggs on the nets examined. This investigation is described in detail in Appendix VI.

The investigation confirmed the presence of spawning grounds in the area (Figure 5.8). The results gave conclusive evidence of spawning in the areas with a blue colour (Here both spawning herrings were caught and eggs observed on the nets). Furthermore, the results strongly indicate the presence of spawning grounds in the areas with a red colour (Here spawning herrings were caught).

Suitable spawning substrate (sand, gravel and stones) is found around Sprogø in the area with a yellow colour (Figure 5.8). From the results it may be concluded that this area is a potential spawning area. However, it may be argued that the dense mussel beds found west, south and east of Sprogø are less suitable substrates. On the other hand, spawning has occurred on the edge of a mussel bed stations 2, 11 and 12 (Figure 5.8).

It should be noted that the maps of spawning grounds given in Figures 5.5-5.8 most likely do not indicate the location and extent of the spawning places quite exactly. It is not indicated which methods have been used in the earlier investigations (presumably catch of spawn mature herrings). As regards the new investigations the mapping is based on catch of spawning mature herrings; and occurrence of eggs on the nets, but not on direct observations of eggs at the bottom. However, catch of spawning mature herrings and occurrence of eggs on the nets reasonably guarantee that spawning places are found in the surrounding areas (Ref. 25).

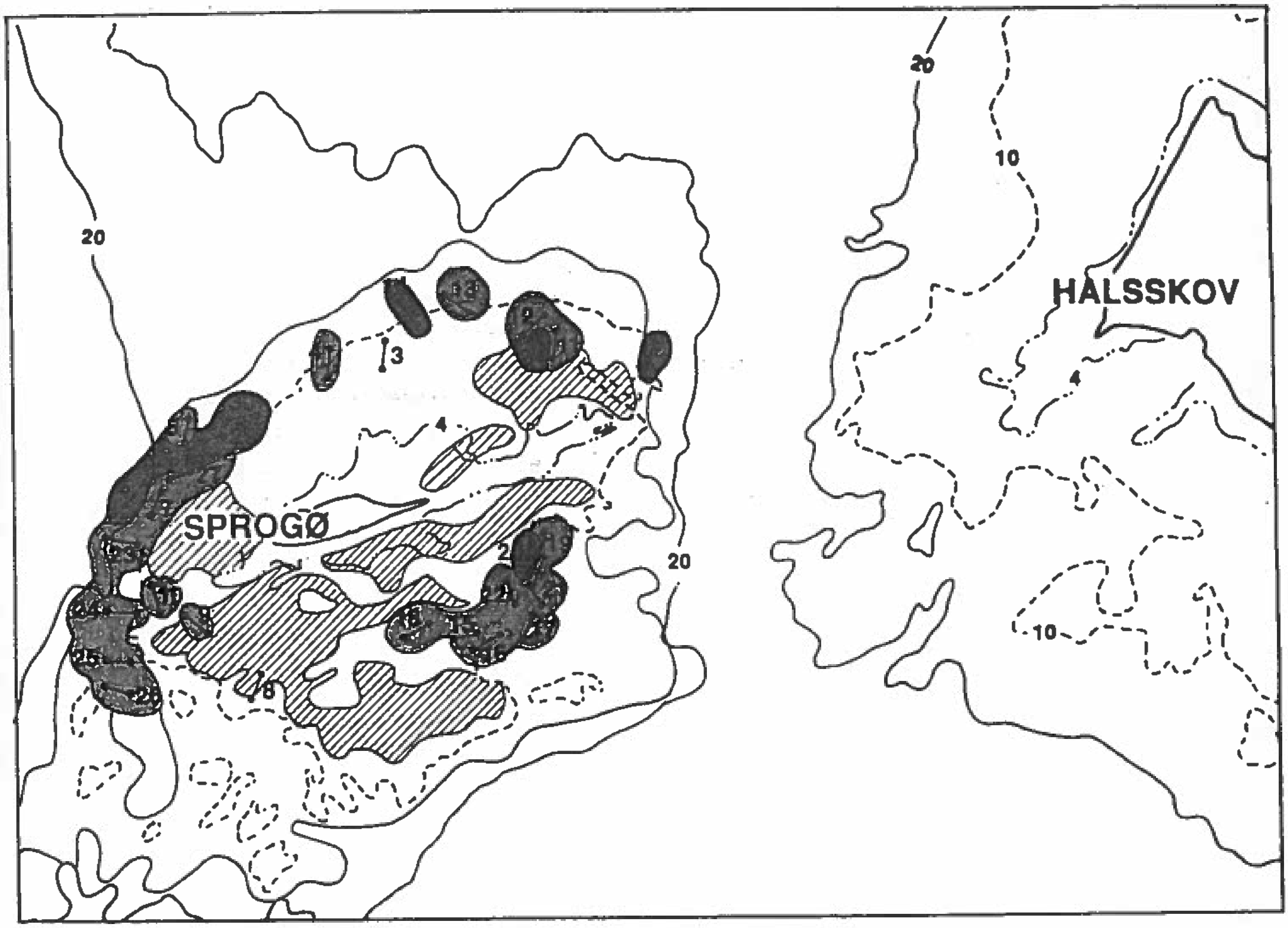


Fig 5.8 Occurence of herring spawning around Sprogø, assessed from the catch of spawning herring and observation of eggs adhered to the nets

■ Spawning herring caught, and eggs adhered to the nets observed

▦ Spawning herring caught

☐ Potential spawning area

▨ Dense mussel beds

5.3.3 Sand Eel

There are two species of sand eel in Danish waters, the sand eel (*Ammodytes lacea*) and the greater sand eel (*Hyperoolus lanceolatur*).

The sand eel spawns on sand bottom along the coast in the Belt Sea, the Sound and the Baltic Sea at depths of 3-20 metres in August to September. The greater sand eel spawns on sand bottom at depths of approximately 20 metres from April to August.

The eggs are deposited on the bottom, sticking to the sand grains (Ref. 4).

Figure 5.9 shows potential spawning places for sand eel in the Great Belt, i.e. areas off the coast to a depth of 20 metres where there is sand bottom (Ref.s 16 and 17).

5.3.4 Lumpsucker (*Cyclopterus lumpus*)

During the period February to May the lumpsucker migrates to the coastal waters in order to spawn. The spawning takes place in areas with large stones and vegetation (especially areas of *Laminaria* growth) (Refs. 14,15). The eggs are deposited on the stones in lumps (the size of a clenched fist). After the spawning the female migrates to deeper waters. The male guards the eggs until hatching, then he also migrates to deeper waters.

During the videosurvey performed in April 1988, several lumpsuckers were observed on the *Laminaria/Delesseria* biotopes around Sprogø (Figure 5.2). Lumpsuckers spawn in the area. One male lumpsucker was thus observed guarding a lump of eggs and one female was attached to a *Laminaria* algae, probably being on the point of spawning.

5.3.5 Garfish (*Belone belone*)

The garfish migrates to our coasts in April to May from wintering places west of the British Islands. During the period May to June the garfish spawns in shallow waters (at a depth of 2-8 metres); mainly in the eel grass belt. The eggs are deposited on the eel grass, algae or stones, to which they glue by means of their sticky barbs. There are no details available on the extent of eel grass in the Great Belt. However, north of Sprogø, north of Vresen and at Halsskov eel grass is found (Figure 5.2) being potential spawning areas.

5.4 Nursery Area for Fish

The most important nursery areas for fish are stone reefs, eel grass meadows and sandbottom on shallow waters (Refs. 14, 23, 24).

5.4.1 Stone Reef and Eel Grass

Stone reefs and eel grass vegetation in shallow waters are important nursery areas for the fry of several of our species of fish. This applies to the cod, which is one of our most important species economically. The cod spawns its eggs in the free water masses in the winter. For some time after the hatching the cod larvae are pelagic, but at the age of approximately 3 months (at a length of 5-10 cm) the fry migrate to the bottom. During the summer the fry of cods stay in particular among algae and eel grass in the shallow water. In the autumn (at lengths of 12-15 cm) the fry migrate to deeper waters (Ref. 23). The fry of garfish and lumpsucker also have their nursery area in shallow waters in areas with algae and eel grass (Refs. 23,24,14).

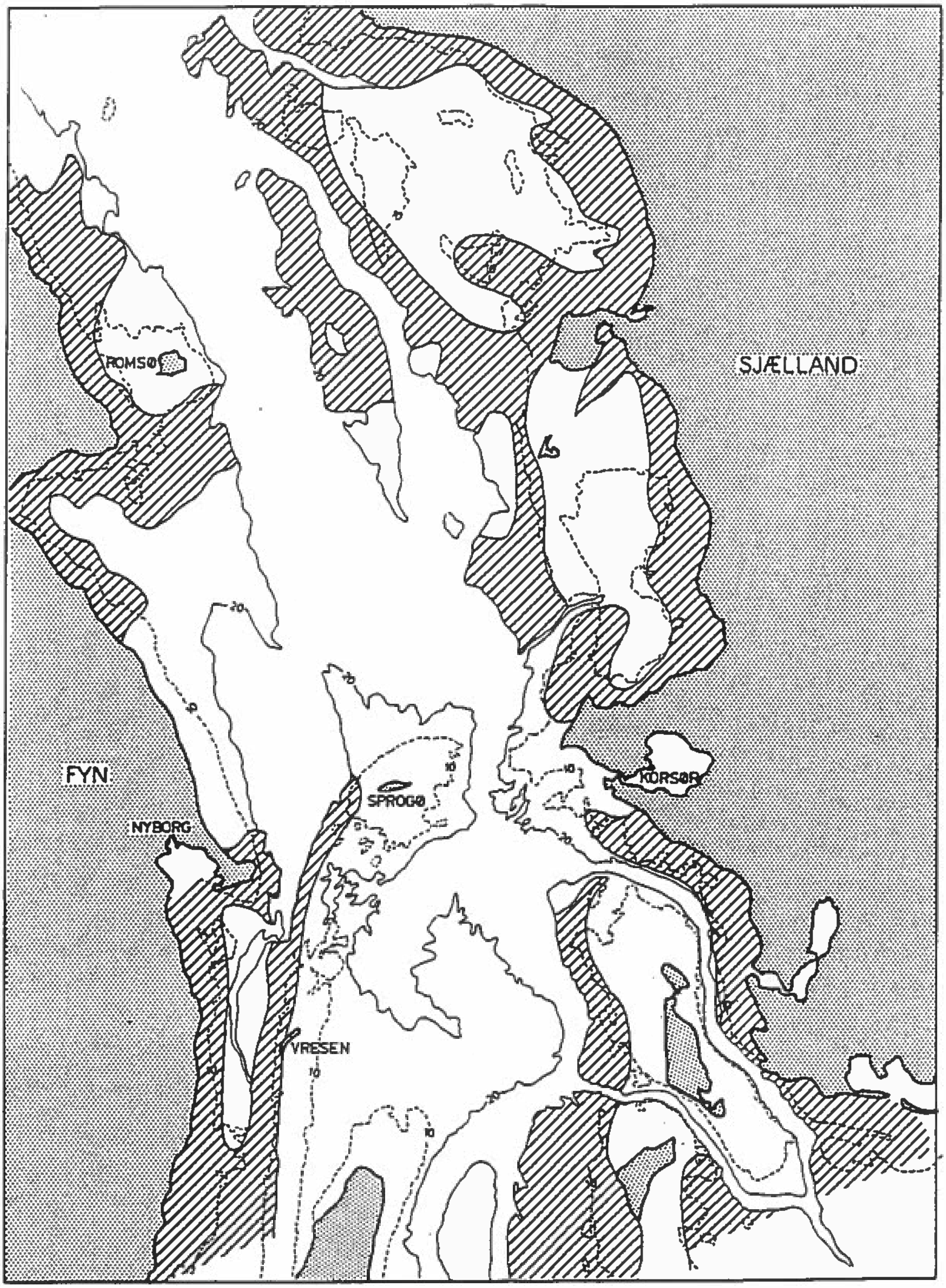


Figure 5.9 - Areas of clean sand bottom at a depth of 20 metres and below that in the Great Belt (Refs. 16,17). These areas are potential spawning places for sand eel.

Besides, stone reefs and eel grass have their own quite special fish fauna. Species that exclusively stay here all life through are: different species of pipefish, fifteen-spined stickleback, goldsinny, corkwing wrasse, butterfish, two-spotted goby and sea-snail (Refs. 23,24,14). Reef on deep sea are favourite refuge areas for cods.

5.4.2 Sandbottom on Shallow Waters

In the summer flatfish (plaice, flounder, turbot and brill) have their nursery area on sand bottom in coastal areas; especially off the coastline at depths of 1-5 metres. Besides flatfish; big shoals of fry of sand eels are found here (Ref. 23).

5.5 Sea Birds in the Great Belt

5.5.1 Important Birds Habitats in the Great Belt

Figure 5.10 shows the areas in the Great Belt that are

- included in the RAMSAR Convention (protection of wet areas of international importance)
- protected under the EEC Bird Directive; and
- protected by national spheres of interest regarding game (by "Vildtbiological Station, Kalø).

Table 5.1 outlines the species of birds that are found in the areas in question and comments on the importance of the areas.

In connection with the contemplated effects of the dredging and reclamation activities the occurence of diving ducks in open waters is particularly interesting. They mainly feed on bottom animals, especially mussels. Thus, the dredging and reclamation activities may destroy the food basis for these ducks.

In the Southern Kattegat and the Great Belt large amounts of diving ducks are found in the moulting time and during the winter. In particular this is the case for eider (*Somateria molissima*), common scoter (*Melanitta nigra*) and velvet scoter (*Melanitta fusca*) (Ref. 8).

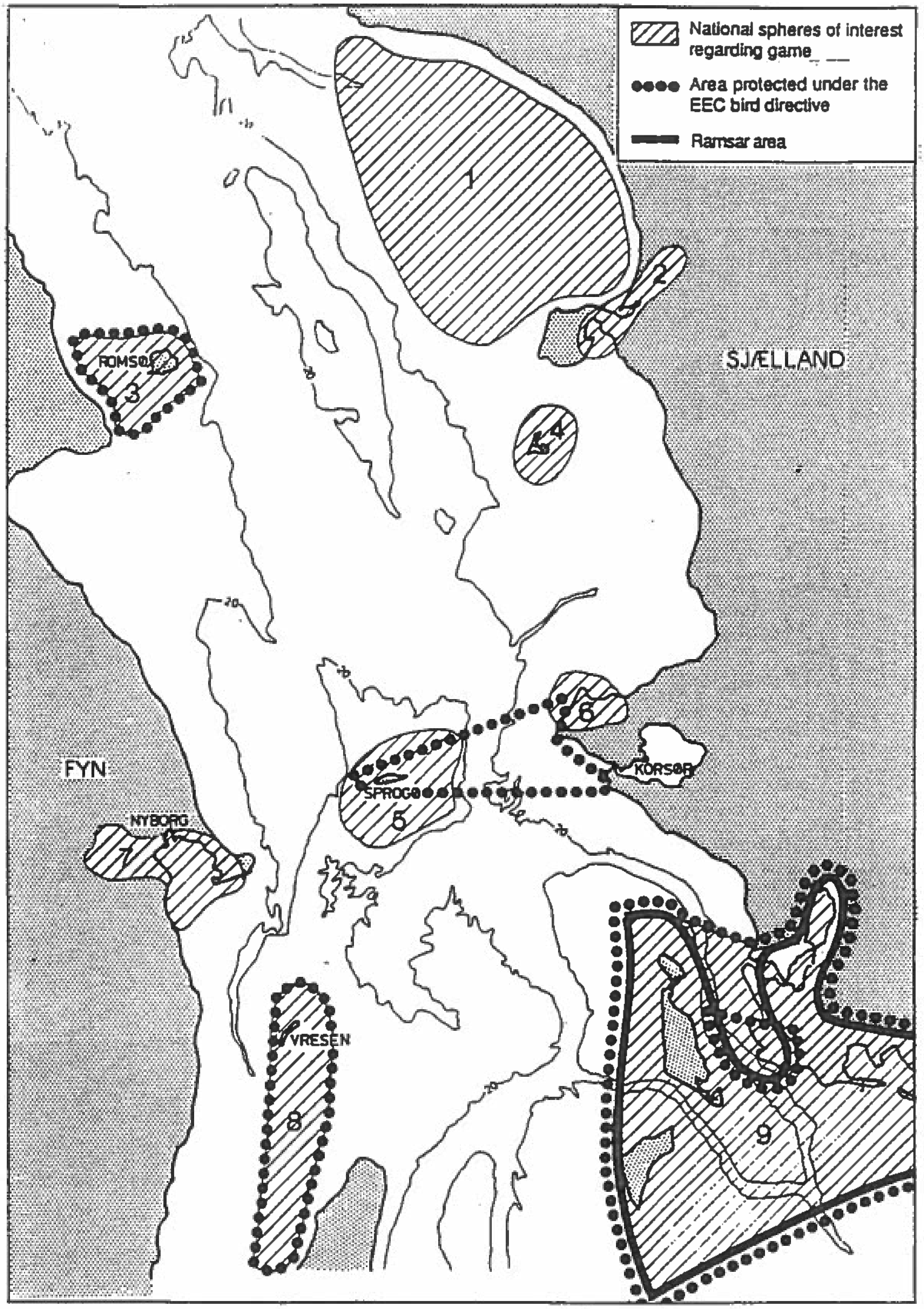


Figure 5.10 - Important places with birds in the Great Belt. National spheres of interest as regards game, areas protected under the EEC Bird Directive, and areas included in the RAMSAR Convention. (Refs. 10,11). Each area is briefly described in Table 5.1.

Table 5.1 - Important bird locations in the Great Belt (refs. 10,11). The occurrence of species in the various areas (the figures refers to map on Fig. 16).

Area	Species/comments
1. The waters in Jammerland Bay	Most important haunts for eider, common scoter, and velvet scoter. Moulting area for eider, common scoter and velvet scoter. Haunt of international significance for eider and common scoter.
2. Bjerge enge, Fællesfolden, Flasken and Vejlen at Reersø	Breeding area for teal, shelduck, shoveler, mallard, red-breasted merganser, mute swan, oystercatcher, lapwing, redshank, ringed plover, kentish plover, dunlin, avocet, black-headed gull, common gull, arctic tern, little tern and rails. Important haunts for mallard, teal, shelduck, wigeon, goldeneye, whooper-swanmute swan, grey lag goose, bean goose, canada goose, oystercatcher, lapwing, ringed plover, golden plover, grey plover, snipe, curlew, bar-tailed godwit, redshank, dunlin, avocet and ruff. The surroundings of Flasken and Vejlen have preserved area status.
3. Romsø	Breeding area for mallard, shelduck, shoveler, red-breasted merganser, grey lag goose, coot, oystercatcher, redshank, common gull, black-headed gull, great black-backed gull, lesser black-backed gull, arctic tern, stock dove, honey buzzard and buzzard. The water areas around the island is haunts for eider, common scoter and velvet scoter. Moulting area for eider and red-breasted merganser. Water areas of international significance as haunt for eider. Protected under the EEC Bird Directive.

Area	Species/comments
4. Musholm	Breeding area for shelduck, red-breasted merganser, eider, oystercatcher, redshank, avocet, ringed plover, black-headed gull, herring gull, common gull, arctic tern, little tern and black guillemot. The waters around the island are haunt for eider.
5. Sprogø/Halsskov Reef	Breeding area for mallard, shoveler, eider, red-breasted merganser, grey lag goose, mute swan, moorhen, coot, oystercatcher, redshank, lapwing, lesser black-backed gull, herring gull, common gull, black-headed gull, water-pipit and yellow wagtail. The waters around Sprogø and Halsskov Reef are very important haunts for eider and common scoter. Sprogø is an important breeding area for small migratory birds. Protected under the EEC Bird Directive.

Area	Species/comments
6. Korsør Nor (Lejodde, the mouth of Tudeå)	<u>Breeding area</u> for mallard, shelduck, garganey, pochard, maybe also teal and tufted duck, grey lag goose, mute swan, red-breasted merganser, oystercatcher, lapwing, snipe, redshank, black-tailed godwit, dunlin, avocet, common gull, black-headed gull, arctic tern, little tern, coot, great crested grebe, red-necked grebe. <u>Important haunt</u> for mallard, pochard, tufted duck, teal, red-breasted merganser, goosander, goldeneye, grey lag goose, brent goose, mute swan, bewick's swan, golden plover, dunlin, curlew and coot. Korsør North is <u>moulting area</u> for mute swan.
7. Nyborg Fjord, Holckenhavn Fjord, Noret and the outer parts of Knudshoved.	<u>Breeding area</u> for mallard, shoveler, garganey, gadwall, pochard, tufted duck, red-breasted merganser, grey lag goose, oystercatcher, redshank, lapwing, avocet, snipe, common gull, black-headed gull, arctic tern, common tern, black-necked grebe, water rail, coot and marsh harrier. <u>Haunt</u> for mallard, shelduck, teal, tufted duck, goldeneye, eider, mute swan, whooper-swan, grey lag goose, lapwing, golden plover, snipe, redshank, avocet, dunlin and coot. <u>The areas around Holckenhavn Inlet and the beach sea Noret have preserved area status</u>.

Area	Species/comments
8. Vresen-Langeland and surrounding waters	Breeding area for eider, red-breasted merganser, grey lag goose, mute swan, oystercatcher, common tern, common gull, great black-backed gull, herring gull and lesser black-backed gull. The waters are important haunts for eider and common scoter and moulting area for common scoter, velvet scoter and eider. Haunt of international significance to eider. Protected under the EEC Bird Directive. Vresen is nature reserve.
9. Skælskør Nor and the waters around Agersø and Omø, Basnæs Nor	Most important breeding areas for pintail, gadwall, mallard, teal, garganey, shoveler, pochard, tufted duck, eider, red-breasted merganser, grey lag goose, mute swan, oystercatcher, lapwing, redshank, snipe, black-tailed godwit, dunlin, avocet, ruff, great balck-backed gull, common gull, black-headed gull, common tern, little tern, sandwich tern, rails, little grebe, great crested grebe, red-necked grebe, marsh harrier, cormorant and grey heron. Important haunts for mallard, teal, shoveler, pintail, wigeon, pochard, tufted duck, goldeneye, red-breasted merganser, eider, common scoter, velvet scoter, grey lag goose, bean goose, brent goose, canada goose, mute swan, whooper-swan, oystercatcher, lapwing, grey plover, golden plover, bar-tailed godwit, redshank, curlew, snipe, dunlin, avocet, ruff, coot. Furthermore, cormorant, white-tailed eagle, rough-legged buzzard, buzzard, hen harrier and marsh harrier are seen. (to be continued)

Area	Species/comments
9. (cont'd)	Moulting area for mute swan and eider amongst others. Haunt of international significance for pintail, shoveler, tufted duck, eider, common scoter, velvet scoter, gey lag goose, bean goose, mute swan, whooper-swan, coot and bar-tailed godwit. On Omø there is one of Denmark's three cormorant colonies (international importance). Basnæs Cove and part of Skælskor Cove are nature reserves Ramsar-area. Protected under the EEC Bird Directive

5.5.2 Eider (*Somateria molissima*)

Occurrence in Denmark
November - March

From November to March the eider is the most numerous sea bird in Danish waters (in 1974 the estimated number approximately 750,000). The birds are found in the Great Belt, the "Sydfynske Øhav", the Little Belt, the Kattegat and the Wadden Sea (cf. Fig. 5.11) (Ref. 8). Besides the local Danish populations wintering birds breeding at the Baltic Sea (Sweden and Finland) and the southern part of Norway are found. The Danish waters are thus the most important wintering place for the eider population in the Baltic Sea. The sea birds from Southern Norway are mainly concentrated in the northern part of the Kattegat, while birds from the Baltic Sea are found in the central Danish waters (Ref. 9).

Occurrence in the Great Belt November - March

In the Great Belt the eiders are particularly concentrated in the following areas from November to March (Figure 5.11):

- the waters around Sprogø
- the waters around Romsø
- the waters around Vresen
- the waters around Omø and Agersø, and
- the waters south of Asnæs.

Table 5.2 shows the number of eiders that has been observed in these areas during the period November to March in 1968-1973. As mentioned in Section 5.5.1 the areas are stated as haunts of international importance to the eider (Refs. 10,11,12).

Furthermore, there are large flocks around Musholm and at Halsskov Reef.

Table 5.2 - Number of birds observed in the waters around Sprogø, Romsø, Vresen, Omø/Agersø and the waters south of Asnæs (November-March) in the period 1968-1973 (Ref. 8)

Area	No.
Sprogø	5,000 - 36,000
Romsø	5,000 - 20,000
Vresen	5,000 - 24,000
Omø/Agersø	approx. 5,000
Asnæs	5,000 - 25,000

Forage possibilities

One of the main reasons for gathering in these particular areas is that the eider has rich forage potentials here.

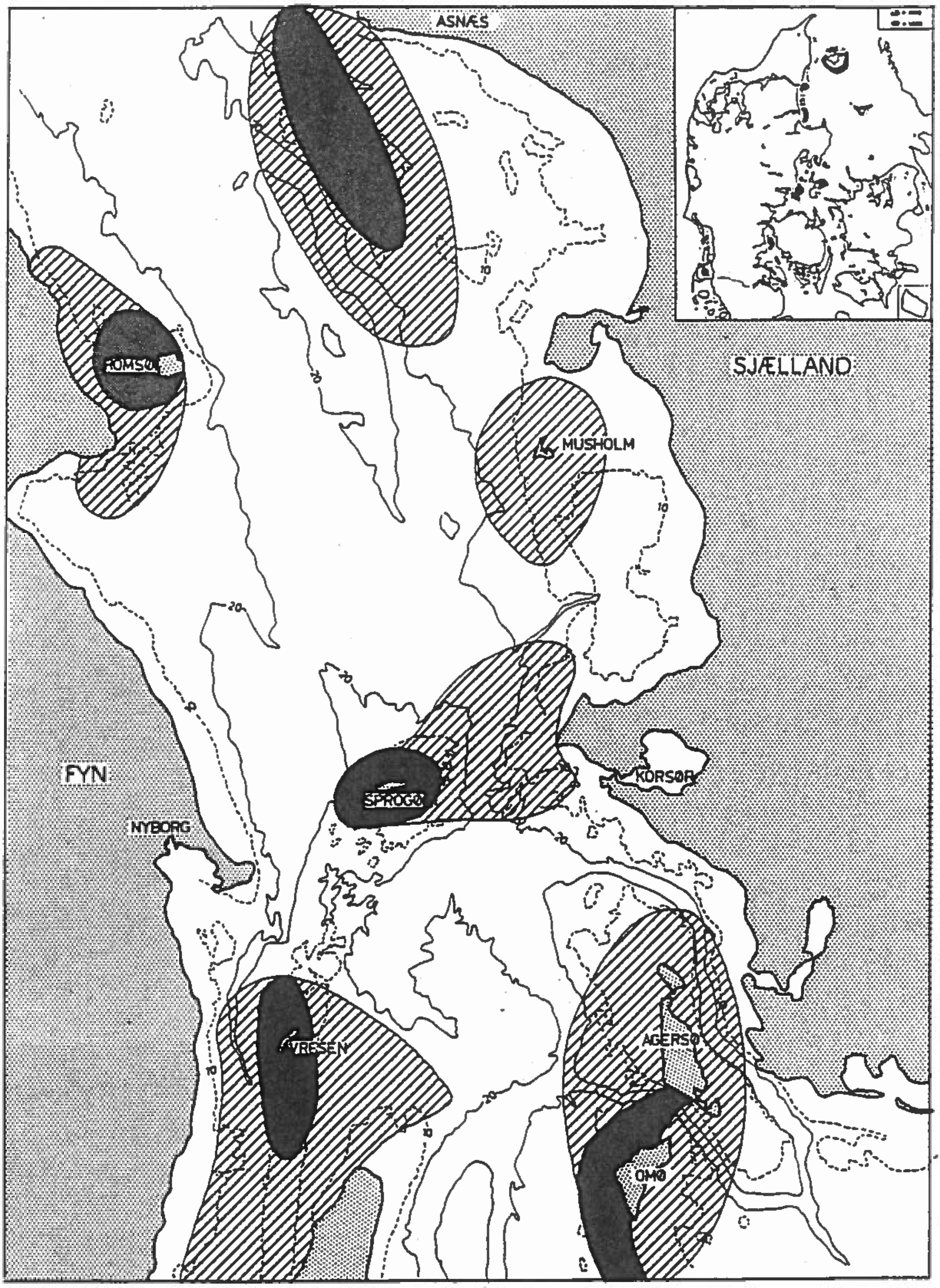


Figure 5.11 - The occurrence of eider in the Great Belt from November to March. Areas with flocks of birds consisting of more than 1,000 at regular intervals (hatched). Areas with flocks of birds consisting of more than 5,000 at regular intervals (dark).

In Danish waters the eider provides its feed from comparatively shallow waters, in particular where stones and mussel beds (*Mytilus edulis*) are to be found. The common blue mussel is by far the most important feed for the eider (about 55% of the feed). It also eats certain snails (*Littoria*), crabs (*Carcinus*) and starfish (Refs. 8,13).

The above areas are precisely characterized by the occurrence of reefs (cf. Figure 5.1), and in any case, around Sprogø and Halsskov Reef large amounts of mussel beds are found (cf. Figure 5.3).

The occurrence of birds in the Great Belt March - July

In March the large flocks of eiders are spread again. The birds migrate to the breeding areas, and in April and May there is a comparatively low number of eiders in the Great Belt (Ref. 9). In the Great Belt breeding areas are found on Sprogø, Vresen, Agersø, Omø and Musholm (Ref. 10).

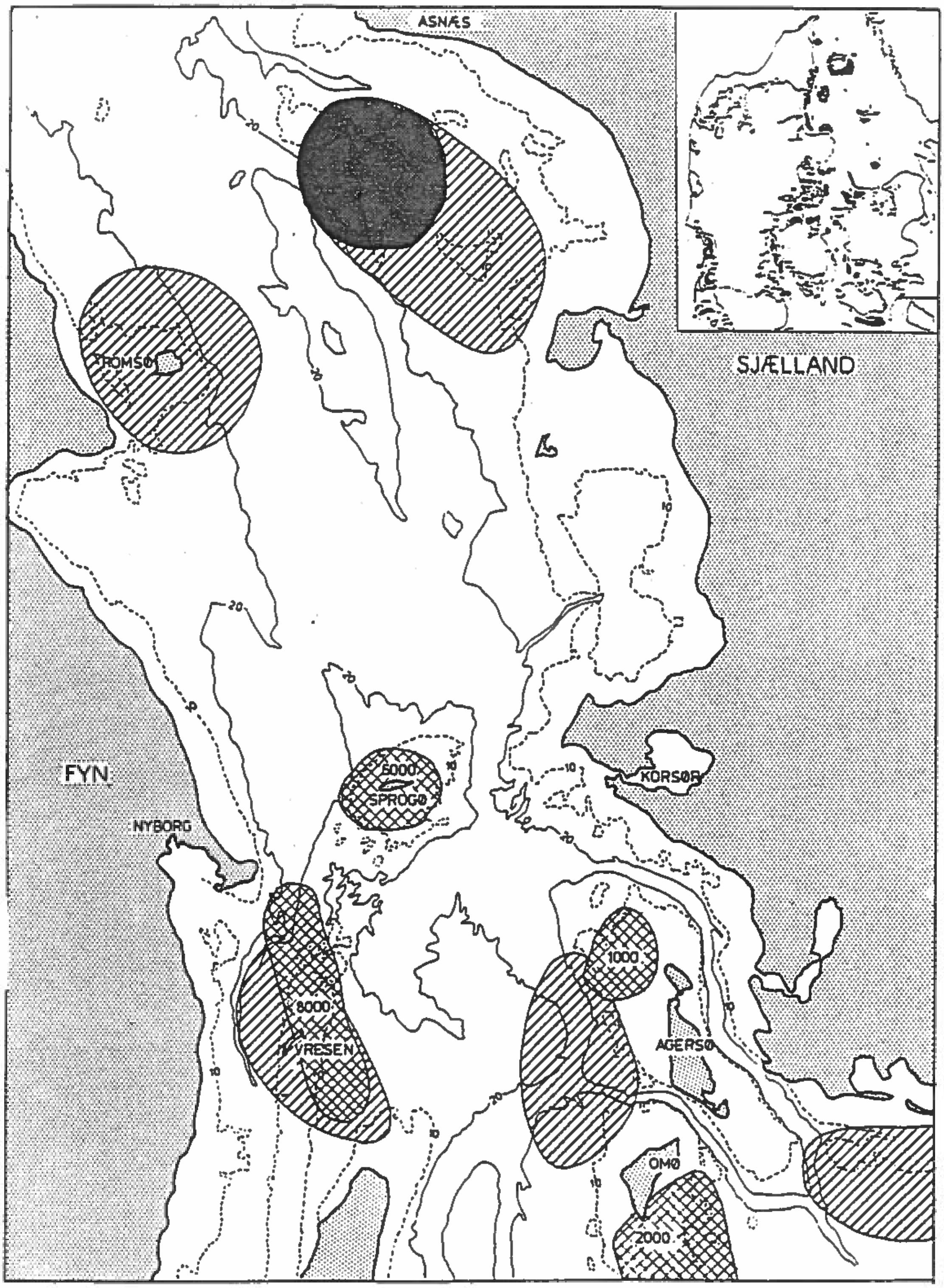


Figure 5.12 - The occurrence of moulting eiders in the Great Belt during July-August. Black: Areas of regular large concentrations in 1966-1972. Hatched (single): Areas of spread population, more unregular occurrence (Ref. 9). Hatched (crossed): Areas of moulting birds 15-31 August 1983. The nos specify the largest amount of birds observed during this period (Ref. 12).

The occurrence of birds
in the Great Belt
July - August

In July and August vast flocks of eiders are again gathering in the Great Belt. They are flight feather moulting birds. To a great extent, the birds are gathering in the same areas as during winter (Figure 5.12). In this period they are not able to fly and therefore they are very sensitive to all kinds of interference.

5.3.3 Common Scoter (*Melanitta nigra*)

The common scoter does not breed in Denmark. However, from June to October the common scoters migrate to our waters from their breeding areas in the Baltic Sea area (Ref. 8).

From July to August there are large flocks of moulting common scoters in Danish waters, especially in the Kattegat and in the coastal areas of West Jutland.

In the Great Belt there are moulting common scoters in the waters around Vresen and in the waters south of Asnæs (Figure 5.13).

From October to April wintering common scoters are found in Danish waters (in particular in the Kattegat and in the Wadden Sea (Ref. 8).

In the Great Belt wintering areas are found in the following areas (Figure 5.14) (Refs. 8,10):

- the waters around Omø/Agersø
- the waters south of Asnæs
- the waters around Romsø
- the waters around Musholm
- the waters around Sprogø, and
- the waters around Vresen.

The waters around Omø and the waters south of Asnæs have been stated as wintering haunt of international significance to the common scoter (Ref. 10).

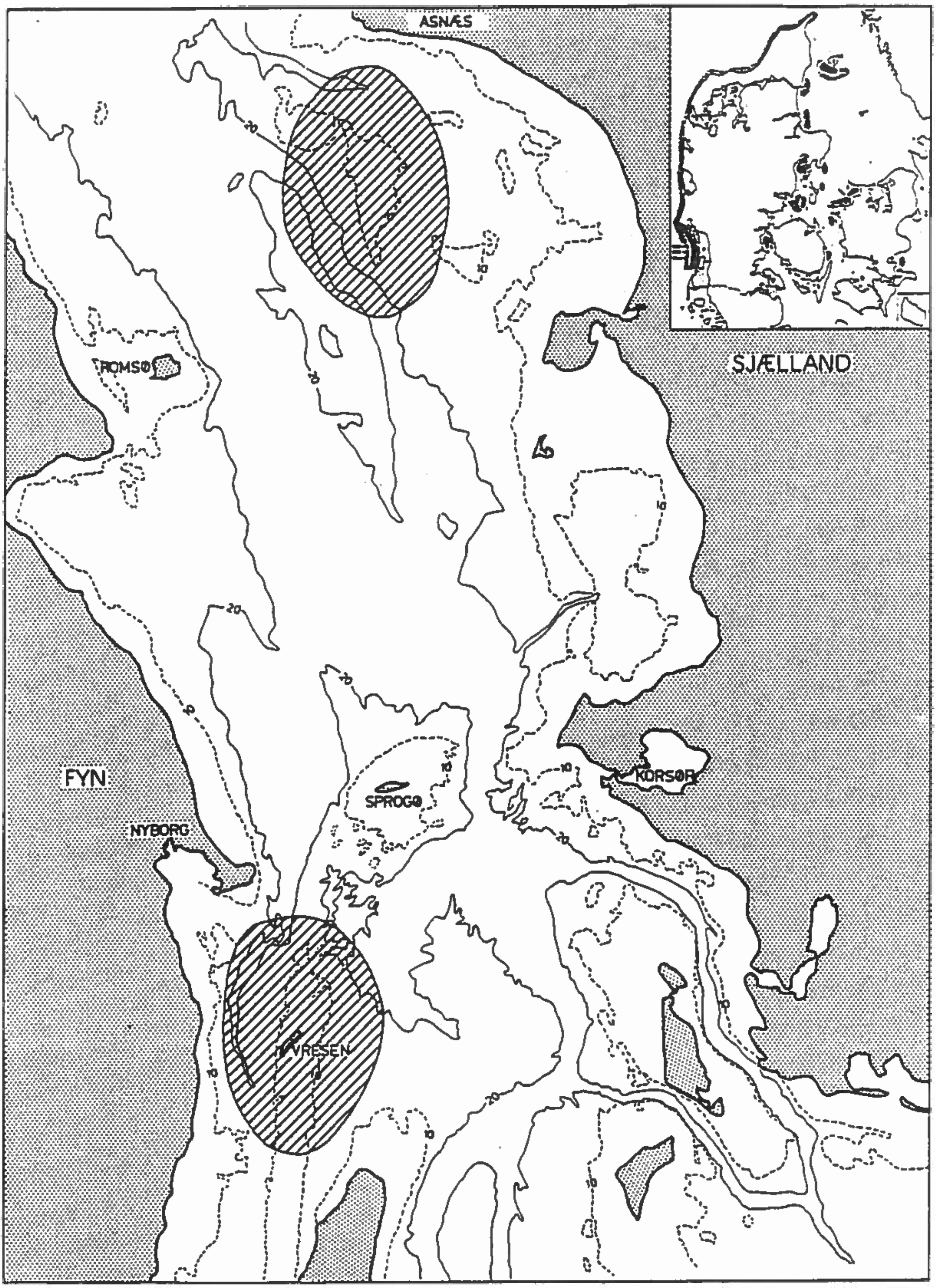


Figure 5.13 - The occurrence of moulting common scoters in the Great Belt during July and August.

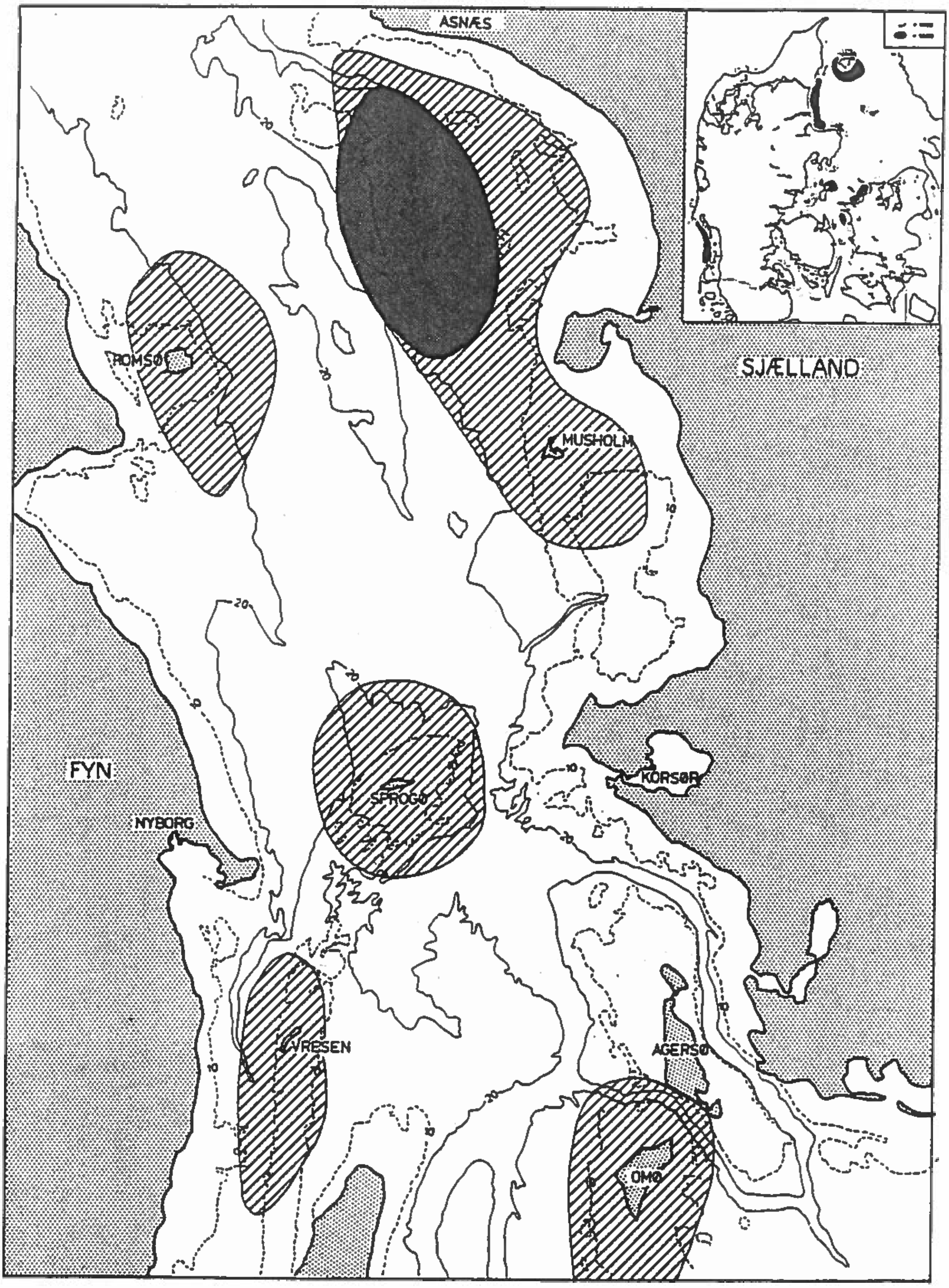


Figure 5.14 - The occurrence of common scoters in the Great Belt from October to April. The areas in hatched and those painted dark show the regular occurrence of flocks of more than 1,000 and 5,000 birds, respectively (Ref. 8).

5.5.4 Velvet Scoter (*Melanitta fusca*)

As is the case of the common scoter, the velvet scoter does not breed in Denmark. However, it quite often visits Danish waters during moulting time, i.e. July and August, and during winter (from October to April).

Occurrence of birds in the Great Belt July - August

In the Great Belt moulting velvet scoters are found in the waters south of Asnæs and in the waters around Vresen (Ref. 9) (Figure 5.15) during July and August.

Occurrence of birds in the Great Belt October - April

In the Great Belt wintering velvet scoters are found in the waters south of Asnæs, around Musholm and in the waters around Vresen and Omø (Ref. 8) (Figure 5.16) from October to April.

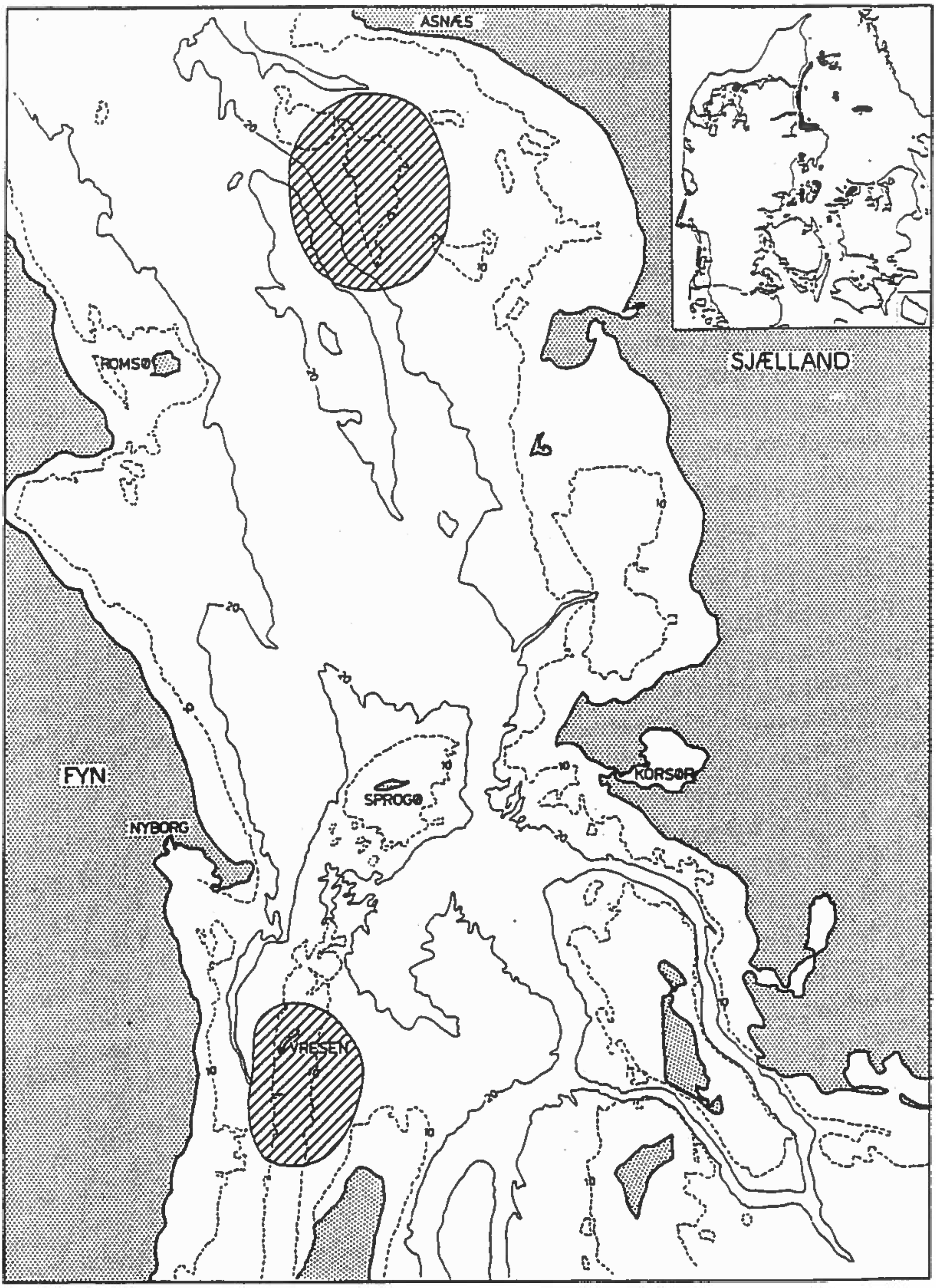


Figure 5.15 - The occurrence of moulting velvet scoters in the Great Belt during July and August (Ref. 9).

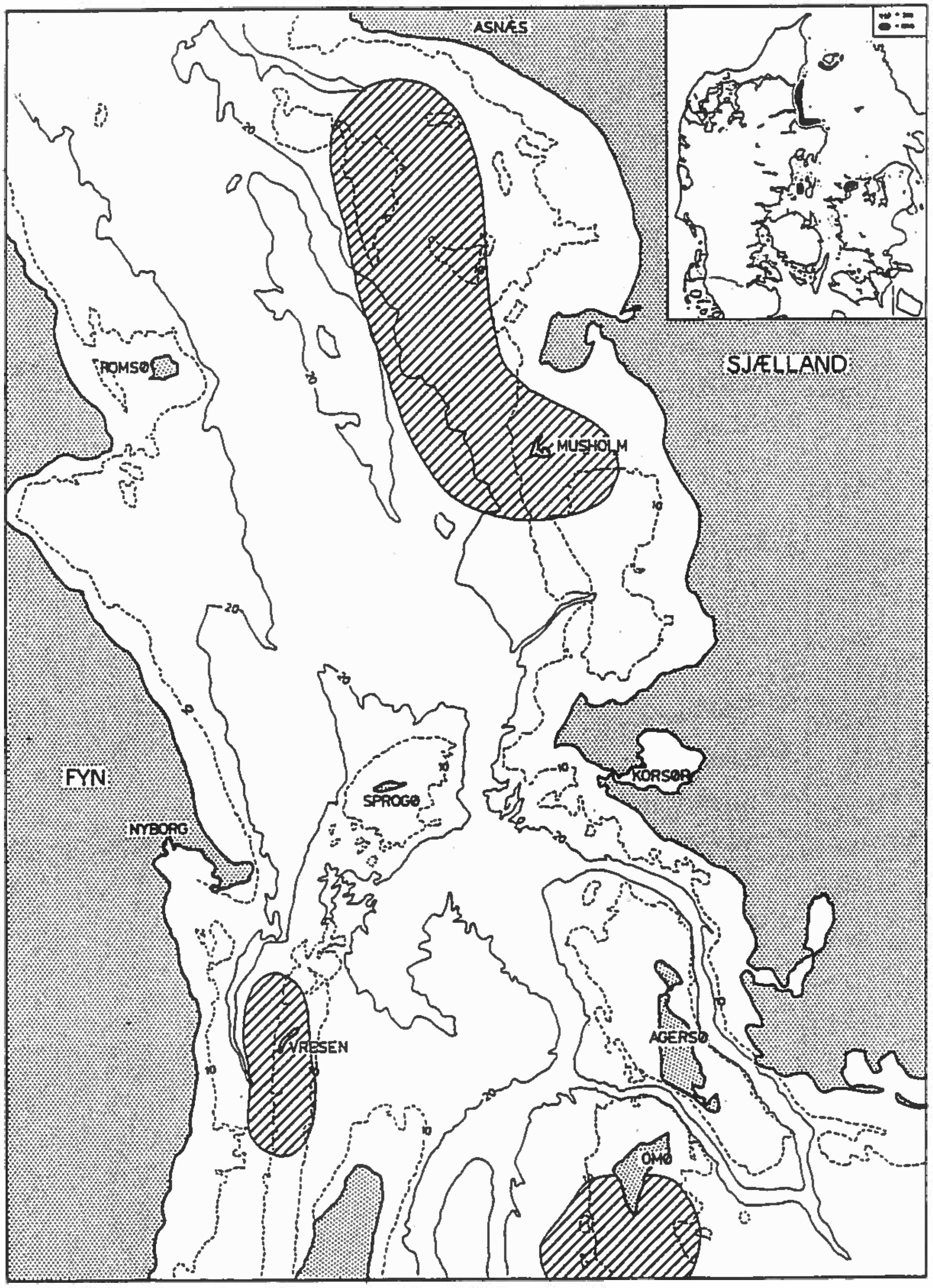


Figure 5.16 - The occurrence of wintering velvet scoters in the Great Belt from October to April (Ref. 8).

5.6 Oxygen Depletion Areas in the Great Belt

5.6.1 Introduction

Fish avoid oxygen concentrations of less than 4 mg/l. If the water becomes anoxic hydrogen sulphide is produced; the attached fauna begins to die, and the bottom will be overgrown by sulphur bacteria. In the autumn of 1981 oxygen depletion was observed for the first time in the open inner Danish waters. Since then, the conditions have deteriorated with still larger areas affected by oxygen depletion in autumn for still longer periods. It was not until 1984 that this general deterioration of the oxygen conditions spread to the Great Belt which had been favoured by a strong current.

5.6.2 Previous Investigations

Fyns amtskommune has investigated the oxygen conditions in the Great Belt for a longer period of years, and from 1984 the county has found areas with oxygen concentrations of less than 4 mg/l (Figures 5.17-5.20, Ref. 26). The results from the investigations from Vestsjællands amt (County of West Zealand) have not been available.

Since 1974 the NAEP's Marine Pollution Laboratory has measured the oxygen concentration in the Great Belt at a singular station between Sprogø and Halsskov. In the autumn of 1986 adverse oxygen conditions were seen for the first time, and the surveyance in the autumn of 1987 had the same result.

5.6.3 Field Investigations

During the video survey in November 1987 oxygen depletion was observed in the form of white coverings of sulphur bacteria at a large area at a depth of approximately 15 metres southeast of Halsskov Reef (Figure 5.21 PL XI). Fig. 5.21 shows the areas where collected bottom samples had a distinct smell of sulphur bacteria. During the video survey in April 1988 a minor area covered by sulphur bacteria was observed south of Sprogø at a depth of approximately 10 m.

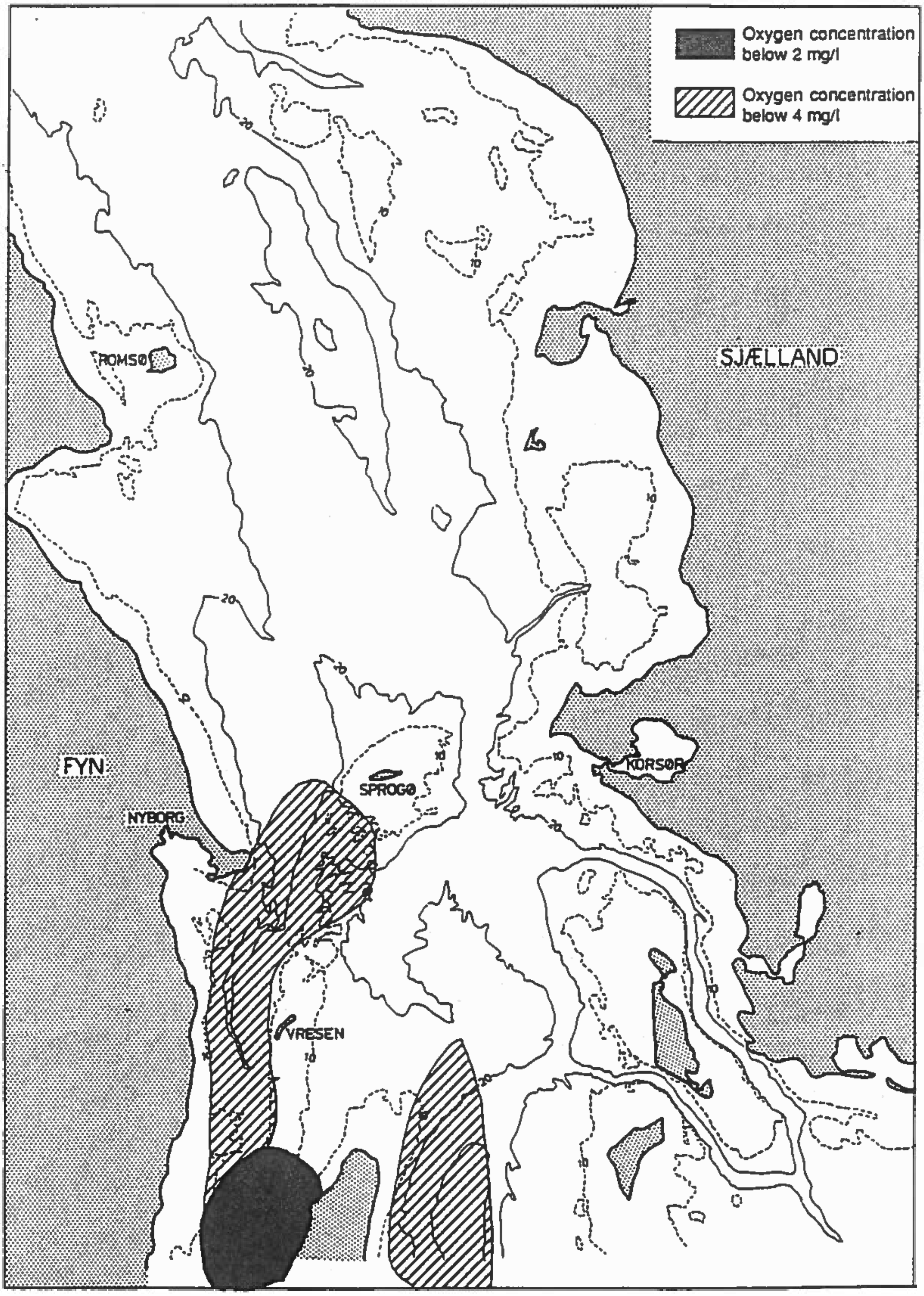


Figure 5.17 - Areas in the western part of the Great Belt with low oxygen concentrations in the bottom water in 1984.

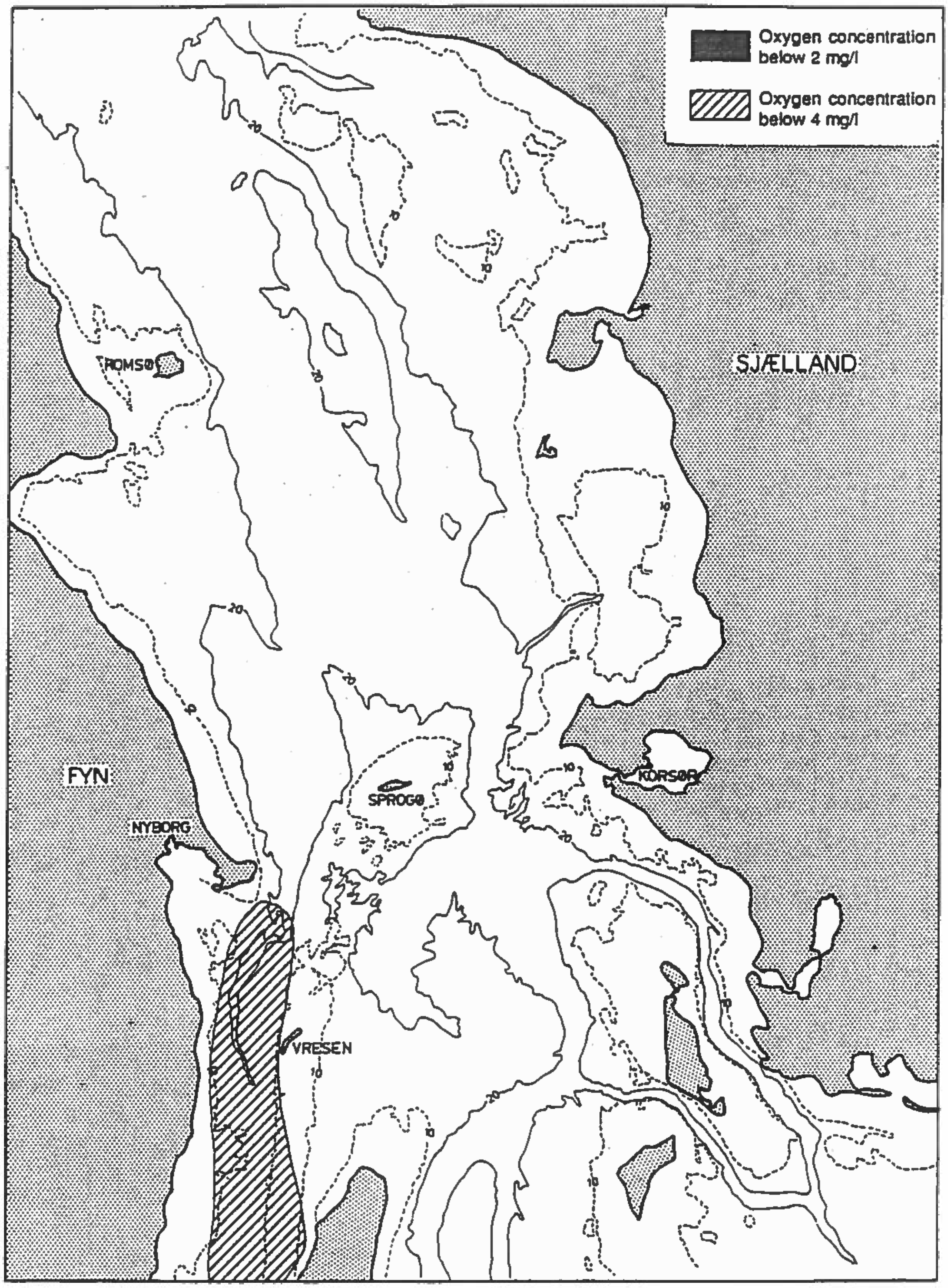


Figure 5.18 - Areas in the western part of the Great Belt with low oxygen concentrations in the bottom water in 1985.

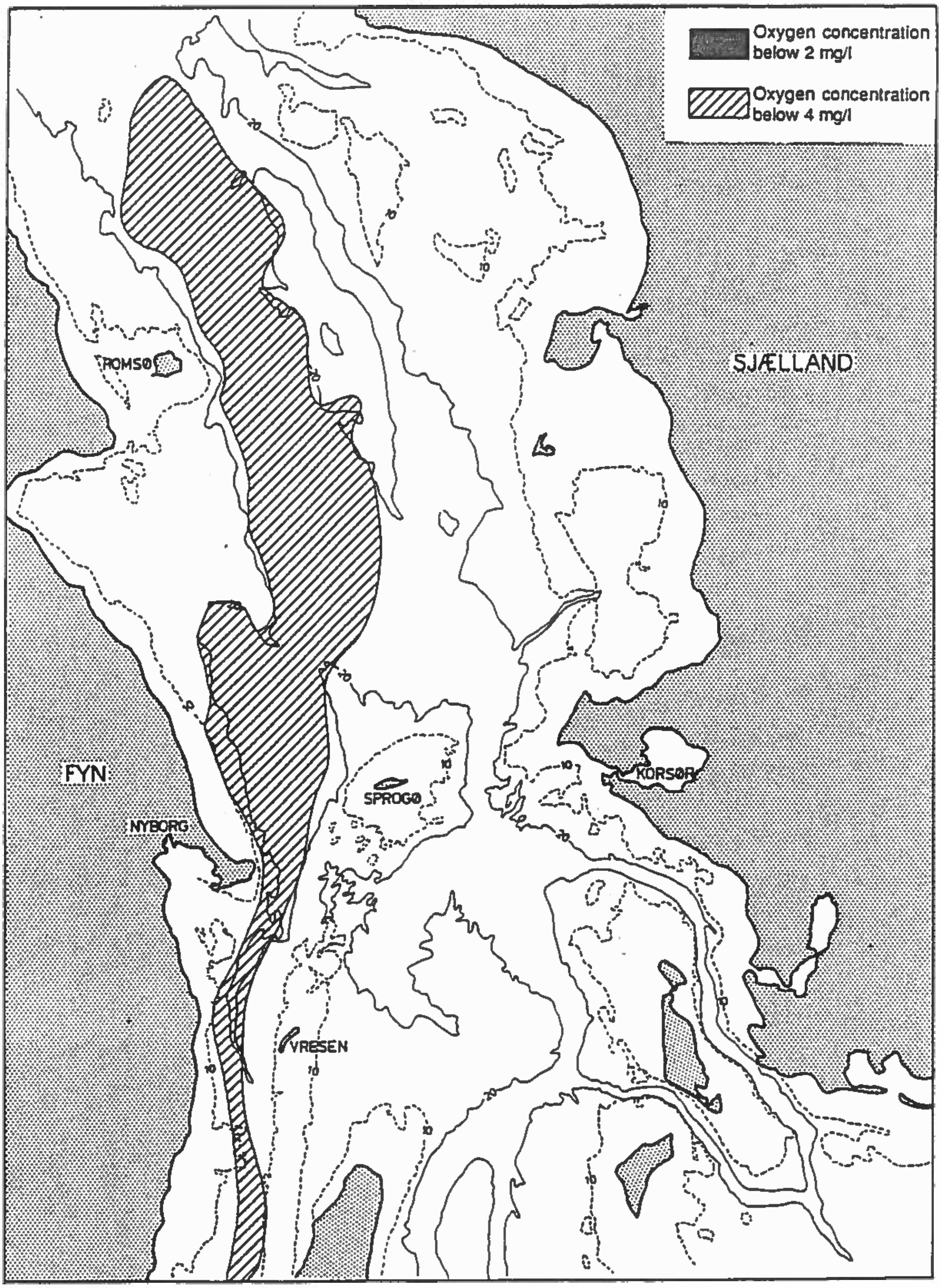


Figure 5.19 - Areas in the western part of the Great Belt with low oxygen concentrations in the bottom water in 1986.

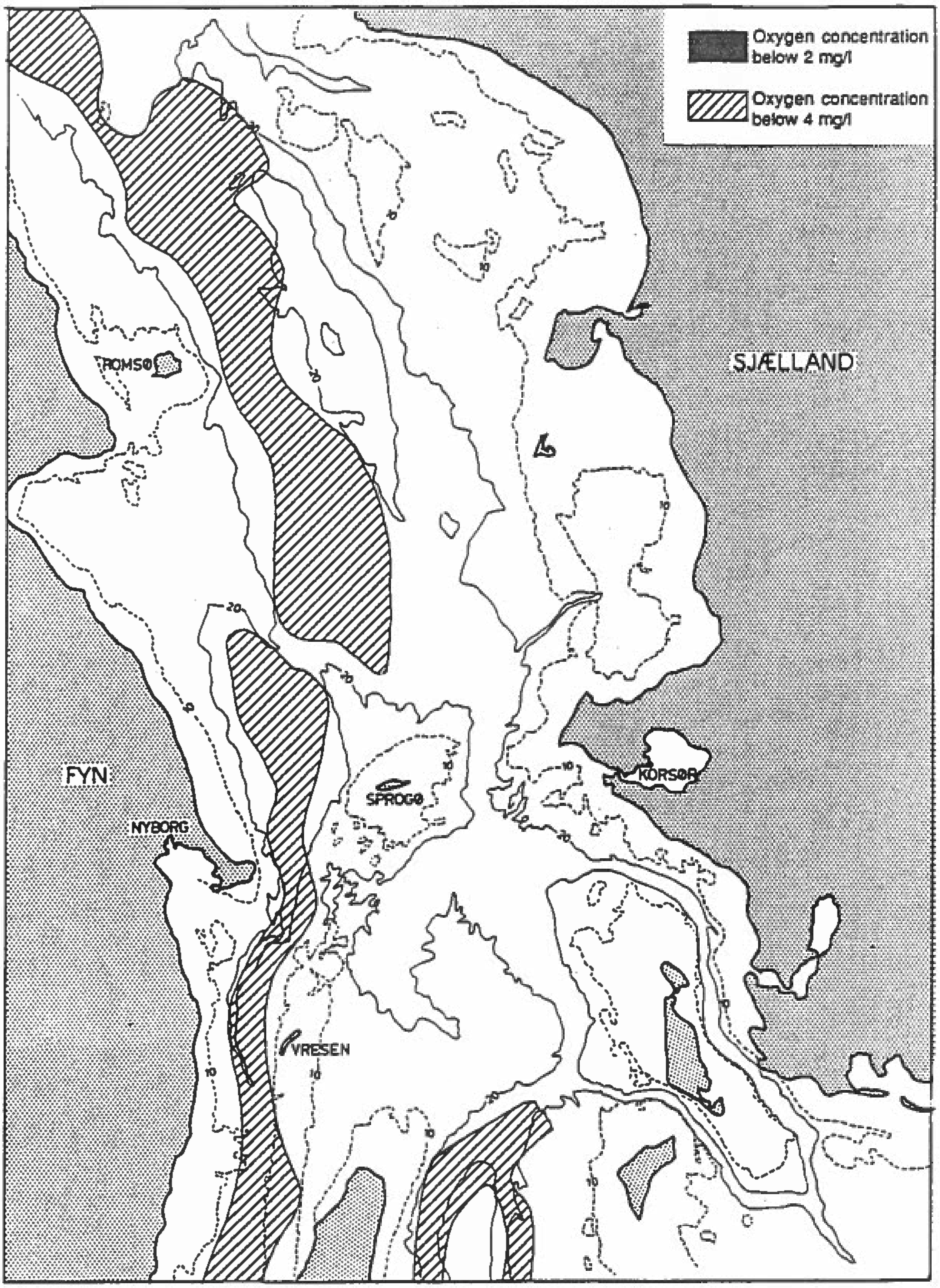


Figure 5.20 - Areas in the western part of the Great Belt with low oxygen concentrations in the bottom water in September 1986.

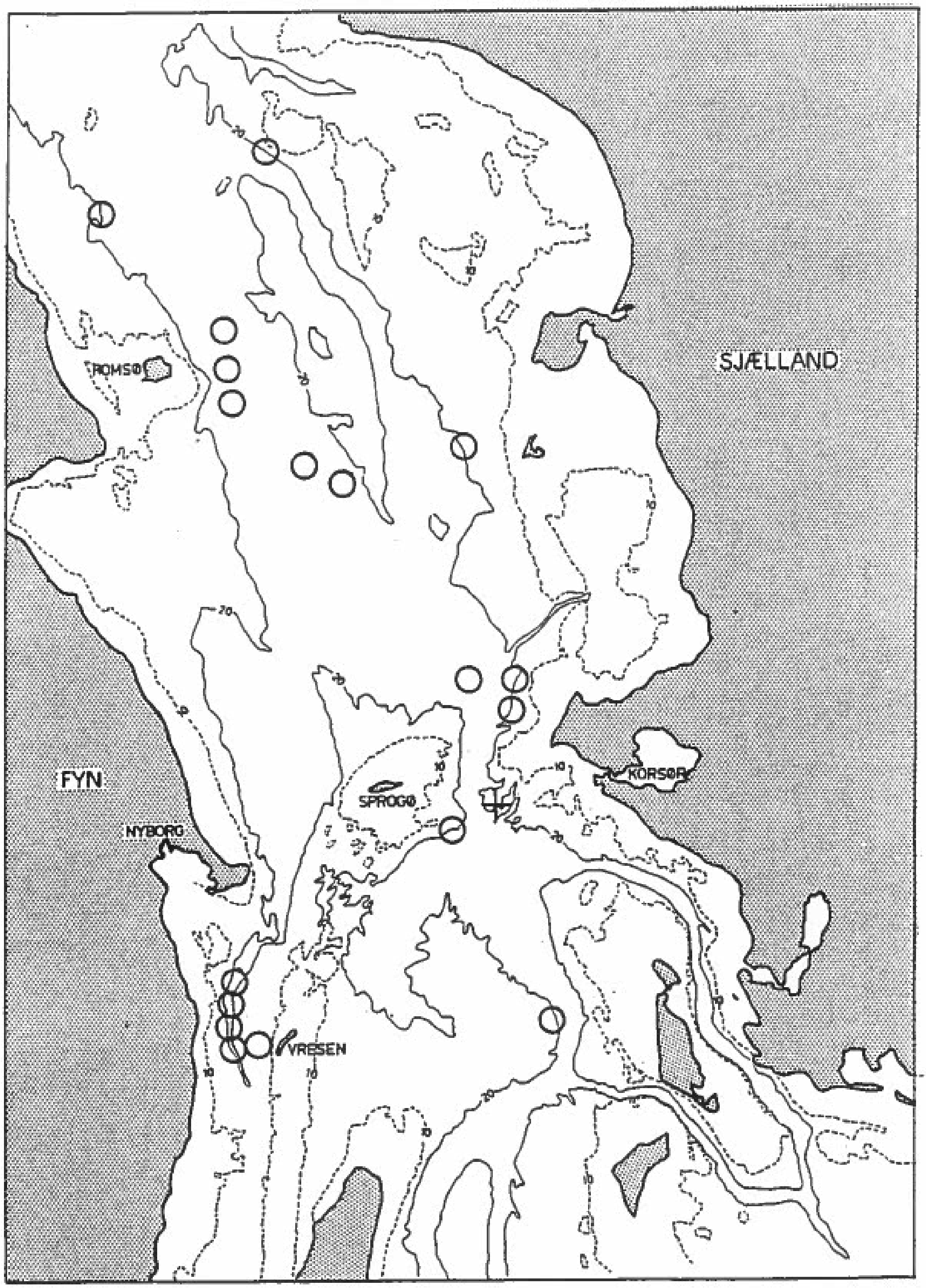


Figure 5.21 - Areas in the Great Belt where, [illegible], oxygen depletion in the form of white coverings of sulphur bacteria (+) were found during video survey in August 1987. Open circles state stations where bottom samples have a pronounced smell of hydrogen sulphide.

6. Impact Assessment

6.1 Scope of Assessment

6.1.1 Areas

This impact assessment addresses the environmental impact on the marine areas of the Great Belt (Figure 6.1) from the proposed civil works related to the tunnel/bridge project. Assessment of the impact on the Baltic Sea (including Langelands Sund) and the Kattegat is beyond the scope of this study.

The study areas are:

- the nearby environment, a 30 km wide area extending 15 km north and south of the link

- the more distant marine areas of the Great Belt where there might be an impact from dredging and dumping.

Special attention is given to the effects of the activities in nearby environment of the link alignment. Activities and effects in other areas of the Great Belt are discussed in more general terms because it has not yet been decided where to dredge and dump.

6.1.2 Activities and the Future Works

The assessment addresses the environmental impact in marine areas from all activities related to the construction and the future presence of the works and structures as described below. The analysis addresses the activities related to Phase 1 (Bridge over Vesterrenden and immersed or bored railway tunnel in Østerrenden) and Phase 2 (Road bridge or immersed road tunnel in Østerrenden).

The following activities and works are components of the array of alternative project designs. These will be studied:

- Construction of **embankments** at Knudshoved, Sprogø Vest, Sprogø Øst and at Halsskov
- Reclamation of an **artificial island** north of Sprogø
- **Compensation dredgings** at Sprogø Eastern Reef or Halsskov Reef.
- **Dredging for materials** at different locations in the Great Belt.
- **Dumping** of surplus dredged materials.

The impact from construction and the subsequent presence of the bridge pillars is felt to be temporary and minor and will not be given any further attention.

An array of alternative project designs have been analysed to demonstrate the likely spectrum from minimum to maximum environmental impact.

6.1.3 Effects

The impact assessment addresses all direct and indirect biological effects in the marine environment related to the said activities.

The studies of effects related to release of nutrients and to oxygen consuming substances are not yet complete and are therefore not included.

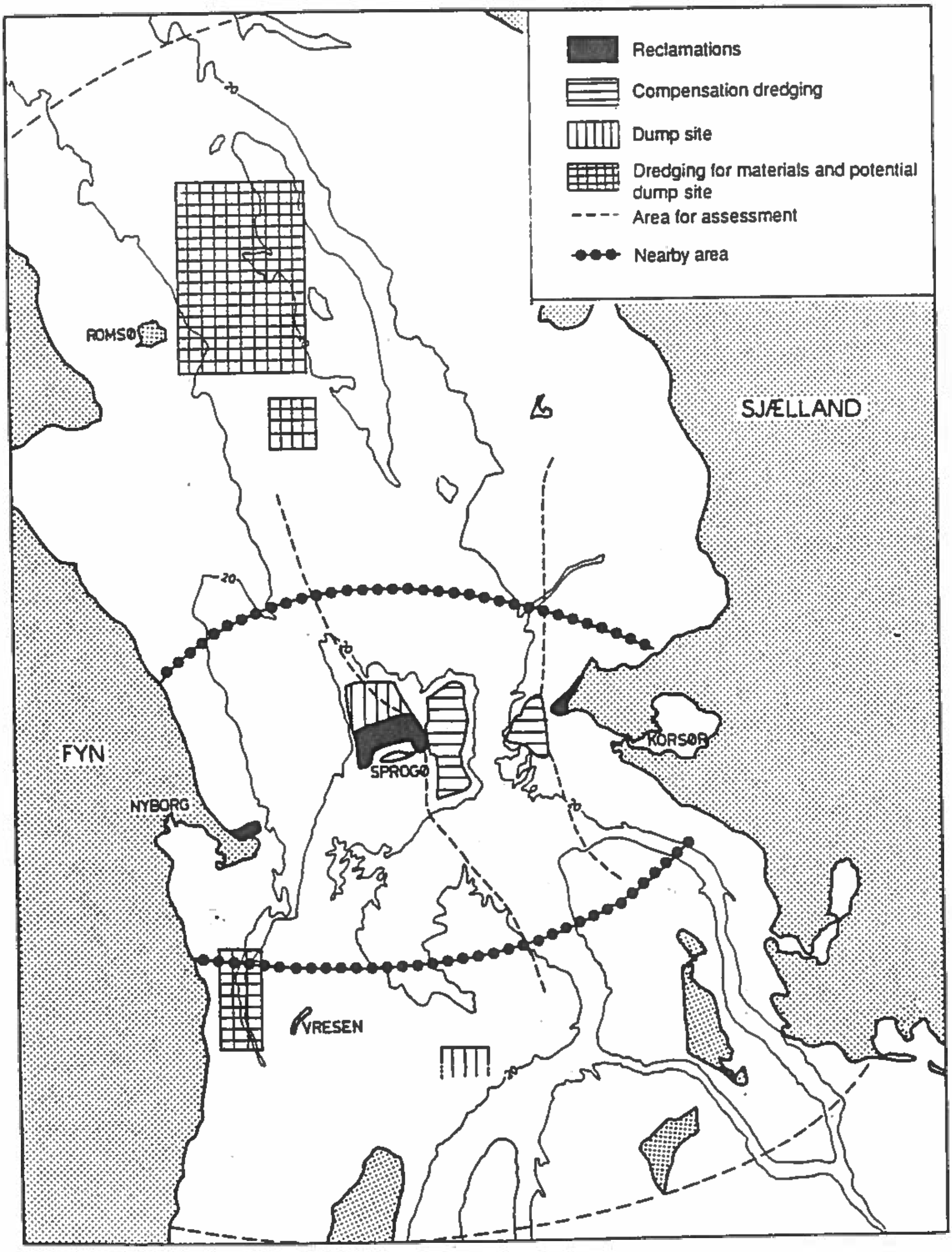


Figure 6.1 - Potential areas for activities and areas covered by this assessment.

6.1.4 Methods and Criteria

The environmental impact assessment is based on the mapping of the biological conditions in the Great Belt which is presented in the previous chapters.

The biological conditions which have been in focus in the mapping are those which *a priori* were known to be either sensitive to the planned activities or felt to be of high priority to be protected.

The assessment of impact is based on the general knowledge of impact from such activities as it is presented in the literature.

6.2 Assessment of Impact

6.2.1 General Description of Potential Effects of Planned Activities and Works

The activities or the subsequent presence of structures and civil works have the following potential effects:

- **Reclamation** will irreversably destroy marine habitats.

- **Dredging or dumping** will destroy the habitat. However, it may reestablish itself or be reestablished.

- **Reclaimed areas** will cause changes in local currents, which may alter marine life.

- **Reclamation, dredging or dumping** may imply the suspension of particles or release of nutrients and oxygen consuming substances in the water column. As a result bottom life may be affected by sedimentation of particles or by a decrease of the oxygen concentration in the bottom water.

Investigations (ref. 1) have shown, more specifically, that dredging operations may have adverse effects on:

- spawning grounds for bottom spawning fish;
- nursery areas for fish fry;
- feeding and resting area for bottom fish;
- reefs with unique flora and fauna, which therefore are of high priority to be protected;
- feeding are for waterfowls.

6.2.2. Potential Impact Areas

Figure 6.2 shows the areas of high priority to be protected in the Great Belt. The map is made on the basis of information described in the previous chapters.

Table 6.1 lists the descriptions of the biology of the areas of high priority.

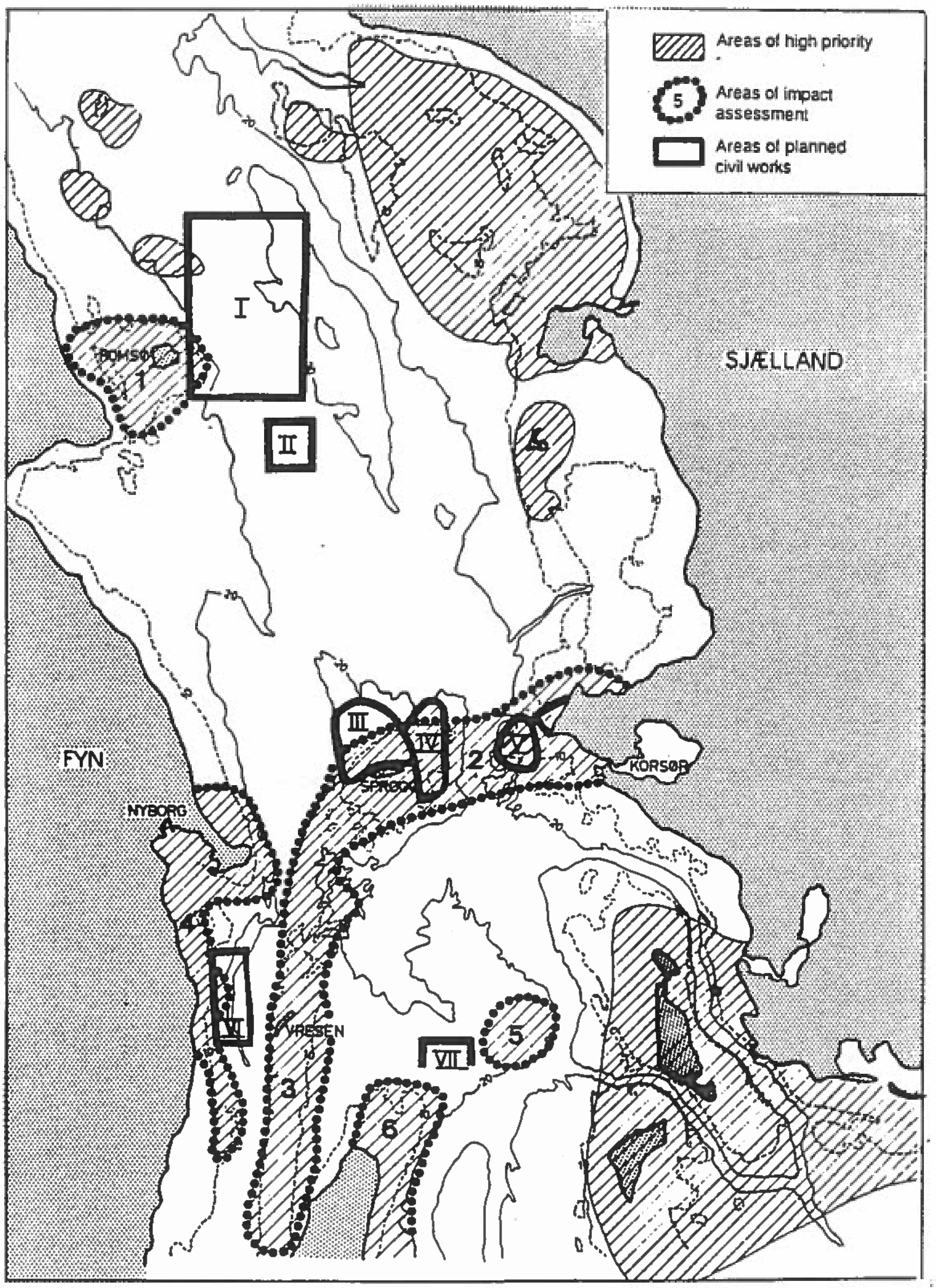


Figure 6.2 - Areas in the Great Belt with high ecological value (hatched). Areas without hatching are mainly sandy or muddy bottom. Areas with planned dredging and reclamation are also shown. (Area no. refers to the no. in Table 6.1.

Table 6.1 - Areas of high priority.

Area	Major biological interests
1. The waters around Romsø.	- Water area of international significance as haunt area for eider. It is also a haunt area for common scoter and moulting area for eider. Protected under the EEC Bird Directive. - Reef (With unique flora and fauna. Potential spawning ground for lumpsucker and nursery area for fry, including cod, lumpsucker and garfish). - Former spawning grounds for autumn-spawning herring (doubtful presence).
2. The waters around Sprogø and Halsskov Reef.	Halsskov Reef: - mussel beds - very important haunt area for eider Protected under the EEC Bird Directive. The area around Sprogø, generally: - very significant haunt area for eider and common scoter - moulting area for eider. Protected under the EEC Bird Directive. - spawning ground for spring-spawning herring. Sprogø Eastern Reef: - mussel beds - former spawning ground for autumn-spawning herrring (doubtful presence). North of Sprogø: - reefs and eel grass/Polysiphonia biotopes (unique flora and fauna. Potential spawning ground for lumpsucker and garfish and nursery area for fry; including cod, lumpsucker and garfish).

Area	Valuable biological interests
3. The waters around Vresen.	- Haunt area of international significance to eider. Important haunt area for common scoter. Moulting area for common scoter, velvet scoter and eider. Protected under the EEC Bird Directive. - Spawning grounds for spring-spawning herring. - Former spawning grounds for autumn-spawning herring (doubtful presence). - Reef (in particular flora and fauna. Potential spawning ground for lumpsucker and refuge area for fry including cod, lumpsucker and garfish).
4. Coastal waters at Nyborg	- Spawning ground for spring-spawning herring. - The area just outside Knudshoved former spawning ground for autumn-spawning herring (doubtful presence).
5. Northeast of Langeland	- Spawning ground for spring-spawning herring.
6. North and East of Langeland	- Spawning ground for spring-spawning herring. - Reef (unique flora and fauna. Potential spawning ground for lumpsucker and nursery area for fry, including cod, lumpsucker and garfish).

6.2.3 Impact on the Nearby Environment

Below is given an evaluation of the biological consequences of reclamation activities and compensation dredging along the alignment.

Project designs

Presently, about 40 alternative project designs are being studied. A selection of these will be discussed below with respect to their environmental impact to demonstrate the spectrum of impact from mimium to maximum.

Table 6.2 summarizes characteristics of the projects which cause to the environmental impact.

Directly affected areas

Table 6.3 gives the areas of biotopes of high priority which will be destroyed corresponding to each activity of the above-mentioned projects (see also figure 6.3).

The biotopes considered in Table 6.3 are in accordance with the biological mapping and the potential effects listed above:

- Eel grass/*Polysiphonia* biotope which has a unique flora and fauna and serves as important spawning and nursery grounds for several fish species.

- Mussel beds which constitute valuable forage areas for eiders and other diving ducks.

- Spawning grounds for spring-spawning herring around Sprogø and off Knudshoved which probably include stone reefs with a variety of biotopes, areas with pebble gravel, areas with less than 20% coverage of mussel beds, and areas with ell grass/*Polysiphonia*. (The last mentioned biotope is taken as a separate category).

- Stone reefs at Halsskov with *Delesseria*/-*Halichondria* or *Laminaria*/*Delesseria* biotopes (under the category 'other areas').

In Table 6.4 the areas have been summarized for each project and type of biotope.

Table 6.2 - Project characterization

Project variant:	Project A Basis Project	Project A Reduced cost	Project B Basis Project	Project B Reduced cost	Minimum (Impact) Project
Code:	A basis b	A 15.1. b	B basis b	B 15.1. b	AB 2.1. b
Link between Knudshoved and Sprogø	- concrete bridge	- concrete bridge	- composite bridge	- composite bridge	- composite bridge
Links between Sprogø and Halsskov	- immersed railway tunnel - immersed road tunnel	- immersed railway tunnel - immersed road tunnel	- bored railway tunnel - road bridge	- bored railway tunnel - road bridge	- bored railway tunnel - immersed road tunnel
Reclamation off Knudshoved	Area: 0.9 km^2	Area: 0.9 km^2	Area: 0.9 km^2	Area: 0.9 km^2	Area: 0.9 km^2
Reclamation to the north of Sprogø	- artificial island Length: 3,650 m Area: 1.5 km^2	- artificial island connected to Sprogø Length: 4,350 m Area: 1.3 km^2	- artificial island Length: 3,650 m Area: 1.6 km^2	- artificial island connected to Sprogø Length: 4,350 m Area: 1.1 km^2	Embankment to the east of Sprogø Length: 600 m Area: 0.8 km^2
Embankment off Halsskov	Length: 1,200 m Area: 0.7 km^2	Length: 1,200 m Area: 0.7 km^2	Length: 1,200 m Area: 0.5 km^2	Length: 1,200 m Area: 0.5 km^2	None
Compensation dredging	Place: Sprogø Eastern Reef Area: 2.2 km^2	Place: Halsskov Reef Area: 2.5 km^2	Place: Sprogø Eastern Reef Area: 3.1 km^2	Place: Halsskov Reef Area: 2.7 km^2	Place: Sprogø Eastern Reef Area: 0.7 km^2

Table 6.3 - Areas of eel grass/*Polysiphonia* biotopes, mussel beds, spawning grounds for herring that are estimated to be affected by the various dredging, dumping and reclamation activities.

Project variant	Direct effects				
	Eel grass/ *Polysiphonia* biotope km^2	Mussel beds[1)] km^2	Spawning grounds for herring[2)] km^2	Other areas[3)] km^2	Totally km^2
Basis Project A					
Reclamation, Knudshoved	-	-	0.9	-	0.9
Reclamation, Sprogø	0.7	0.6	0.2	-	1.5
Compensation dredgings, Sprogø Eastern Reef	-	1.3	0.9	-	2.2
Reclamation, Halsskov	-	0.6	-	0.1	0.7
Project A, Reduced cost					
Reclamation, Knudshoved	-	-	0.9	-	0.9
Reclamation, Sprogø	0.4	0.8	0.1	-	1.3
Compensation dredgings, Halsskov Reef	-	2.0	-	0.5[3)]	2.5
Reclamation, Halsskov	-	0.6	-	0.1	0.7
Basis Project B					
Reclamation, Knudshoved	-	-	0.9	-	0.9
Reclamation, Sprogø	0.7	0.5	0.4	-	1.6
Compensation dredgings, Sprogø Eastern Reef	-	1.3	1.8	-	3.1
Reclamation, Halsskov	-	0.4	-	0.1	0.5
Project B, Reduced cost					
Reclamation, Knudshoved	-	-	0.9	-	0.9
Reclamation, Sprogø	0.5	0.4	0.2	-	1.1
Compensation dredgings, Halsskov Reef	-	2.0	-	0.7[3)]	2.7
Reclamation, Halsskov	-	0.4	-	0.1	0.5

(to be continued)

Table 6.3 (cont'd)

	Direct effects				
Project variant	Eel grass/ *Polysiphonia* biotope km^2	Mussel beds 1) km^2	Spawning grounds for herring 2) km^2	Other areas 3) km^2	Totally km^2
Minimum Impact Project					
Reclamation, Knudshoved	-	-	0.9	-	0.9
Reclamation, Sprogø	0.3	0.3	0.2	-	0.8
Compensation dredgings, Sprogø Eastern Reef	-	0.4	0.3	-	0.7
Reclamation, Halskov	-	-	-	-	0.0

1) 20-100% of the bottom are covered by mussels

2) The eel grass/*Polysiphonia* biotope is also potential spawning grounds for herring. This biotope has been calculated separately.

3) With compensation dredgings at Halskov Reff, the remaining areas consist of reefs with *Delesseria*/*Halichondria*-biotopes and *Laminaria*/*Delesseria*-biotopes.

Table 6.4 - Areas of high protection value which are destroyed by the various dredging, dumping and reclamation activities.

	Direct effects				
Project variant	Eel grass/ *Polysiphonia* biotope km^2	Mussel beds 1) km^2	Spawning grounds for herring 2) km^2	Other areas 3) km^2	Totally km^2
Basis Project A	0.7	2.5	2.0	0.1	5.3
Project A, reduced cost	0.4	3.4	1.0	0.6 3)	5.4
Basis Project B	0.7	2.2	3.1	0.1	6.1
Project B, reduced cost	0.5	2.8	1.1	0.8 3)	5.2
Minimum Project	0.3	0.7	1.4	0.0	2.4

1), 2), and 3): See notes at Table 6.3.

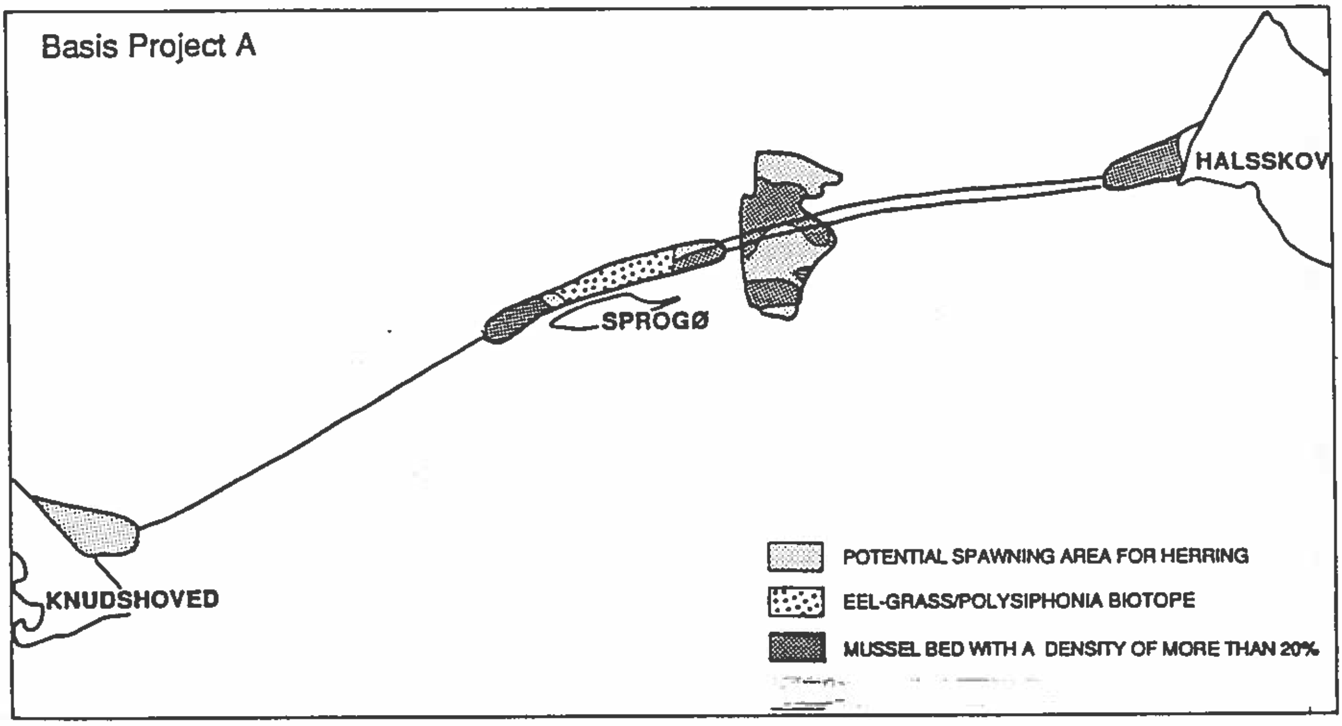


Figure 6.3.a - Basis Project A. Reclamation and compensation dredging areas.

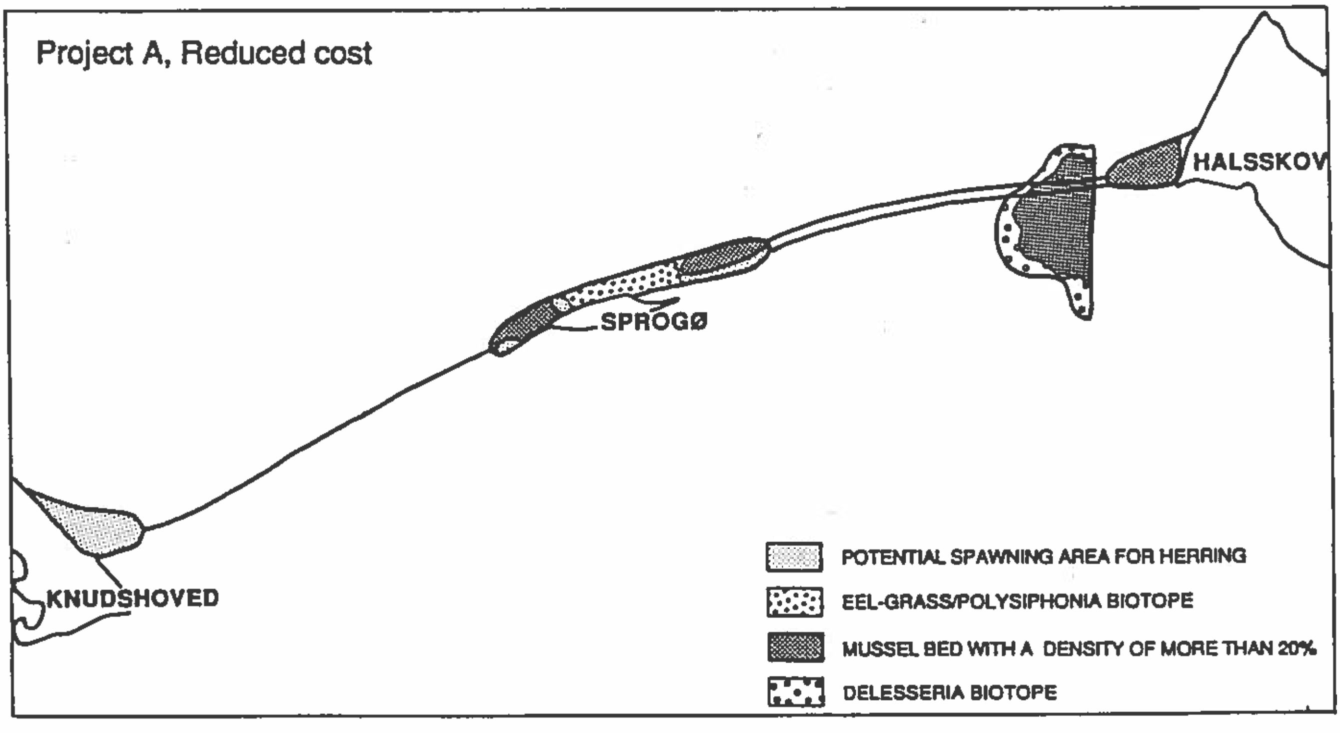


Figure 6.3.b - Project A, reduced cost. Reclamation and compensation dredging areas.

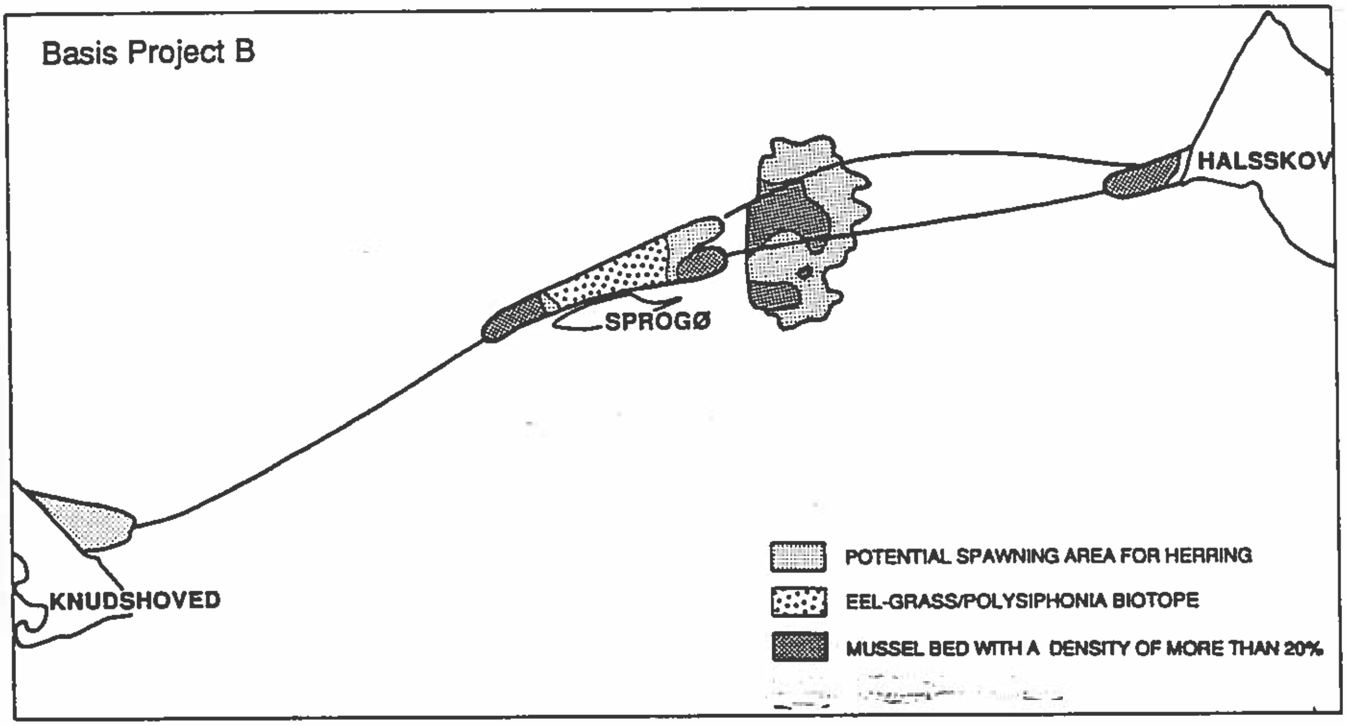


Figure 6.3.c - Basis Project B. Reclamation and compensation dredging areas.

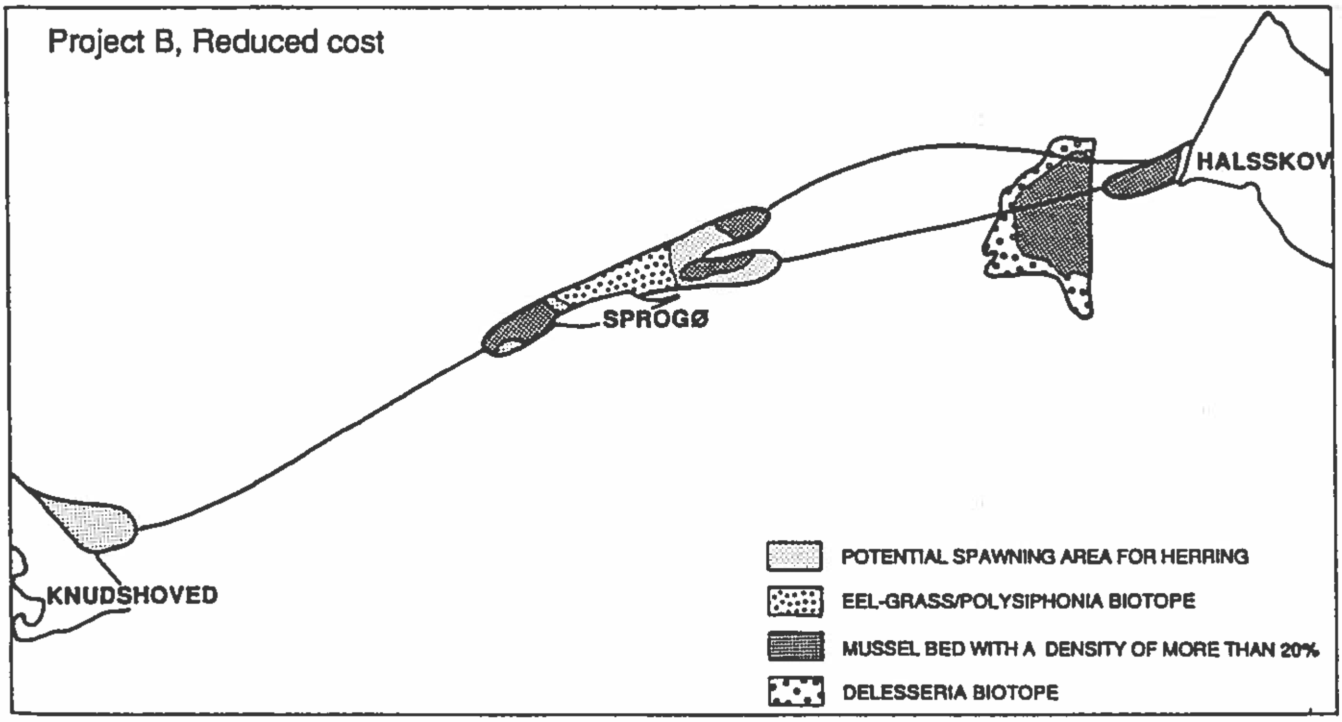


Figure 6.3.d - Project B, reduced cost. Reclamation and compensation dredging areas.

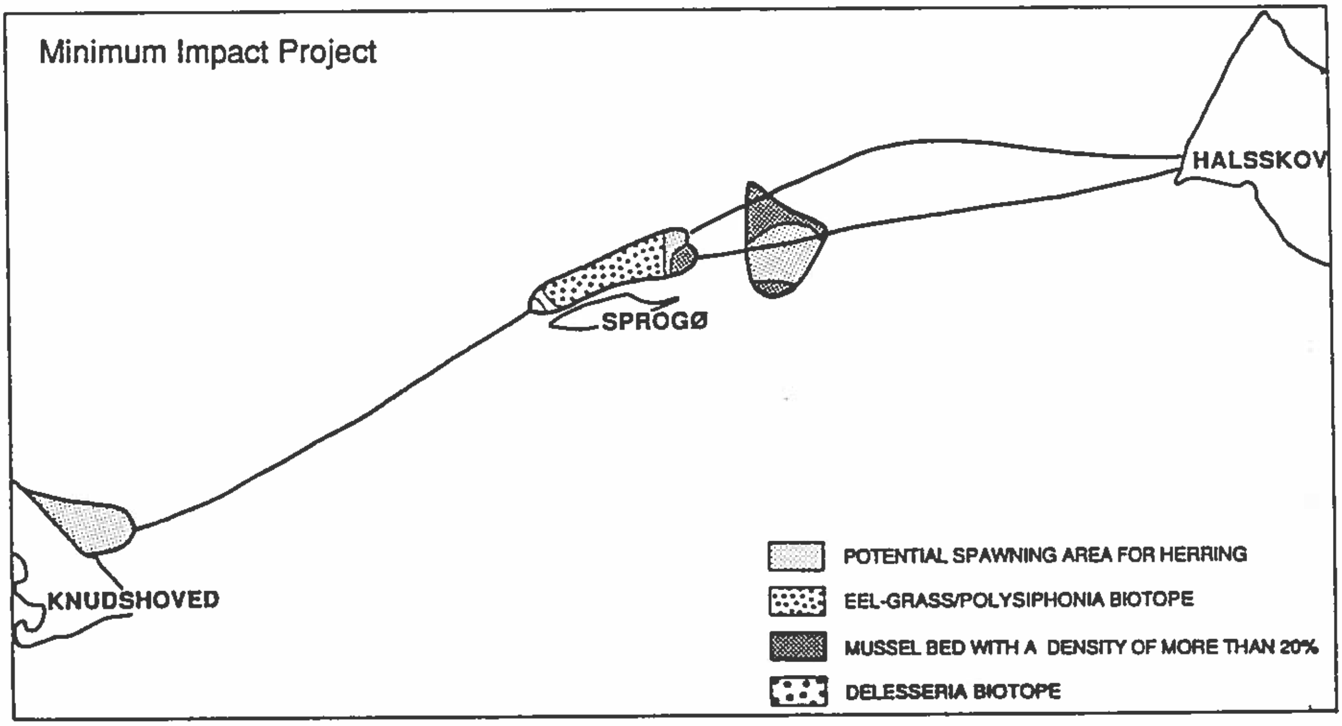


Figure 6.3.e - Minimum Impact Project. Reclamation and compensation dredging areas.

Relative importance of impact

Herring spawning area. Autumn-spawners have decreased considerably, and apparently they do not any longer spawn in the Great Belt. However, investigations of spawning of herring in the spring of 1988 support previous reports of spring-spawning around Sprogø.

The entire spring-spawning area in the Great Belt is about 150 km² of which 0.9-2.6 km² is expected to be ruined by the construction. This corresponds to a total of 1-2%. The impact area is reduced to 1.0 km² in the minimum impact project.

The potential spring-spawning area around Sprogø is estimated at approximately 27 km². In the basis projects an area of 1.1-2.2 km² or 4-8% of the spawning grounds will be ruined. Less than 1% of the spawning grounds will be ruined in the reduced cost projects. In the minimum impact project approximately 2% of the spawning grounds are Sprogø will be ruined.

Mussel beds and diving ducks. As mentioned above the area around Sprogø and Halsskov Reef is covered by the EEC Birds Directive due to the large amount of moulting and wintering diving ducks (especially eider, see Figures 5.11 and 5.12) feeding on the mussel beds in the area.

It is estimated that approximately 10% of wintering eiders in the Danish waters are wintering in the reef area around Sprogø and Halsskov. The number may be larger in periods of hard winters.

The embankments, the artificial island and the compensation dredgings will remove an area of mussels of 1.0-3.4 km^2 in the case of the the basis project and in the case of the reduced cost project. An area of 0.6-0.7 km^2 will be ruined in the minimum impact project. These areas comprise 8-23% and 4-5%, respectively, of the total area covered by mussels around Sprogø and at Halsskov Reef.

It is planned only to dredge to a maximum of 10 m which seems to be the depth limit for the extent of blue mussels in the Great Belt. Therefore, it may be possible that blue mussel banks may be reestablished in the dredged areas. Apparently, the optimum depth of mussels in the area is 5 to 7 m (cf. 5.2.1). However, dense mussel beds are found down to a depth of 8 m. Therefore, if compensation dredging is carried out to a maximum depth of 8 m, the mussel beds will probably be reestablished. Reestablishment of mussel beds is less likely, if compensation dredging is carried out at deeper levels than 8 m.

Indirect effects

As mentioned in Section 6.2.1 the planned activities may have the following indirect effects:

- spreading of sediments
- release of nutrients and oxygen consuming substances
- change of local currents

Spreading of sediments. It has been estimated that fine sediments (clay and silt) will be deposited in the amount of 0-2 mm (the uncertainty of the estimate is plus/minus a factor of 3 (ref. 27). Laboratory measurements of sinking rates are in progress. Preliminary results indicate sinking rates to be higher than anticipated in the above-mentioned calculations.

Effects of sedimentation of fine particles are difficult to quantify. It is anticipated that eel grass and herring spawning areas may be affected. Eel grass may be affected due to a shading effect of a possible sediment coating of the leaves, and herring spawning areas due to a change in the sediment texture which may be critical for the herring's selection of spawning grounds.

Release of nutrients and oxygen consuming substances. Laboratory measurements are underway which will lead to estimates of rates for release of nutrients and oxygen consuming substances. Based on these rates, a model will be established to describe the effects on nutrient load and oxygen levels.

Changes in current conditions. Reclamation areas may result in permanent changes in the currents in the surrounding areas. The reclamations primarily an effect the current shade related to north or south-going flow.

The ecological mapping has shown that both mussels and eel grass are found in the present current shadow of Sprogø. Changed local currents in consequence of the reclamations are therefore supposed not to affect these conditions. Spawning grounds of herring may be more sensitive to changes in flow conditions.

6.2.4 Impact in Other Areas of the Great Belt

Activities

In relation to the construction of the Great Belt link it has been planned to dredge for construction material and to dump surplus material from e.g. the compensation dredgings. The amount of materials to be dumped and dredged depend on which project will be selected. Figure 6.1 shows the potential locations for these activities.

Impact

The potential impact from the dredging and dumping activities has been described above. It is estimated that only activities in area no. VI close to Vresen and no. VII north of Langeland may have an impact on biological conditions of high priority, (i.e. the herring spawning grounds and the stone reefs) due to spreading of sediments.

A more detailed impact assessment can be performed when the volume of materials to be shifted and areas for dredging are known.

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A/S STOREBÆLTSFORBINDELSEN

ENVIRONMENTAL IMPACTS CAUSED BY DREDGING, RECLAMATION AND DISPOSAL OPERATIONS.

TOTAL IMPACT ASSESSMENTS, INCLUDING LEE EFFECTS AROUND SPROGØ

DATE	: March 9, 1990	
ISSUE	: 1, Preliminary	
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DHI/LIC REQUISITION : DLI033/1402 RKR,ID:9M9.3K, 900702

COWI/VKI REQUISITION: CVK 001/1043 RKR,ID:9M9.3L, 901301

Danish Hydraulic Institute - LICengineering A/S Joint Venture

in cooperation with

COWIconsult A/S - Water Quality Institute Joint Venture

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1. INTRODUCTION

The construction of the Fixed Link across Storebælt includes substantial earth works at sea. The earth works will inevitably result in spreading of suspended sediments, nutrients etc. to the surroundings.

A/S Storebæltsforbindelsen (SBF) has requested Danish Hydraulic Institute / LICengineering A/S Joint Venture (DHI/LIC) in cooperation with COWIconsult A/S / Water Quality Institute Joint Venture (COWI/VKI) to study the possible environmental effects of the marine earth work operations.

The present study does not include assessments of possible effects from cutting of the railway tunnel and future drainage water from the tunnel.

Two assessment reports for the marine earth work operations were prepared in early 1989:

- ENVIRONMENTAL IMPACTS CAUSED BY DREDGING OPERATIONS. Compensation Dredging and Dredging for Bridge Piers. January 1989 (Ref. 1)

- ENVIRONMENTAL IMPACTS CAUSED BY DREDGING OPERATIONS. Disposal Operations and Total Impact Assessments. Memorandum, February 7, 1989 (Ref. 20)

This report updates the two previous assessments.

The approach for the assessment of impacts is basically the same as in Ref. 1 and 20. For detailed description of the approach is therefore referred to Ref. 1.

In February 1989 the Expert Panel reviewed the two previous assessments and made a list of recommendations for improvements to the assessments (Ref. 41). The two consultant joint ventures have commented on the Expert Panel recommendations and have proposed additional studies. However, this updated assessment only includes a part of the Expert Panel recommendations.

The updated assessment is revised compared to the previous assessments due to:

- more specific information of planned and performed earth work operations,
- more information on spills for the individual operations gathered during surveys.

Further, this assessment also includes a preliminary assessment of the permanent current lee effects north and south of Sprogø due to the extension of Sprogø by ramps.

At the moment of this assessment (January 1990) the extension of Sprogø by ramps, the West Bridge part, the train crossing part of Østerrenden and the Phase 1 part of the compensation dredging (CD) are fixed. For the road crossing of Østerrenden a suspension bridge with a span of 1400 m has been assumed. Further, the Phase 2 part of the CD has been assumed to involve 4 mio. m^3 of moraine clay.

The assessments have been worked out in cooperation between DHI/LIC and COWI/VKI. DHI/LIC is responsible for the majority of the physical impact assessments, whereas COWI/VKI is responsible for the ecological impact assessments.

2. SUMMARY AND CONCLUSION

This updated study of the environmental impacts of the marine earth work activities for the Fixed Link across Storebælt is based on the available information up till January 1990 on relevant activities, spill specifications and ecological response of changed environmental conditions.

The study includes the following aspects of the marine earth work activities:

- Sediment spills:
  Amounts, plume concentrations of suspended sediments and areas affected by settling of suspended sediments.
- Nutrient release:
  Amounts and effects on macrovegetation and phytoplankton production.
- Oxygen conditions:
  Initial oxygen concentration reduction in the plume downstream operation, effect on sea bed oxygen consumption due to settling of suspended sediments and nutrient release, and effect on oxygen concentrations in the lower water layer of Storebælt.
- Release of other substances:
  Sulphide, heavy metals and other substances.
- Ecological impacts:
  Impacts on stone reefs, mussel beds, soft bottom communities, eelgrass beds and herring spawning grounds along the alignment of the Link.

Further, the study updates the extent of the expected erosion from the exposed moraine clay surfaces and the study gives a preliminary assessment of the current lee effects around the extended Sprogø.

A summary of the main findings of the study is given below.

Marine Earth Work Quantities

The Phase 1 of the marine earth works includes:

- the west bridge construction,
- the extension of Sprogø by ramps,
- construction harbours at Lindholm and Halsskov,
- the first part of the compensation dredging (CD).

Phase 1 of the marine earth works will include about 10 mio. m^3 of soil to be handled (Table 3.2). Up till the end of November 1989 about 5.5 mio. m^3 had been handled (Table 3.1).

Phase 2 of the marine earth works includes:

- the high bridge in Østerrenden,
- possible re-alignment of navigation Route-T,
- the second part of the CD.

About 5 mio. m^3 of mainly moraine clay is assumed dredged in Phase 2 (Table 3.3). Still, the Phase 2 volume is uncertain.

Phase 2 will result in an excess volume of moraine clay, which either has to be disposed on land, used for construction or dumped. A preliminary discussion of the environmental effects of the alternative disposals is given. It is recommended that further evaluation of dumping at Romsø SE or direct pumping of clay slurry into the lower layer of Østerrenden is accomplished.

Sediment Spills

Based on measurements from surveys in Storebælt in 1989 spill conditions for sediments and nutrients have been revised (Tables 4.1 - 4.3),

Based on these spill specifications the sediment volume brought into suspension during the marine earth work operations has been calculated. Till the end of November 1989 the sediment spill is estimated at 1.2 mio. m^3 (Table 5.1). Totally Phase 1 will result in 1.7 mio. m^3 of suspended sediments, which will spread and settle in Storebælt. In Phase 2 0.3-0.9 mio. m^3 is expected to be suspended, depending on the dredging/deposition method of the moraine clay (mechanical or cutter suction dredger).

The main part (about 64%) of the suspended sediments originates from sand extraction at Romsø SE. About 6% originates from dredging in the CD area.

The primary settling of suspended sediments is simulated by use of System 21. The primary settling will exceed 0.5 mm in an area of about 300 km^2 and 5 mm in an area of 46-65 km^2 (Table 5.2). The maximum potential settling thickness will be about 100 mm outside the dredging areas.

The final settling area after resuspension will be the natural sedimentation areas (soft bottom) of Storebælt (Fig. 5.3).

The maximum concentrations of suspended sediments will occur in the sediment plume downstream the operation (Fig. 5.8). In the area affected by the sediment plume the light penetration will be reduced due to attenuation by the suspended particles.

Nutrient Release

The nutrient release during the individual marine earth work activities will normally be in the range of 30-300 kg N/day and 1-25 kg P/day (Table 6.1). This corresponds to up till 30% of the summer discharge of N and P from Nyborg town+catchment area, or the emission of nitrogen from 1,900-19,000 persons.

During the short periods with soft sediment infilling in the basins at Sprogø the release by the overflow from the basins may reach 900 kg N/day and 270 kg P/day. When dredging in clay the release of nutrients is very limited, except for direct discharge of clay slurry dredged by a cutter suction dredger.

Totally, the release of nutrients during the marine earth work activities amounts to about 260 ton N and 29 ton P (Table 6.3), corresponding to in the order of ½ year's discharge from Nyborg town+catchment area.

The major part of the released nutrients will be incorporated into phytoplankton, but 25-30% will be incorporated into macrovegetation on the sea bed of the shallow areas near Sprogø, Halsskov and Knudshoved (Table 6.4).

Oxygen Conditions

Effects on oxygen concentrations in Storebælt due to the marine earth work activities may appear:

- in the plume downstream the operation location as a consequence of the initial oxygen consumption
- in general in the water body as a consequence of the increased sea bed oxygen consumption.

The plume reduction in oxygen concentration has been estimated for the major earth work activities (Table 7.2). The sand excavation at Romsø SE results in the largest potential initial reduction (less than 1 mg O_2/l for 90% of time). Most of the plume cases will only affect the upper water layer, where oxygen conditions normally are good. Downstream the plume will mix with unaffected water and the oxygen deficit will diminish.

Disposal of the excess moraine clay by discharging slurry in the lower layer below the interface may reduce the oxygen concentrations initially in the lower layer plume by less than 0.6 mg O_2/l for 90% of time.

The changes in the sea bed oxygen consumption affecting the general oxygen concentration of the water body have been evaluated based on the effect of:

- exposure of underlying sediments at the dredging location,
- settling of suspended sediments from earth work activities,
- release of nutrients.

Laboratory experiments have shown that exposure of underlying sea bed on the dredging location does not increase the sea bed oxygen consumption, and therefore does not contribute to lower oxygen concentrations. The major part of the dredging area is situated in the upper layer.

The effect of settling of suspended sediments has been estimated on the basis of a conservative interpretation of laboratory experiments on the effect of superposing new sediments. Six major dredging activities have been studied (Fig. 7.5). The most affecting activities increase the background sea bed oxygen consumption about 35-70% close to the activity. 10% increase in the background consumption will affect areas of about 2-32 km^2 for the individual activities (Table 7.3).

Release of nutrients will affect the shallow areas around Sprogø, Halsskov and Knudshoved by increasing production of macrovegetation. During autumn the degrading biomass will increase the oxygen demand (Table 7.5). However, as these areas are situated in the upper layer of Storebælt the effects on oxygen concentrations is expected to be non-significant. The increase in sea bed oxygen consumption in the lower layer due to increased plankton production which eventually settles will be up till 1% of the background consumption.

The effect of the above mentioned changes in sea bed consumption on the oxygen concentrations in the lower water layer have been estimated, based on conservative assumptions:

- During flowing conditions the reduction in the oxygen concentration will at maximum reach 0.1 mg O_2/l.
- During stagnant condition for 40 hours the reduction in oxygen concentration will be at maximum 0.4 mg O_2/l for dumping of moraine clay, more for discharge of a clay slurry and less for the other dredging activities affecting the lower layer.

This reduction may be compared to the recorded oxygen concentrations at 30-35 m depth at Halsskov Rev (Fig. 7.2), which have a minimum of 1.9 mg O_2/l in 1987.

All together, effects from earth work activities on oxygen concentrations in the free water is only expected to be detectable during large operations which coincide with nearly stagnant conditions in Storebælt. Further, potential ecological impacts of reduced oxygen concentrations are limited to the period July-October, where the oxygen concentrations in general are low (see comments on ecological impacts below).

For the disposal alternative of discharging clay slurry, the simple analyses used so far indicate a potential of critical impact on oxygen conditions in the lower layer. As the present analysis is based on conservative assumptions, it is recommended to perform a more detailed analysis of the activity before the clay slurry alternative is selected.

Release of Other Substances

Free hydrogen sulphide (H_2S) in concentrations in the order of 0.09-0.4 mg/l may occur in the plume downstream dredging when dredging in mussel beds. In other dredging materials the concentration will be at least one order of magnitude less. Short exposure to the expected concentrations are not critical to fish.

Release of heavy metals is expected to be low and without significant effects on marine life, as the concentrations in the dredged materials are low and unaffected by human sources (Appendix B). Further, potential release processes are slow relative to the time of residence of a sediment particle in suspension and the dilution is high.

In the dredging areas there are no indications of disposed solid waste or other matter of any important kind that may spread during the activities.

Lee Effects Around Sprogø

Lee effects around Sprogø have been analyzed based on preliminary hydrodynamic current simulations for the reference condition and for an extended Sprogø by ramps. The simulations (Fig. 9.1 and 9.2) show a reduced mean current in the area within up till 1000 m from the new coastline of Sprogø and in a narrow area where the top of the Sprogø Østrev has been removed. North and south of the CD area the current speed will increase up to 35%. The ecological effects of the current changes are assessed below.

1989 Results of the Biological Monitoring Programme

In addition to the emission monitoring of the sediment and nutrient plumes which form the basis of the previous load assessments, 'key biological and feedback' monitoring of the effect of the earth works on important ecological elements in Storebælt has been initiated in 1989.

On the basis of the programme which has run soforth some questions may be answered with a high degree of certainty, i.e.:

> Will the permanent and temporary destruction of the mussel beds affect the population of wintering eider ducks around Sprogø?
>
> > As it has been shown that:
> >
> > - the biomass of mussels is totally turned over (consumed and lost at spawning) during one year, indicating that the population of eiders is limited by the food supply, and
> > - no alternative feeding possibilities are likely to exist close to Sprogø, except at greater depths southwest of Sprogø
> >
> > the reply to this question is in the affirmative.
>
> How large is the amount of mussels which will be permanently destructed by the reclamation and compensation dredging?
>
> > Mussel bed mapping has shown that the destruction is equivalent to the food supply for approximately 8000 wintering eider ducks.

As the monitoring programme has only run for a short period, and because many activities have not yet been initiated, some questions may only be answered with some uncertainty, i.e.:

> Has the emission of nutrients from the dredging and land fill activities contributed to phytoplankton blooms in 1989?
>
> > The monitoring of the emissions compared with the information obtained from other monitoring programmes in the Great Belt indicate an affirmative reply.
>
> Will increased sedimentation lead to reduced growth rates of mussels?

The first investigation of mussel growth indicates that this is not the case as to the effect of the sediment in the bottom near water layer. A video inspection at few selected stations did not indicate strong effect on the mussels. However, sediment trap inspections showed large sedimentated layers which will bury the mussels and may hamper their growth. More investigations are needed to anser this question.

Do increased concentrations of phytoplankton or decreased concentrations of oxygen occur in the sediment plume?

No indications of such effects have been found, but plume tracing in connection with sand dredging has not been sufficiently covered to fully answer this question.

For the same reasons as mentioned above, some questions with respect to environmental effects may only be replied <u>very uncertainly</u>, i.e.:

Have the activities led to a decrease in the population of wintering eiders in Storebælt?

Countings from airplane showed a decrease in the number of eiders in Storebælt in December 1989 compared to November 1989 as well as December 1988. More than one counting is needed to give an affirmative answer to the question.

Two questions about vegetation have been raised: Will increased sedimentation lead to reduction in kelp (Laminaria) growth and will an increase of epiphytic growth on the kelp occur?

Video inspection showed that at the day of observation no sediment cover on the macroalgae, and no drastic change in the epiphytic cover or the macroalgal composition could be observed. However, as other observations have shown occasional substantial sedimentation, more measurements are needed before this question can be replied.

A series of questions implied in the description of the Biologial Monitoring Programme can still not be answered, either because too few observations have been made or because the relevant monitoring has not yet been initiated. These questions are addressed in the annual report of the Biological Monitoring Programme (Ref. 46).

Ecological Impacts

In general, the impact area of the earth work activities has been defined by 0.5 mm increase in primary sedimentation. The major part of the defined impact area of 300-350 km^2 for Phase 1+2 is soft bottom (Table 10.1). Other areas affected are herring spawning grounds, stone reefs, mussel beds and eelgrass beds (Figs. 10.1-10.4).

For the total Phase 1+2 activities the following short-term effects are stated:

- Nutrient release may accelerate algal blooms. Further, released nutrients may contribute to the general phytoplankton production by about 1% for an area in the order of 350 km^2.

- Shading from the sediment plume will not have any significant effect on phytoplankton growth.

- No ecological effects due to the minor changes in oxygen conditions are expected in the upper or lower water layers.

- The composition of the soft bottom fauna may change locally due to sedimentation and resuspension of unconsolidated sediment. However, any such effects are expected to be of short duration only.

- Heavily affected areas of the soft bottom will tend to show an increased risk or frequency of anoxic conditions at the sediment surface. If oxygen deficiency occurs, the ecological effect will be changes in the bottom fauna as tolerant or opportunistic species are favoured. Such changes may favour dab on the expense of plaice.

- 20% of the herring spawning grounds in Storebælt is influenced by the operations. Changes in the sediment composition of the spawning grounds may cause herring to abandon the spawning grounds around Sprogø, temporarily or permanently. However, surveys in 1989 showed a rapid resuspension of settled sediments. Due to other spawning areas in Storebælt, total destruction of eggs deposited around Sprogø is not expected to affect significantly the standing stock of herring in Storebælt.

- The stone reefs have been considered potentially vulnerable areas with respect to sedimentation of fine particles. However, the surveys have shown that down to depths of about 15 m the settled sediments will resuspend. Therefore, for the shallow areas the most important factor for impacts on the reefs is the shading and the nutrient release. These impacts will favour annual species on the expense of perennial species. Detectable effects are not expected around Halsskov and Knudshoved due to the limited period of construction activities.

- The vegetation on the stone reefs north of Sprogø are expected to show a reduced production in the order of 10% due to shading effects during the working period.

- The eelgrass beds around Sprogø are fully enclosed in the impact area. The release of nutrients will increase the total production in the eelgrass beds (Table 10.2), but reduce the growth of the eelgrass due to shading effects from epiphytes and bottom-living macroalgae. Shading of the eelgrass beds by the sediment content of the plume is not expected to have severe effects as each part of the area is expected to be affected by the shading less than 5% of the time. Further, eelgras beds have a good ability to recover.

- The mussel beds are not expected to be affected by the changes in the oxygen conditions, as the mussels are situated above the interface with high reairation.
- It cannot be excluded that the destruction of mussel beds due to compensation dredging and reclamation will reduce the number of feeding wintering eiders in the waters around Sprogø.

- A major part of the mussel beds is situated in the lee area (5-15% reduced current speed). This may reduce the mussel beds as feeding depend on the water exchange, but the magnitude of reduction is not known.

The <u>long-term effects</u>, which can be observed 10 years or more after the completion of the marine earth work activities, are foreseen to be restricted to:

- Possible reduction of the area of herring spawning grounds around Sprogø.

- Increase in the area of eelgrass beds due to lee effects around Sprogø.

- Incomplete recovery of perennial species of algae at stone reefs and eelgrass beds (epiphyte reduction).

- Possible decrease in population size of wintering eiders and other diving ducks which feed on mussels.

It should be noted that some of the long-term effects will be difficult to distinguish from a regional development due to the land-based nutrient load as well as other human activities such as traffic, fishing and hunting.

Erosion

After end of the construction period erosion of the new, exposed moraine clay surfaces in the CD area, the Route-T re-alignment, the shaping reefs at the anchor blocks and at the dumping site is expected to persist until the surface develops a sand and gravel protection against erosion. The erosion will take place during storm events, probably lasting for several years, when the material will be suspended.
The erosion volume is estimated at about 0.8 mio. m^3 totally during a period of several years. For comparison, the total erosion volume corresponds to 30-40% of the total suspension volume from the marine earth work activities, which takes place during a 5-6 years period.

3. LINK LAYOUT

3.1 Description of Link Layout

The Fixed Link across Storebælt is constructed in two main phases:

Phase 1 (1988-1993)

- Land fill north of Knudshoved Harbour
- Low bridge for railway and road in Vesterrenden
- Extension of Sprogø by ramps to the east and west
- Bored railway tunnel in Østerrenden
- Part 1 of compensation dredging (late and post-glacial deposits)
- Construction harbours at Lindholm and Halsskov.

Phase 2 (1991-1996)

- High bridge for road traffic in Østerrenden
- Part 2 of compensation dredging (moraine clay) including deposition of surplus material
- Re-alignment of Navigation Route-T (not finally decided)

At present all contracts for Phase 1 are fixed.

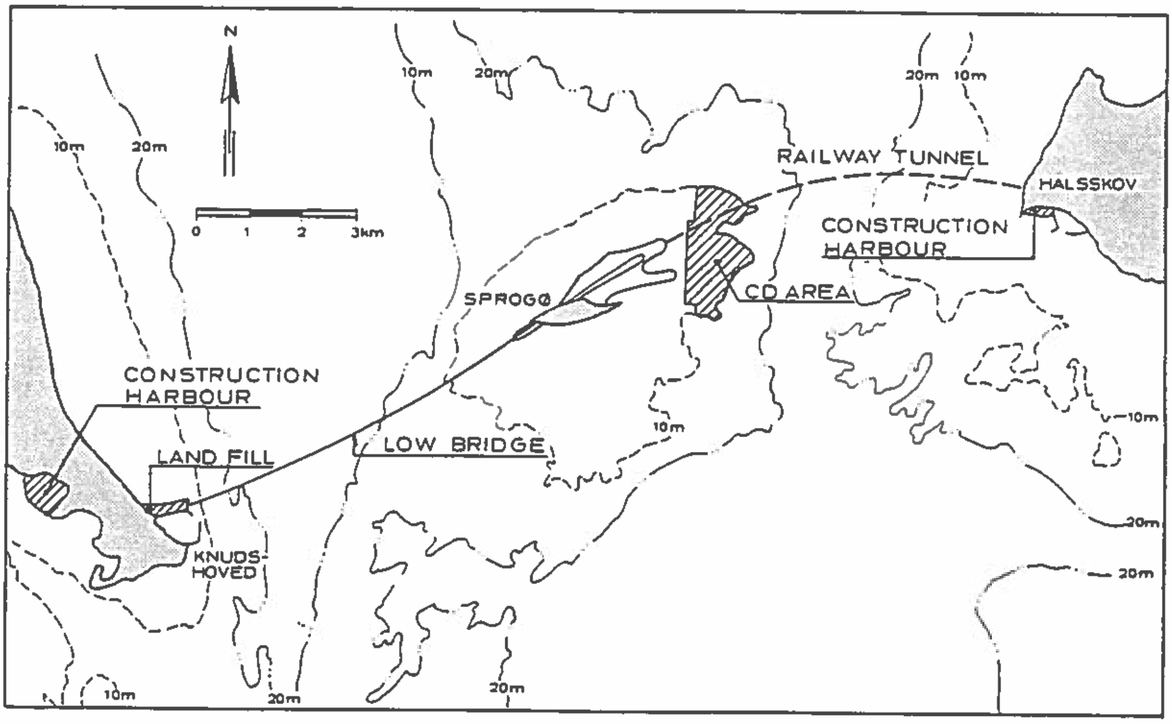


Fig. 3.1 Construction activities along the Link alignment in Phase 1.

The land fill north of Knudshoved Harbour ends at the tip of the northern harbour breakwater, see Fig. 3.1. The low bridge in Vesterrenden will be a concrete bridge. The extension of Sprogø includes a 400 m western ramp and two ramps to the east (reaching about 1100 m further east than Sprogø). The bored railway will be between the extended Sprogø and Halsskov (inland), and will not affect the current cross section in Østerrenden. Part 1 of the CD (compensation dredging) will mainly take place at Sprogø Østrev (east reef) but a minor CD will also take place at Sprogø Vestrev (west reef) in combination with dredging of an construction phase access channel to the western ramp of Sprogø. Part 1 of the CD totally includes about 3.1 mio. m^3 according to information received from SBF.

For the reclamation in Phase 1 sand is being taken from 4 resource areas off the Link alignment: Romsø, Romsø SE, Slettings Grund and Musholm, see Fig. 3.2. These extraction activities are included in the present assessments as well.

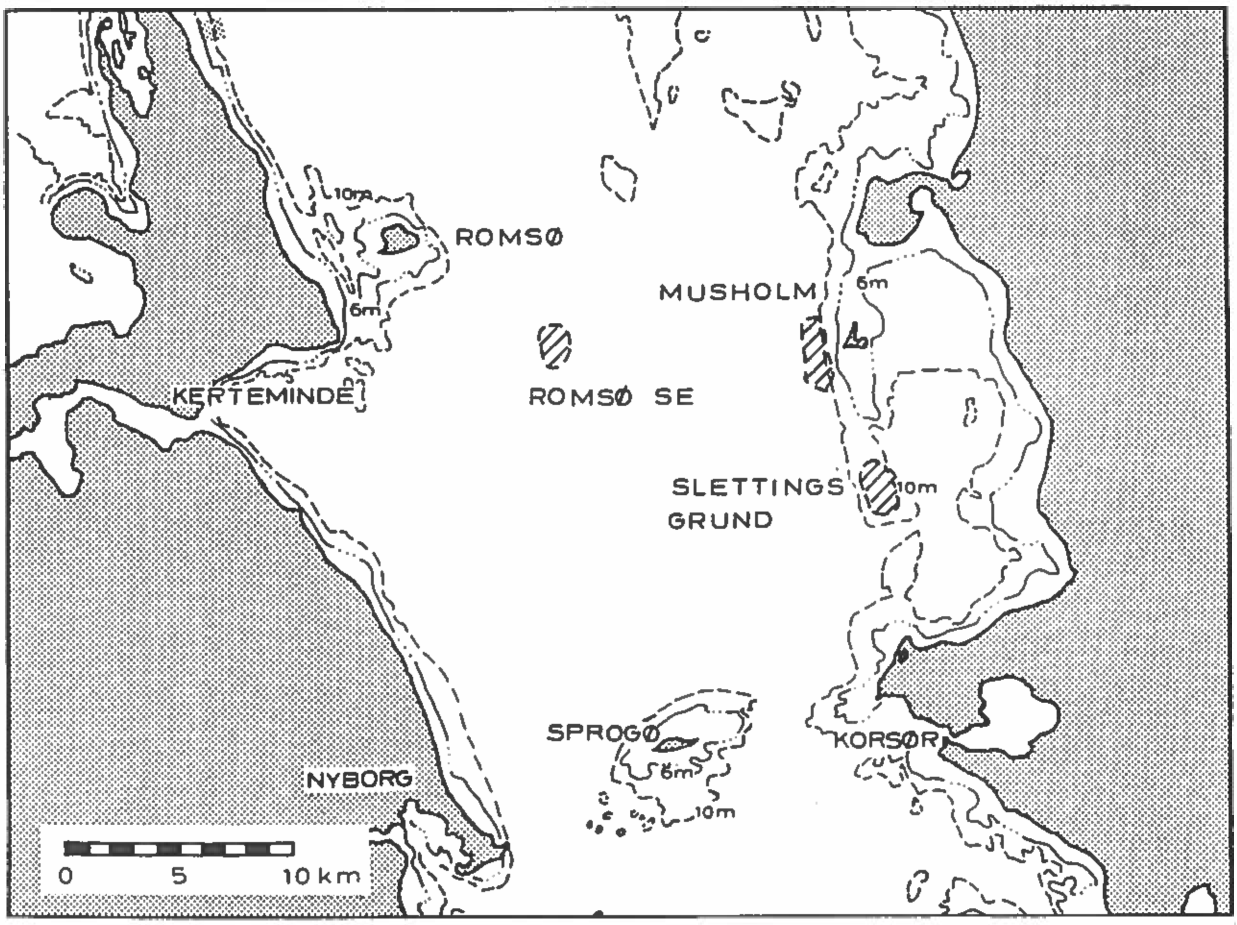


Fig. 3.2 Sand resource areas off Link alignment used in Phase 1.

Phase 2 has not yet been determined in details. For this updating of the assessment of marine impacts the following has been assumed, see Fig. 3.3:

- The high bridge in Østerrenden is a suspension bridge with a 1400 m wide navigation span and concrete approach spans (S1400).
- The part 2 of the CD involves 4 mio. m^3 of moraine clay dredged at Sprogø Østrev.
- Re-alignment of Route-T involves dredging of 0.6 mio m^3 moraine clay.
- Moraine clay is used as shaping reefs at the anchor blocks.
- The surplus moraine clay (about 4.3 mio. m^3) is dumped northwest of Sprogø at 15-20 m water depth (see Section 3.3).

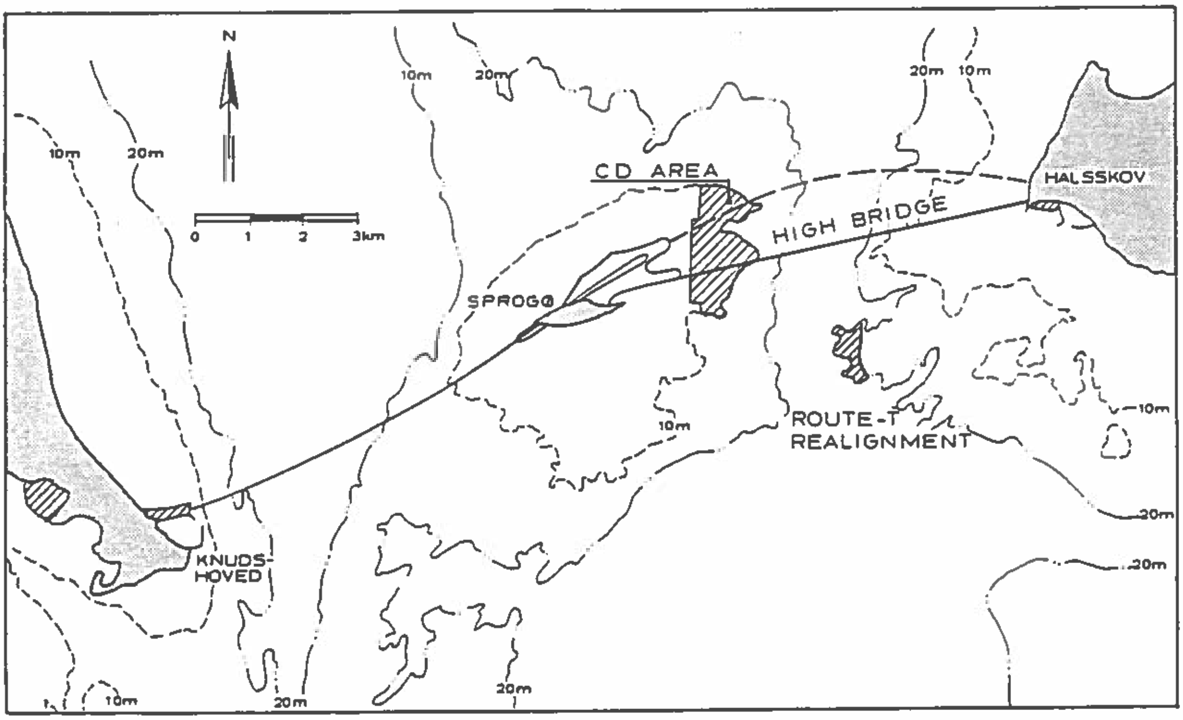


Fig. 3.3 Marine construction activities in Phase 2.

3.2 Dredging and Deposition Quantities

The dredging and deposition quantities in general involves the following types of material:

Sand : Extracted for reclamation (construction purpose and CD)

Soft bottom : Exchange of sea bed due to construction aspects or dredging as CD. Deposited in basins at Sprogø

Moraine clay: Dredged as CD and Route-T re-alignment

Marl : From boring of tunnel

A short description of the different types of sediments is given in Ref. 1. Soft bottom includes sediments with a content of more than 5% of organic matter (as gyttja, peat and organic mixed sand).

In the following the quantities handled for three stages of the construction works are listed:

- By end November 1989 (in Phase 1)
- After Phase 1
- After Phase 1+2

Some of the activities of Phase 2 may be initiated before the completion of Phase 1. Therefore, the splitting up into Phase 1 and Phase 2 reflects a division between activities which have been fixed and activities which are still to be determined, more than it reflects a splitting between activities separated in time.

3.2.1 By end November 1989

Until the end of November 1989 the marine earth work activities have included:

- Sand extraction (Romsø, Slettings Grund and Musholm) and first stage of land fill at Knudshoved Harbour (1988 and 1989).

- Construction harbour at Halsskov and first stage of sea bed replacement and reclamation for construction harbour at Lindholm (1989).

- Sea bed replacement for Sprogø eastern railway ramp (1989).

- Sand extraction (Romsø SE and CD area) and construction of eastern railway ramp and sedimentation basins at Sprogø (1989).

ACTIVITY AND AREA (net production)	Sand	Soft	Moraine	Other	TOTAL
	1000 m³				
Sand extraction					
Romsø, Musholm and Slettings Grund	2,035	-	-	-	2,035
Romsø SE	2,054	-	-	-	2,054
CD east	987	-	-	-	987
Soft bottom dredging					
Halsskov	-	81	-	-	81
Lindholm	10	145	-	-	155
CD east	-	19	-	-	19
Railway ramp	-	207	-	-	207
Sum dredging	5,086	452	0	0	5,538
Deposition					
Basins Sprogø	10	452	-	-	462
Knudshoved	1,705	-	-	-	1,705
Lindholm	330	-	-	-	330
Halsskov	428	-	-	-	428
Sprogø east ramps	2,613	-	-	-	2,613
Sum deposition	5,086	452	0	0	5,538

Table 3.1 Dredging and deposition quantities up until end November 1989 (in Phase 1). Excluding gravel and stones imported from outside Storebælt. Ref. SBF.

Table 3.1 gives the marine earth work quantities.

Fig. 3.4 shows the time of completion of the different construction parts at Sprogø.

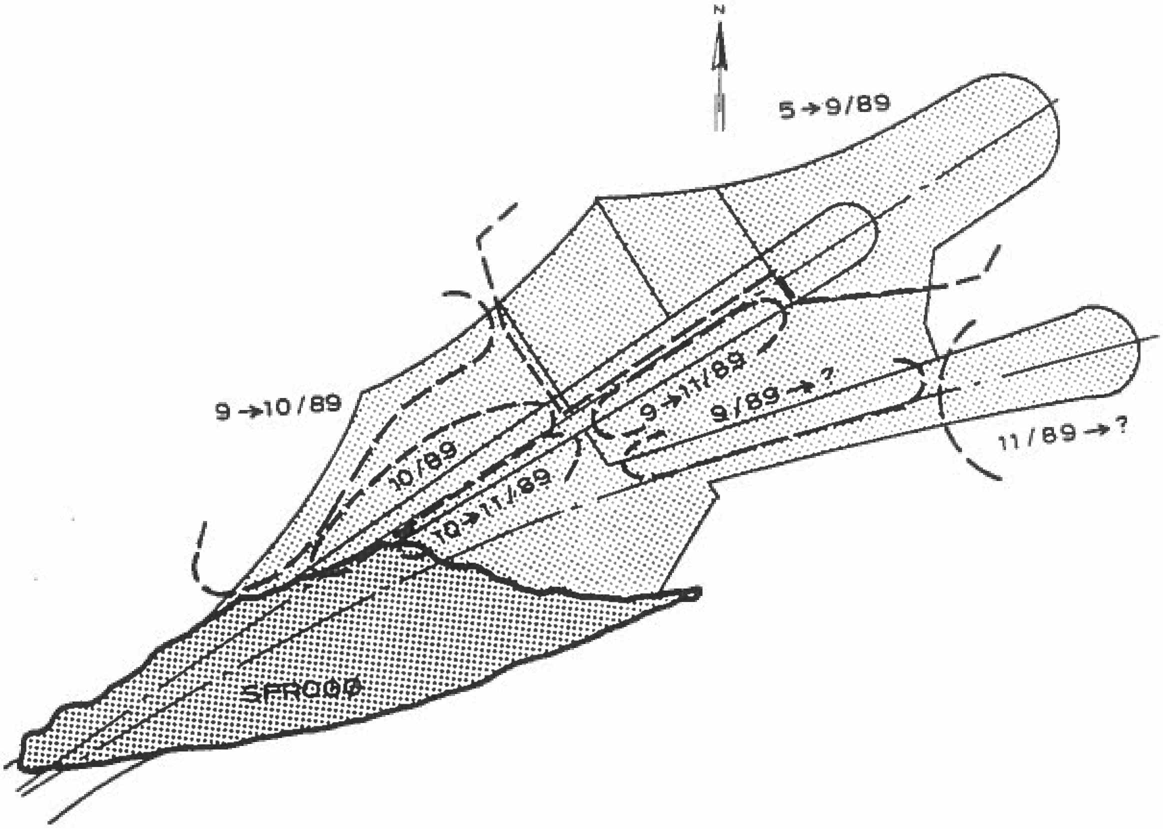


Fig. 3.4 Time of construction of the different parts at Sprogø east until end November 1989.

3.2.2 After Phase 1

The marine earth work activities for the remaining part of Phase 1 include:

- Sand extraction (Slettings Grund and Musholm) and completion of ramp at Knudshoved Harbour (1989 and 1990).
- Dredging for construction harbour at Lindholm (1990).
- Sea bed replacement for western ramp and CD west (1990).
- Sand extraction (Romsø SE and CD area) and construction of eastern road ramp and western ramp at Sprogø (1990).
- Dredging for bridge piers for the west bridge (1990).

Table 3.2 gives the marine earth work quantities, based on information received from SBF. For a minor part of the sand excavation the resource areas are not fixed yet. In this assessment these sand extraction activities are assumed to be taken from Romsø SE, Slettings Grund and Musholm.

ACTIVITY AND AREA	SEDIMENT TYPE				TOTAL
(net production)	Sand	Soft	Moraine	Other	
	1000 m^3				
Sand extraction					
Slettings Grund and Musholm	727	-	-	-	727
Romsø SE	793	-	-	-	793
CD east	1,545	-	-	-	1,545
CD west	36	-	-	-	36
Other dredging					
Lindholm	-	120	75	-	195
West ramp	-	200	-	-	200
CD east	-	100	-	-	100
CD west	-	400	-	-	400
West bridge	-	175	155	-	330
Tunnel boring	-	-	-	-*	-*
	-----	-----	-----	--	-----
Sum dredging	3,101	995	230	0	4,326
Sum dredging Phase 1	8,187	1,447	230	0	9,864
Deposition					
Basins Sprogø	-	995	75	-*	1,070*
Sprogø road ramp	1,830	-	-	-	1,830
Knudshoved	440	-	-	-	440
Sprogø	170	-	-	-	170
Sprogø west ramp	661	-	-	-	661
Dumping Sprogø NW	-	-	155	-	155
	-----	-----	-----	--	-----
Sum deposition	3,101	995	230	0	4,326
Sum dep. Phase 1	8,187	1,447	230	0	9,864

Table 3.2 Dredging and deposition quantities for remaining Phase 1 and total Phase 1. Ref. SBF.
*: material from tunnel boring not included as well as gravel and stones imported from outside Storebælt.

3.2.3 After Phase 1+2

The marine earth work activities in Phase 2 include:

- CD of moraine clay.
- Re-alignment of Route-T (not finally decided).
- Construction of shaping reefs around anchor blocks.
- Dredging for bridge piers for the east bridge.
- Disposal of surplus moraine clay.

For the assumed east bridge in this assessment (S1400) the additional CD of moraine clay is estimated at 3-5 mio. m^3 (Ref. 21). The range in quantity is due to uncertainty of the water depth for the existing Sprogø Østrev. For the assessments an average value of 4 mio. m^3 moraine clay as part 2 of the CD has been assumed.

The re-alignment of the Route-T is set at 0.35 - 0.85 mio. m^3 in Ref. 22, depending on the extent of the re-alignment. For the present assessments a value of 0,6 mio. m^3 has been assumed.

The assumed quantities of the marine earth work in Phase 2 are listed in Table 3.3:

ACTIVITY AND AREA	SEDIMENT TYPE				TOTAL
(net production)	Sand	Soft	Moraine	Other	
	1000 m^3				
Dredging Phase 2					
CD east	-	-	4,000	-	4,000
East bridge	-	97	257	-	354
Route-T	-	-	600	-	600
	-----	-----	-----	--	-----
Sum dredging Phase 2	0	97	4,857	-	4,954
Sum dred. Phase 1+2	8,187	1,544	5,087	-	14,818
Deposition Phase 2					
Basins Sprogø	-	97	-	-	97
Anchor reefs	-	-	600	-	600
Surplus moraine clay	-	-	4,257	-	4,257
	-----	-----	-----	--	-----
Sum deposition Phase 2	0	97	4,857	0	4,954
Sum dep. Phase 1+2	8,187	1,544	5,087	0	14,818

Table 3.3 Dredging and deposition quantities for Phase 2 and total Phase 1+2. Ref. SBF.

The earth balance shows an excess of 4.3 mio. m^3 of moraine clay. The actual value will depend on the selected east bridge design, the selected re-alignment of the Route-T and the use of moraine clay for construction of shaping reefs around anchor blocks, but an excess portion is expected for all combinations.

In the assessment of ecological impacts the excess moraine clay has been assumed to be dumped at the dumping location Sprogø NW.

However, as the decision of where to deposit the excess material has not yet been taken, the following Section discusses the ecological impacts of alternative disposals.

3.3 Marine Deposition of Surplus Moraine Clay

In Table 3.3 the excess is about 4.3 m^3 moraine clay after 0.6 mio. m^3 of the dredged moraine clay has been used for construction of shaping reefs for the anchor blocks.

The excess volume (or a part of the volume) may be deposited in one of the following ways:

- used for marine constructions
- deposited on Sprogø
- deposited at sea (dumped or discharged as a slurry)

The different types of deposition have different environmental effects.

The use of moraine clay for shaping reefs is an example of a marine construction, where the deposition has a positive marine effect, as the shaping of the blocks reduces the necessary total CD volume. From an environmental point of view this type of deposition has a high priority.

Deposition on Sprogø is only expected to give minor negative environmental effects. If the moraine clay is dredged by a mechanical dredger (bucket or backhoe dredger) the deposition can take place in lumps, and the spill to the sea will be minimal. If the material is dredged by a cutter suction dredger the deposition on Sprogø has to take place by use of sedimentation basins to reduce emission of the fine sediment fractions to the sea.

The impact of deposition at sea depends on the method of deposition as well as the method of dredging of the moraine clay.

If the moraine clay is dredged by a mechanical dredger (bucket or backhoe dredger) the material will be loaded into splitbarges for transport to the disposal place, where the material is dumped. The dumping will result in suspension and spreading of a part of the material, as well as release of nutrients from the material. The spreading of sediments is in the order of 5% of the material dumped (see Section 4.2) and the release of nutrients is estimated at about 5% of the total nutrient pool in the material. The losses will be distributed over the water column, thus mainly affecting the upper layer in Storebælt if dumping takes place at water depths less than about 15-20 m.

For moraine clay dredged by a cutter suction dredger the transport of the material to the disposal location may take place in pipes which discharge the slurry directly near sea bed level, or by splitbarges and dumping.

The discharge from a pipe at the disposal location is estimated to result in comprehensive suspension and spreading of material (order of 20% of material) and nutrient released from the moraine clay (about 50% of nutrient pool). However, if the discharge takes place below the interface between the upper and lower layer in Storebælt, the effect of the nutrient release will be limited as the lower layer normally contains free nutrients, whereas the upper layer is devoid of nutrient and consequently the production is nutrient limited from March to September. Further, the sediment spreading will mainly take place in the lower layer with less effects on the vegetation.

If material dredged by a cutter suction dredger is loaded into splitbarges at the dredging position this will result in comprehensive spreading of sediments and nutrients from the overflow of the splitbarges in the upper water layer. The material loaded into the splitbarge will not be disintegrated as much as material pumped in pipes for a longer distance. Therefore, the suspension part will be somewhat less than 20%, and the nutrient release less than 50% of the nutrient pool. However, the effects on vegetation (phytoplankton and benthos) may be large, as the spreading takes place in the upper layer. Besides, an extra spreading of sediments and nutrients will occur at the dumping location (in the order of 5% of sediment volume and nutrient pool).

The location of the marine disposal site is not fixed. SBF has permission for dumping of a minor volume northwest of Sprogø at 15-20 m water depth, see Fig. 3.5. Other locations may also be evaluated, for example:

- dumping at Romsø SE, where a depression has been generated from extraction of resource sand
- dumping further northwest of Sprogø, where the water depth is larger (> 17-20 m) and the impacts on the vegetation around Sprogø will be less
- discharging the slurry (dredged by cutter suction) directly to the lower layer in Østerrenden

From an environmental point of view dredging by grab and dumping at Romsø SE could be one of the more satisfactory solutions. This area is already affected by the extraction of sand. The dumped material is expected to settle permanently here, fill up in the dredged area and thereby reestablish the bottom. The plume from the dumping will mainly go north or south and will not reach areas of special interest within 20 km.

The dumping near Sprogø is expected to affect the local reefs to a greater extent than the Romsø SE dumping. If the material is dumped at a depth of 15-20 m instead of >20 m it is more likely that resuspension will happen.

Direct discharge to Østerrenden could also be one of the more acceptable solutions although the suspension volume will be large (≤ 20%) and the initial spreading will affect a large part of the lower layer in Storebælt. The plume from the discharge will spread in the water mass under the halocline and only a minor part of nutrients will be brought directly to the surface water.

From the above it is concluded that deposition of surplus material would be preferred on the deep locations. It is likely that dumping at Romsø SE or direct pumping to Østerrenden from an environmental point of view are the most satisfactory solutions when surplus material has to be deposited at sea.

A more detailed evaluation is required to give a more exact priority to the different solutions.

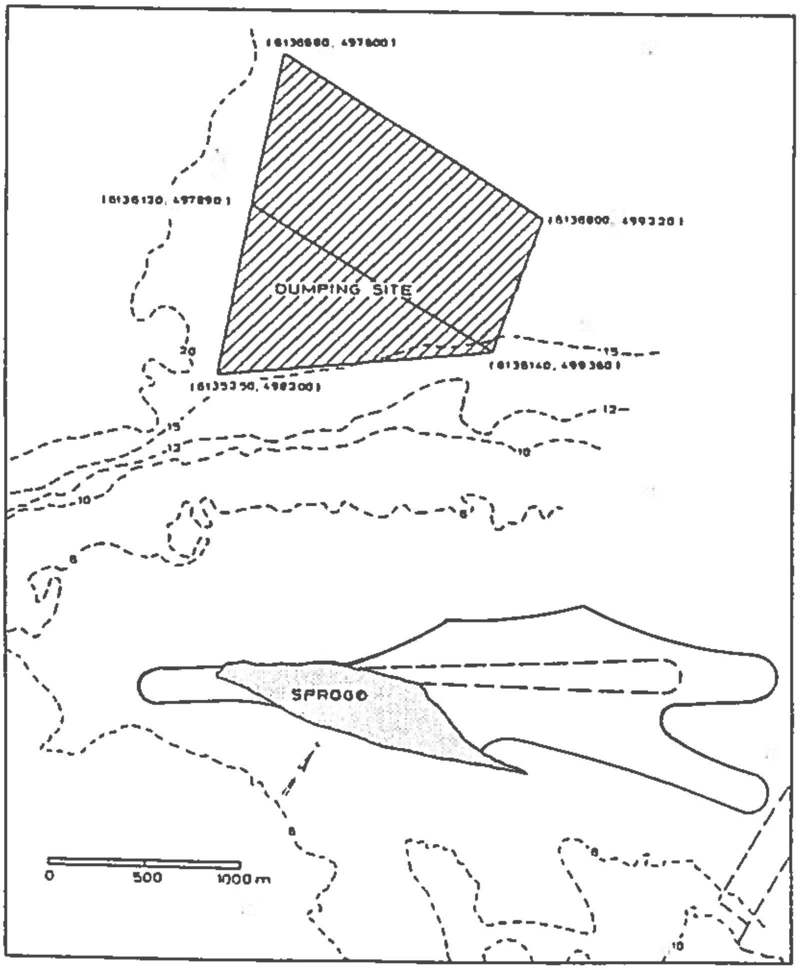


Fig. 3.5 Location of disposal site Sprogø NW.

4. REVISED SPILL CONDITIONS

4.1 Dredging Capacities

The different types of dredgers and their production rates are discussed in Ref. 1. Table 4.1 lists the assumed dredging capacities of the different types and for the actual types of sediment.

DREDGER TYPE	PRODUCTION RATE FOR DIFFERENT SEDIMENTS		
	Sand	Soft Sediments	Moraine Clay
	m³/hour		
Mechanical Dredger			
Bucket dredger Large	200-300	200-300	200-300
Backhoe dredger Large	?	?	100-150
Hydraulic Dredger			
Trailing suction Large (James Ensor)	1,700*	n.a.	-
Cutter suction Large (Leonardo da V.)	1,700	800	800

Table 4.1 Assumed production rates of different dredger types and sediment types. n.a. = not allowed used in Phase 1 contracts.
*: only effective for about 8 hours per day.

4.2 Suspension Percentages

Table 4.2 shows the assumed percentage of sediment spilled and brought into suspension as a function of dredger and sediment type.

Spills from trailing suction at Romsø SE and at the compensation dredging area are estimated on the basis of results from surveys in July and September 1989. Losses during unloading of sand from Romsø SE is estimated on the basis of grain size analyses of cargoes, all silt and clay are assumed lost. Sediment lost by small trailing suction dredgers extracting sand is estimated on the basis of the silt and clay fraction of the dredged material, assuming 2/3 lost during dredging and 1/3 during unloading.

Losses from bucket or backhoe dredgers and disposal from splitbarges are based on estimations presented in the previous assessments (Ref. 1, 21).

DREDGER TYPE	SEDIMENT TYPE		
	Sand	Soft Sediments	Moraine Clay
	-------- percent sediment spilled -----------		
Bucket or backhoe dredger			
Dredging	0.5-3[G]	1	0.2
Disposal Splitbarges	1[F]	-	5
Trailing suction, Romsø SE, James Ensor			
Dredging	31[B]	-	-
Unloading	3.5[F]	-	-
Trailing suction, CD area, James Ensor			
Dredging	11[C]	-	-
Unloading	2.5[C,F]	-	-
Trailing suction, shallow water, small dredgers			
Dredging	2[E]	-	-
Unloading	1[E]	-	-
Cutter suction dredgers			
Dredging	1.5[A]	1	1.5
Slurry Outlet	1.5-4[F(C)]	-	18
Outlet via basins	-	1.5	2.5

Tabel 4.2 Percentage of sediment spilled, as function of type of dredger and sediment.
A: Survey, June 1989, Ref. 23
B: Survey, July 1989, Ref. 24
C: Survey, September 1989, Ref. 25
D: Survey, October 1989, Ref. 26
E: Silt-clay fraction in dredged material
F: Silt-clay fraction in cargo
G: 1/3 silt-clay fraction in dredged material

4.3 Nutrient Release

Release of nutrients from sediment operations have initially been estimated from spill percentages and nutrient releases in slurry experiments (Ref. 27). These estimates have been improved by information from four emission surveys in 1989.

In Table 4.3 the revised release of nutrient from different types of sediment and types of operations are listed.

DREDGER TYPE	SEDIMENT TYPE					
	Sand		Soft Sediments		Clay	
	N	P	N	P	N	P
	g/m³ handled sediment					
Bucket or backhoe dredger						
Dredging	1.5[F]	0.1[F]	0.44[E]	0.14[E]	0.03[E]	0[E]
Disposal Splitbarges	13.5[F]	0.9[F]	-	-	0.75[E]	0[E]
Trailing suction, Romsø SE						
Dredging	22.8[B]	1.5[B]	-	-	-	-
Unloading	11.4(C)	0.75(C)	-	-	-	-
Trailing suction, shallow waters						
Dredging	11.4[C]	0.3[C]	-	-	-	-
Unloading	5.7[C]	0.15[C]	-	-	-	-
Cutter suction dredgers						
Dredging	0.54[E]	0.11[E]	0.44[E]	0.14[E]	0.23[E]	0[E]
Slurry outlet	15(C,D,E)	1(C,D,E)	44[E]	13.5[E]	8.5[F]	0[F]
From basins Sprogø	-	-	44[E]	13.5[E]	17[F]	0[F]

Tabel 4.3 Nutrient spill from different dredgers and types of sediment.
A: Survey, June 1989, Ref. 23
B: Survey, July 1989, Ref. 24
C: Survey, September 1989, Ref. 25
D: Survey, October 1989, Ref. 26
E: from 52 days slurry experiments, Appendix A
F: from 12 hours slurry experiments, Appendix A

The spill from the cutter and trailing suction dredgers are estimated on the basis of results from the surveys. The other nutrient releases are based on spill percentages and measured releases from slurry experiments, see Appendix A.

5. SEDIMENT SPREADING

5.1 Estimate of Sources

The sediment lost during the earth work operations is brought into suspension and spread in the sea.

In Table 5.1 the suspension volumes for each main area are listed, based on the individual activities of Phase 1 and 2 (Table 3.1 - 3.3) and the revised suspension percentages in Section 4.2.

AREA	SEDIMENT SUSPENDED			
	Up till end Nov. 1989	Remaining Phase 1	Phase 2	Total
	1000 m³			
Slettings Grund	9	9	-	18
Musholm	23	9	-	32
Romsø	9	-	-	9
Romsø SE	923	356	-	1,279
Halsskov	15	-	-	15
Knudshoved	17	4	-	21
Lindholm	5	1	-	6
West bridge	-	3	-	3
Sprogø				
East construction	86	70	-	156
West construction	-	25	-	25
Discharge from basins	6	18	1	25
CD east	66	53	8*	127
CD west	-	5	-	5
Dumping Sprogø NW	-	8	213*	221
East bridge	-	-	34	34
Route-T re-alignment	-	-	1*	1
Sum sediment loss	1,159	560	257	1,976

Table 5.1 Sediment volume suspended during marine earth work operations in Phase 1 and 2.
*: assumed dredged by mechanical dredger and dumped by splitbarges.

The sand extraction at Romsø SE contributes about 64% of the total volume. Other large contributions are CD east, construction of the two east ramps of Sprogø and dumping of the excess moraine clay.

If the dredging of moraine clay in the CD area in Phase 2 is performed by a cutter suction dredger and the slurry is pumped to the disposal location northwest of Sprogø, the loss during dredging is expected to increase from 8,000 m^3 to 60,000 m^3 and the loss during deposition from 213,000 m^3 to about 770,000 m^3. Thus, in that case, the total sediment loss will be about 2.6 mio. m^3.

5.2 Settled Layer Thickness

The sediments brought into suspension during the marine earth work activities will be spread by the current. At the same time the sediment particles will tend to settle due to the excess density.

The transport and primary sedimentation of suspended sediments is modelled by DHI's System 21. The model is a one-layer model consisting of a Hydrodynamical stage and a Transport-dispersion stage. The model area is described in a rectangular computational grid. In the present case a grid size of 700 m x 700 m is applied. The model topography is shown in Fig. 5.1.

The hydrodynamic model solves the depth integrated flow equations, giving the water surface elevation and depth averaged current velocity vector in each grid point for each time step.

The hydrodynamic simulation is based on the wind field and the distributions of water levels along the open boundaries.

The present study uses a design period of 10 days: 3 to 13 June, 1984. The design period comprises situations with northbound and southbound current and a period with no significant net current. The design period has been chosen in such a way that it is representative for normal flow conditions in Storebælt.

The topography in the model area is the real topography. However, at depths greater than 20 m, an artificial bottom has been introduced, Fig. 5.2. This artificial bottom is introduced because of the effect of the interface between the upper fresher layer and the lower more saline layer in Storebælt. The friction at the artificial bottom is calibrated to represent the friction at the interface.

In reality the mean level of the interface is approx. -13 m and spreading of suspended sediments takes place both in the upper and the lower layer (in areas where the water is deep and a two layer flow condition exists).

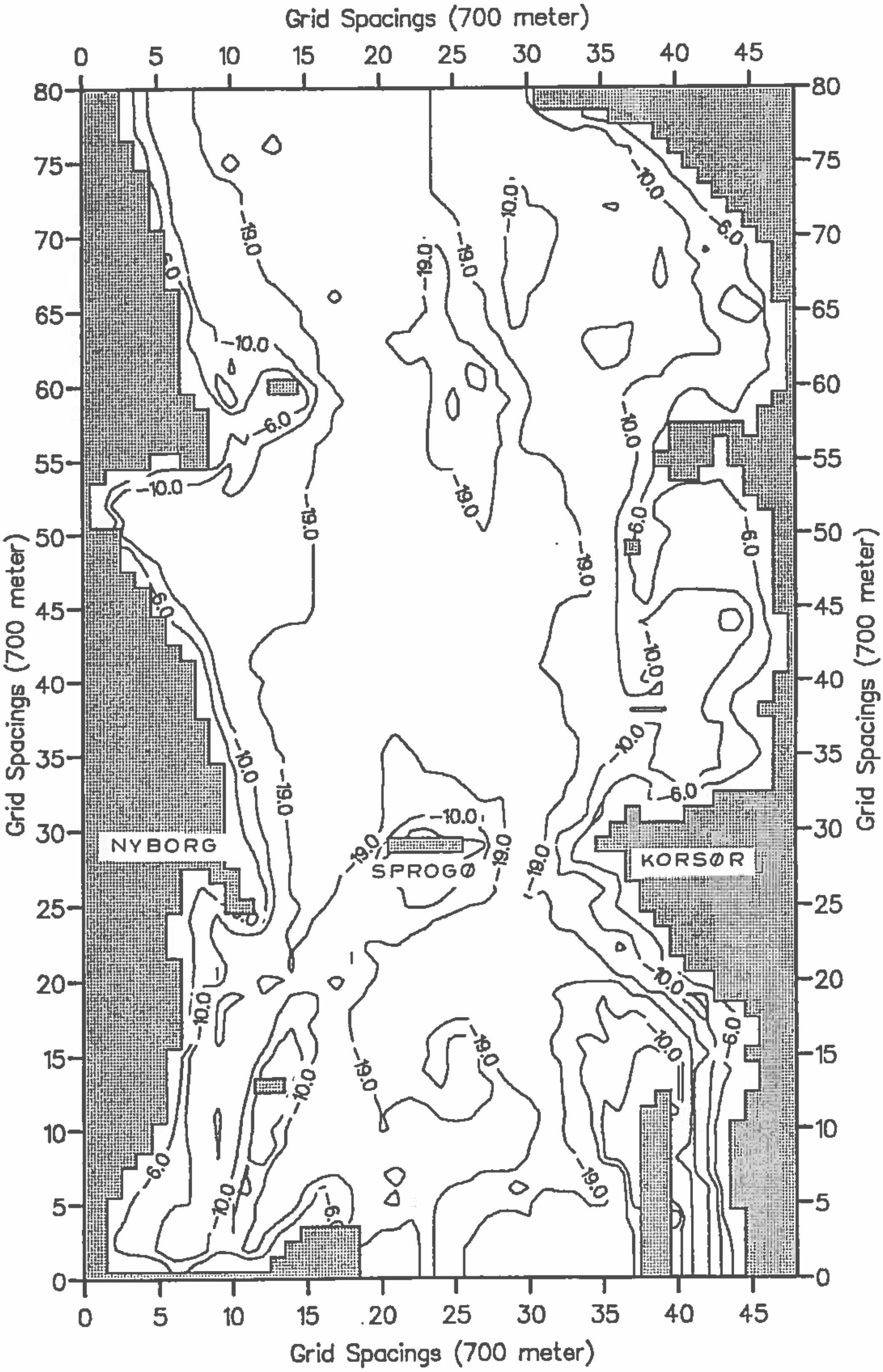


Fig. 5.1 Model topography of the applied System 21 model.

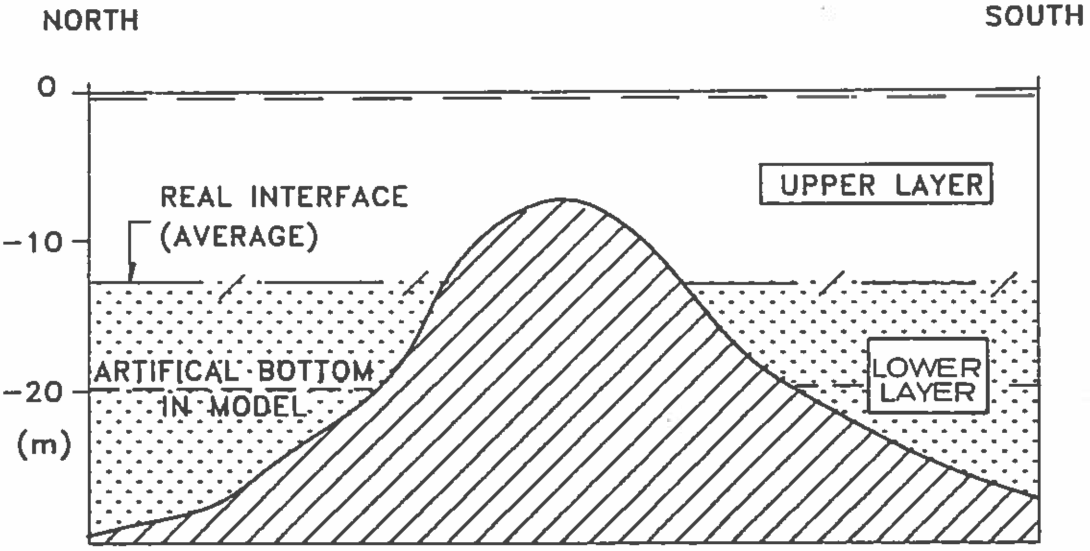


Fig. 5.2 Cross section of hydrodynamic model topography showing the principle of an artificial bottom in level -20 m.

In the simulation with the System 21 one-layer model the spreading of sediments in the lower layer is thus represented by the spreading between the real interface level (mean level approx. -13 m) and level -20 m. The level of the artificial bottom is an approximation, but represents the real sediment spreading fairly well, as the lower layer velocities generally are smaller than upper layer velocities. The spreading in the lower layer is thus limited even at water depths greater than 20 m.

The transport and sedimentation of the suspended sediment are modelled by the Transport-Dispersion stage of System 21. The model calculates the depth integrated concentration field of suspended sediment by solving the mass balance equation for each grid point for each time step, taking the following mechanisms into account:

- Advection of suspended sediment according to the current field obtained from the Hydrodynamic stage.
- Dispersion due to water motions which is not resolved in the time space grid, included by a mixing coefficient.
- Settling of sediment to the bed or to the lower layer.
- Suspension of sediment due to the marine earth work operations.

The sedimentation of the material is described through a settling velocity, W, the depth integrated concentration, C and the actual, V, and critical ambient velocity V_C:

$$\text{Sedimentation rate} = W \cdot C\ (1-V/V_C)^2$$

It is thus assumed that the suspended sediment is uniformly distributed over the vertical.

The suspension of material due to dredging is modelled by placing sources of sediment in the model area, see Table 5.1. The source points are evenly distributed over the individual areas which may be subject to dredging activities. Each source point discharges sediment at a constant rate, which is introduced into the model.

No other sediment sources are considered for the present calculations, and the water entering the model is assumed to carry no suspended sediments.

Resuspension, where sediment once settled out on the sea bed is brought back in suspension, may occur for waves and larger flow velocities. In the present study no resuspension criterion is introduced in the model. The settling relation is assumed always to be effective.

This approach is conservative with respect to the maximum thickness of the settled layer after the dredging operations. However, the impact area will be less than if resuspension was included.

In the video survey of the stone reefs around Sprogø (Ref. 28) no fine grained sediment was seen to accumulate from the shoreline out to about 15 m depth. Therefore, resuspension of exposed sediments originating from dredging operations is also expected to take place.

For a sandy sea bed resuspension of settled material at Sprogø Østrev is estimated to occur several times a year out to sea bed depths of about the interface level. However, the resuspension criteria for sea beds covered by vegetation, stone reefs and mussel beds are not known, and no calculation of the average interval between resuspension conditions can be performed.

A plan of the soft sea bed areas around Sprogø is shown in Fig. 5.2. These areas will be the final settling areas for the suspended sediments if resuspension takes place around Sprogø. Within 5-6 km from the CD area the soft sea bed covers 25-45 km^2. Sediments which are resuspended from the shallow areas around Sprogø are estimated to settle out finally within a distance of 5-10 km or more in the natural sedimentation basins.

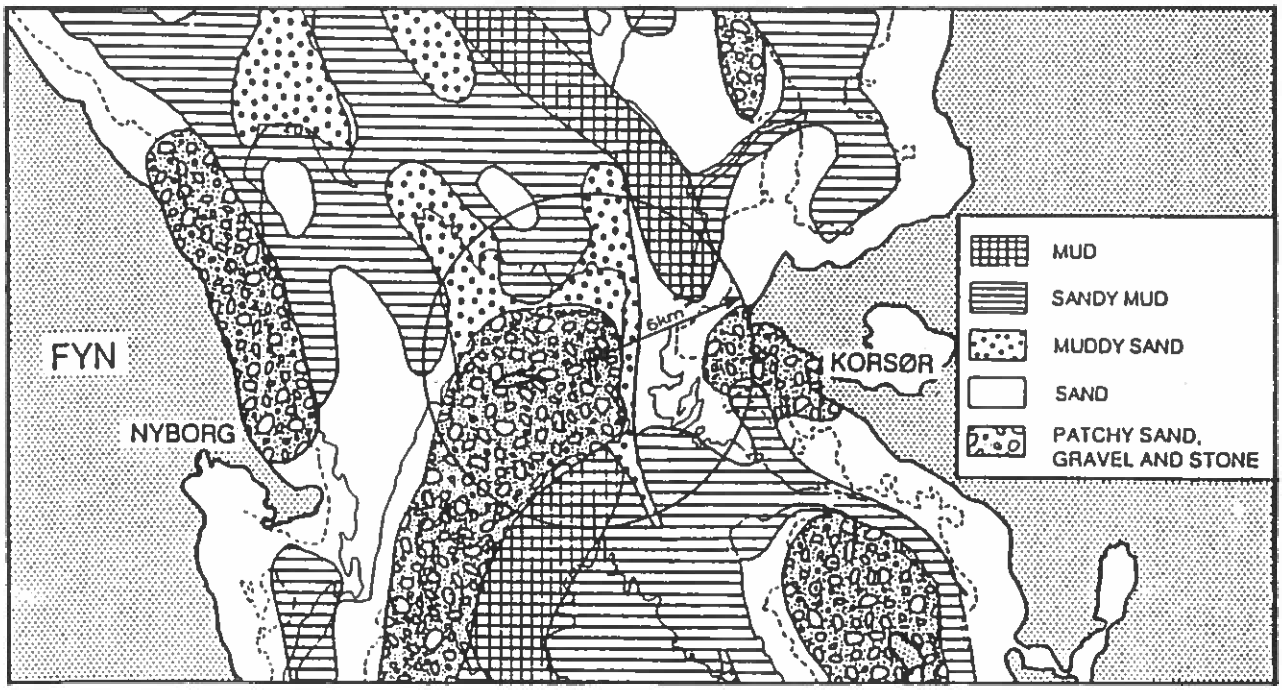


Fig. 5.3 Soft sea bed areas around Sprogø which act as final sedimentation areas. Ref. 28.

The main assumptions for the calculations of the primary settling are summarized as follows:

1. A 10-day simulation period which is representative for the long-term flow conditions.

2. The suspended material consists of the following grain size fractions, each fraction contributing with 50%:

   d_{50} = 0,055 mm; settling velocity W = 0.0022 m/s
   critical ambient velocity V_c = 10 m/s
   d_{50} = 0,014 mm; settling velocity W = 0.00014 m/s
   critical ambient velocity V_c = 0.2 m/s

3. The density and porosity of settled material correspond to the density and porosity of dredged material.

4. Suspended volumes listed in Table 5.1 (excluding Lindholm).

5. No resuspension criterion is included.

The calculated resulting primary sedimentation for the three stages of the construction works is presented in Fig. 5.4 - 5.6. The source from construction works at Lindholm has not been included in the calculations due to less confidence with the large grid model in this area.

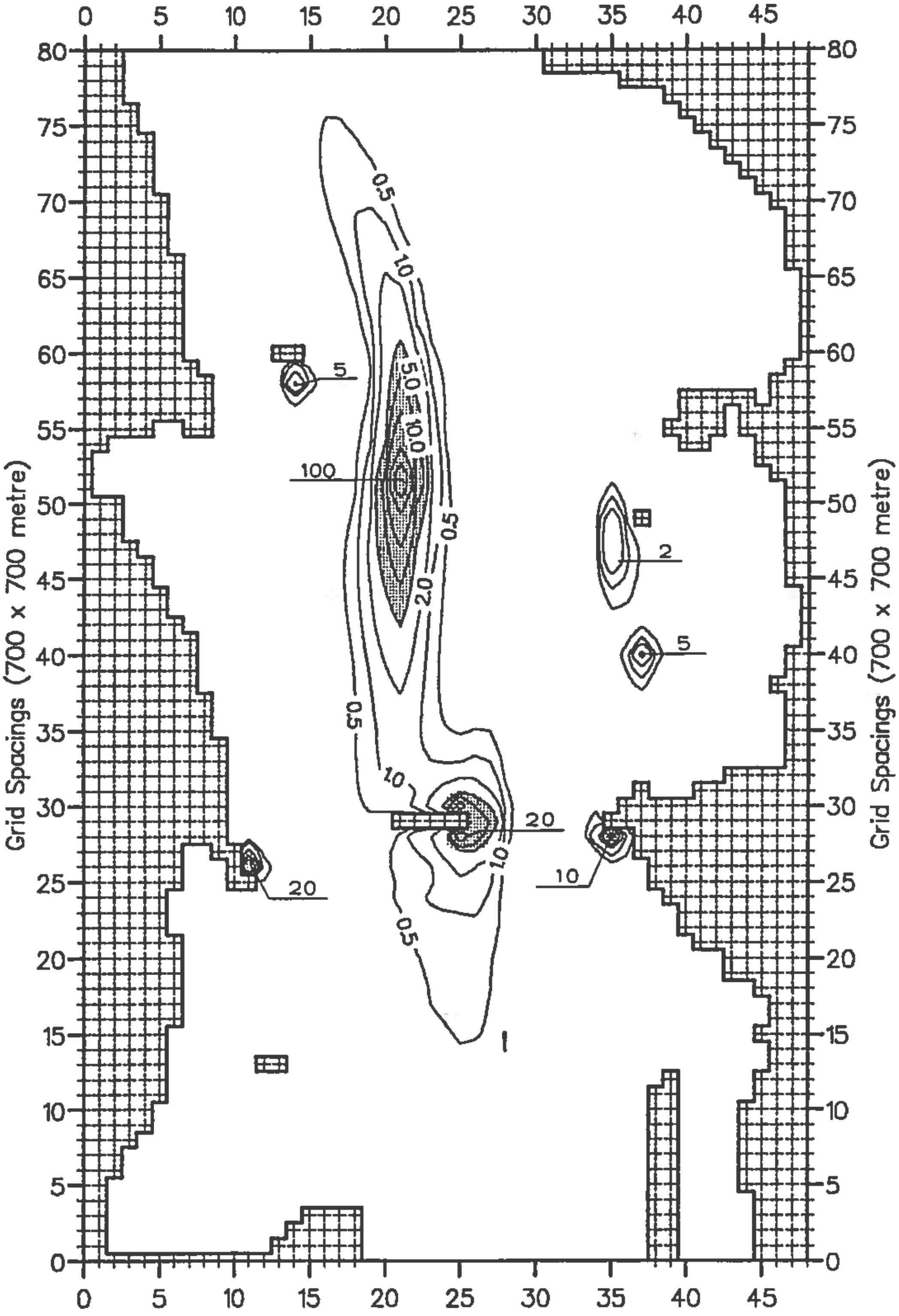


Fig. 5.4 Primary settling layer thickness (in mm) pr. end of November 1989 (in Phase 1). Excluding Lindholm source.

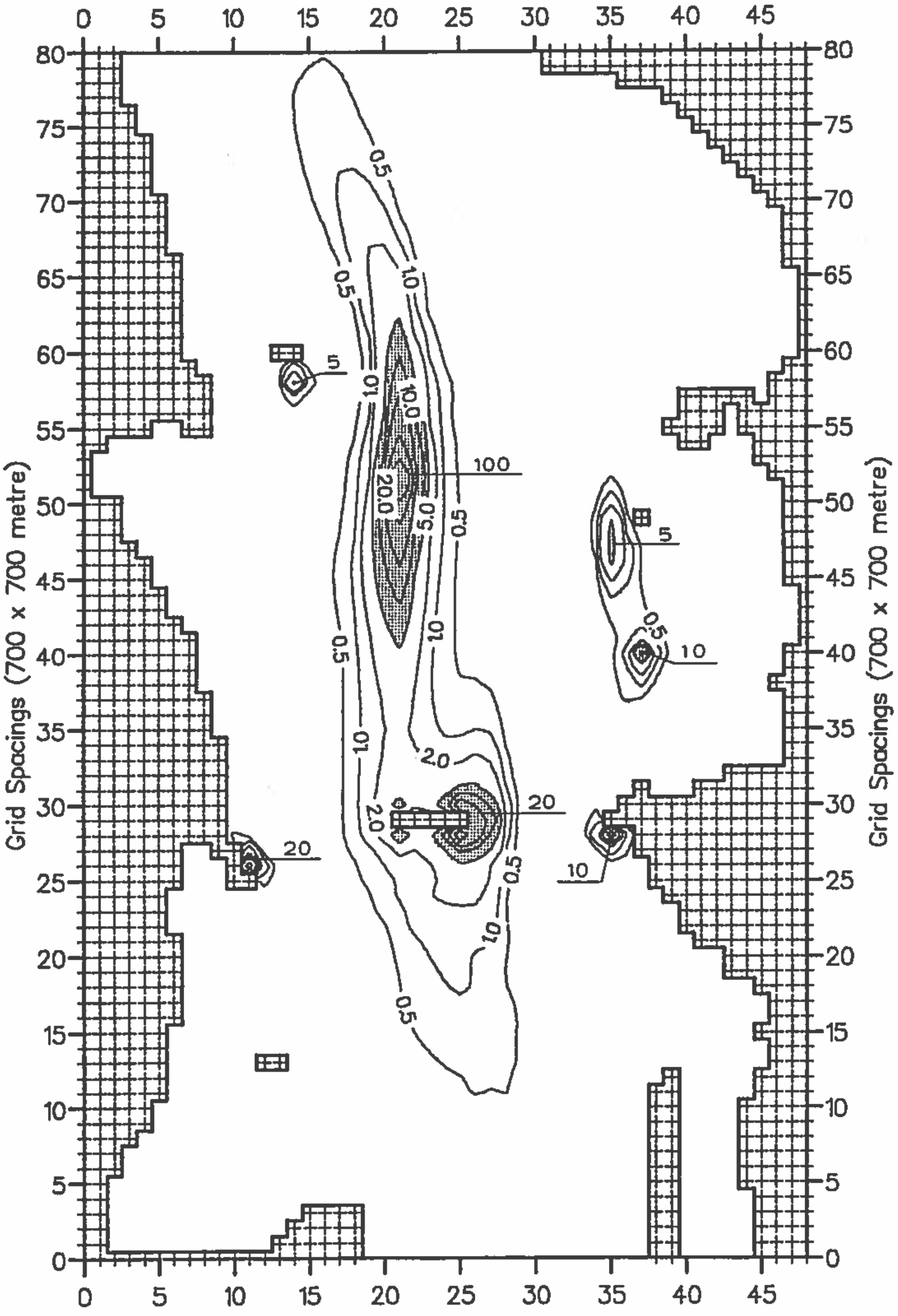


Fig. 5.5 Primary settling layer thickness (in mm) after completion of Phase 1. Excluding Lindholm source.

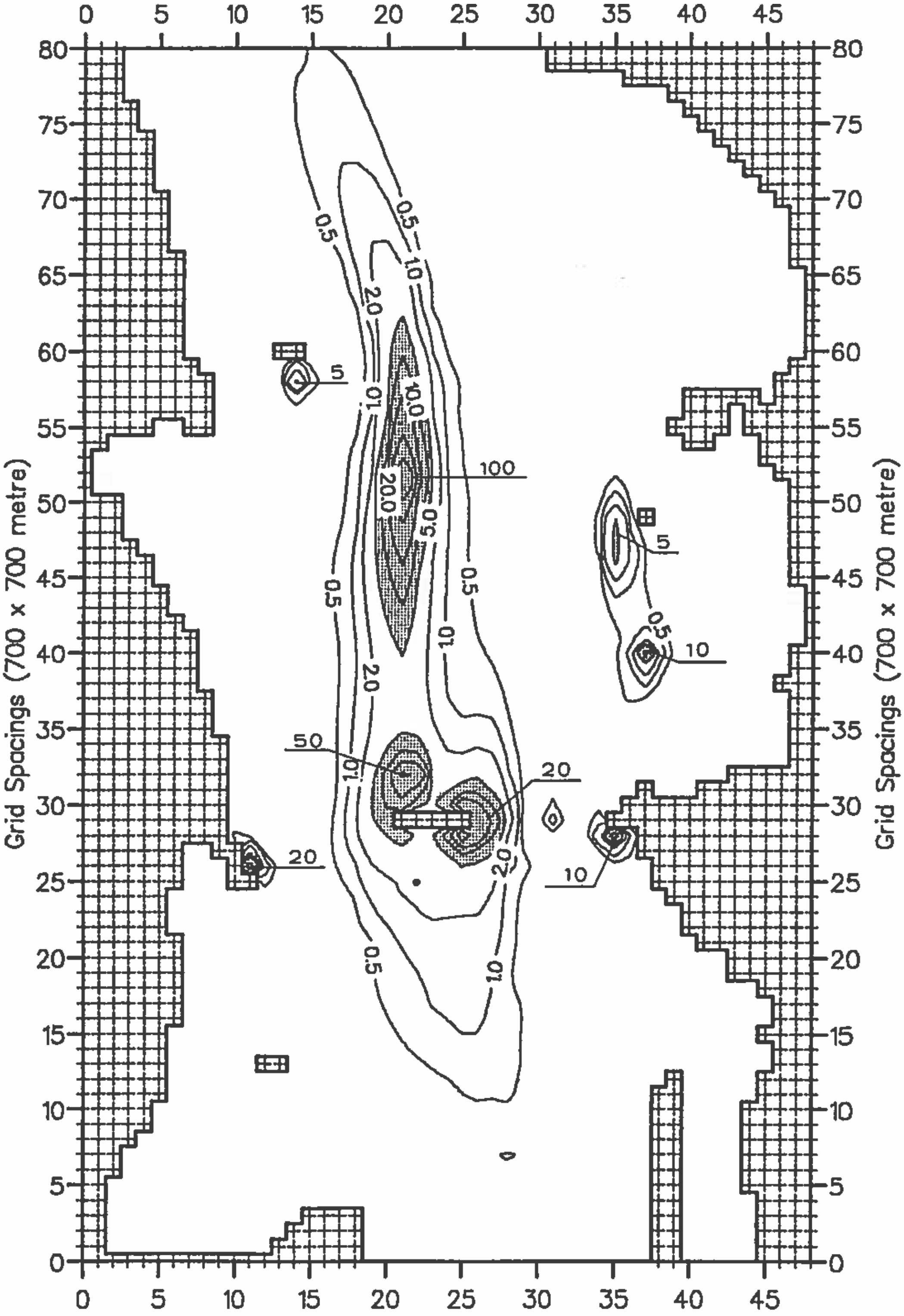


Fig. 5.6 Primary settling layer thickness (in mm) after completion of Phase 1+2 if the moraine clay is dredged by mechanical dredgers and dumped at Sprogø NW. Excluding Lindholm source.

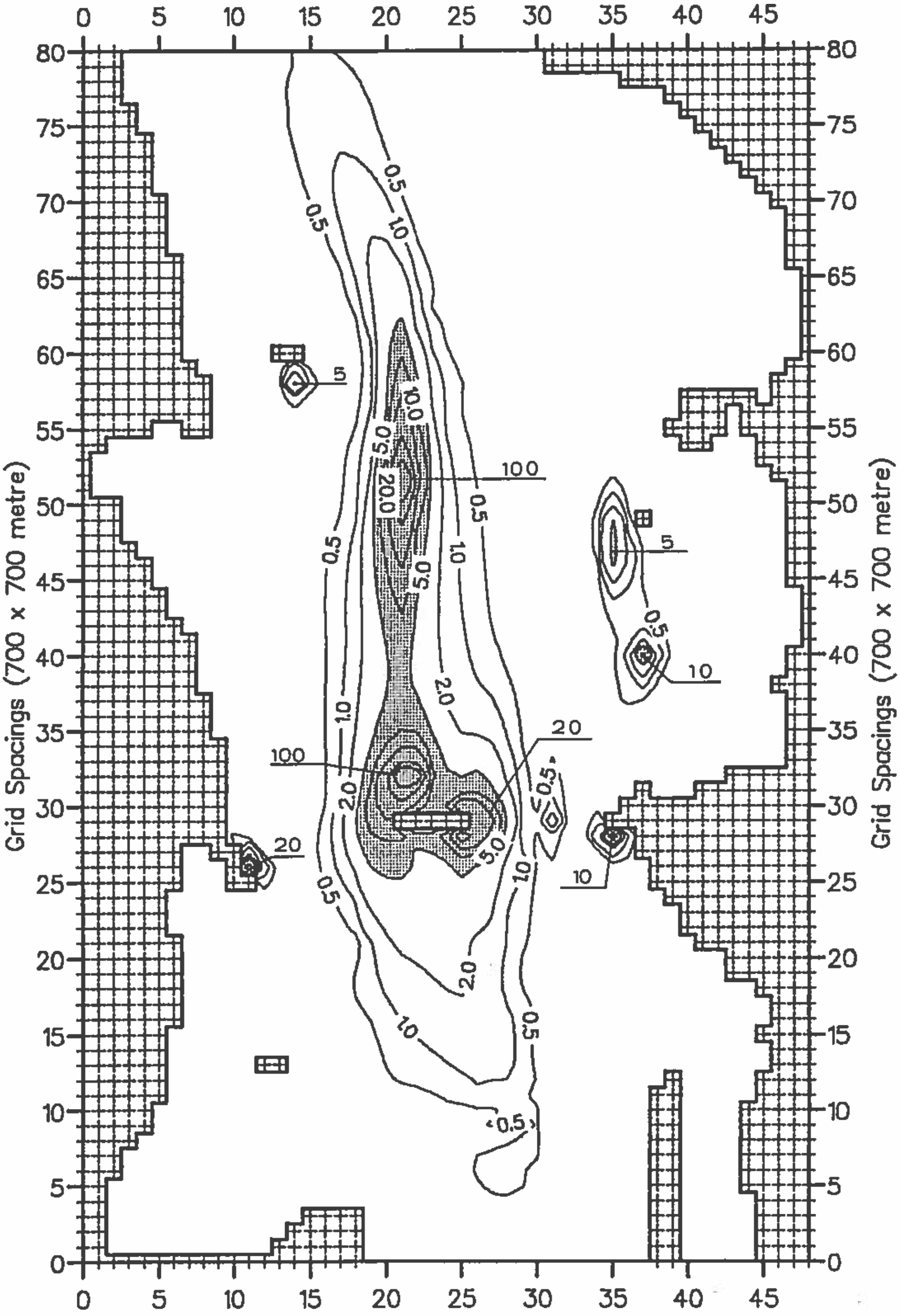


Fig. 5.7 Primary settling layer thickness (in mm) after completion of Phase 1+2 if the moraine clay is dredged by cutter suction and the slurry is discharged at Sprogø NW. Excluding Lindholm source.

Fig. 5.7 shows the resulting sedimentation if the moraine clay of Phase 2 is dredged by a cutter suction dredger and the slurry is discharged directly at the deposition location (Sprogø NW).

Table 5.2 summarizes the areas affected by settled sediments and the maximum settled layer thickness for the three stages of the marine earth works.

CASE	LAYER THICKNESS OF SETTLED SEDIMENTS						
	Area Affected by Stated Thickness					Max. Thickness	
	>0.5	>1	>5 (mm)	>10	>50	Total	Outside Dredging Area
	km²					mm	
Phase 1							
- Up till Nov. 1989	180	100	25	15	2	160	73
- Total Phase 1	260	150	36	20	3	220	100
Phase 1+2							
- Total excl. deposition of surplus clay	264	154	36	20	3	220	100
- Total incl. dumping of surplus clay (Sprogø NW, mech. dredged)	295	180	46	25	4	220	100
Phase 1+2 alternatively							
- Total incl. discharge of surplus clay slurry (Sprogø NW, cutter suction)	352	224	65	34	5	220	100

Table 5.2 Areas affected by primary settling of suspended sediments from marine earth work operations (dredging/disposal). Excluding Lindholm source.

To illustrate the effect of the deposition of the excess moraine clay volume the Phase 1+2 values are listed for:

- excluding deposition of excess clay
- including dumping of mechanical dredged clay
- alternatively cutter suction dredging and discharge of slurry at Sprogø NW

5.3 Suspended Plume Concentrations

The maximum concentrations of suspended sediments will appear in the sediment plume downstream of the marine earth work operation or the overflow from the sedimentation basins.

By a simple stationary plume analysis model the suspended sediment concentrations of Fig. 5.8 have been calculated. The ambient velocities are selected to represent the average plume velocity as well as a low plume velocity (0.1 m/s) of each main plume case.

Seven main plume cases have been analyzed:

1: Romsø SE, sand dredging, James Ensor (trailing suction): 31% = 0.21 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 13 m.

2: CD, sand dredging, James Ensor (trailing suction): 11% = 0.073 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 6 m.

3: CD, sand dredging, Leonardo da Vinci (cutter suction): 1½% = 0.007 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 6 m.

4: CD, moraine clay dredged mechanical: 0.2% = 0.0002 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 6 m.

5: Sedimentation basin A, soft sediment infilling, Leonardo da Vinci (cutter suction): 3% = 0.007 m^3/s lost, settling velocity 0.5 m/h, water depth 6 m.

6: Road ramp construction, sand infilling, Leonardo da Vinci (cutter suction): 3½% = 0.016 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 6 m.

7: Sprogø NW, dumping moraine clay dredged mechanical: 5% = 0.006 m^3/s lost, settling velocity 8.0/0.5 m/h, water depth 15 m.

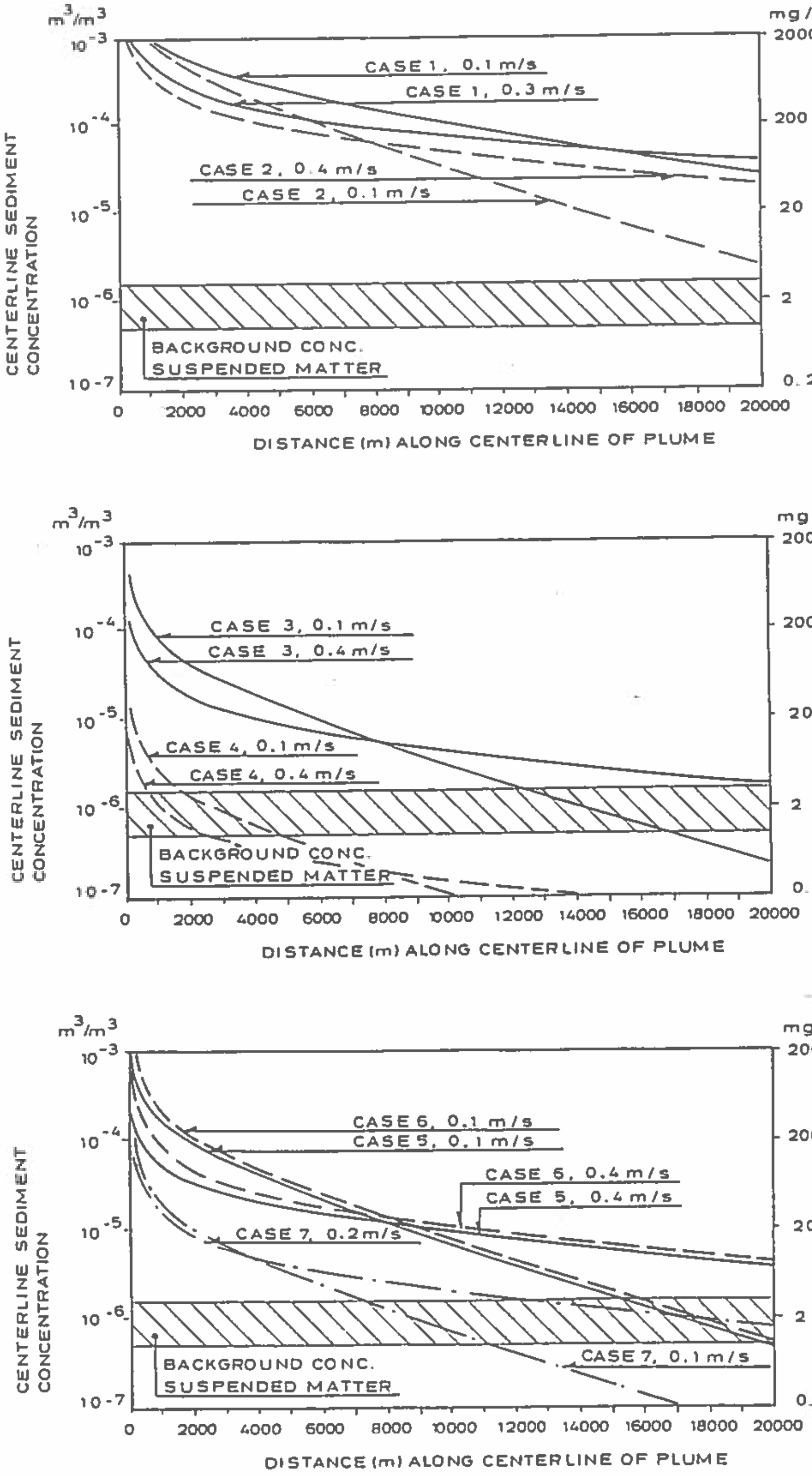


Fig. 5.8 Centerline suspended sediment concentrations in the plume downstream of the position of sediment release for the seven main plume cases.

The plume width will be in the order of 100 m at a distance of 1,000 m downstream, 200-300 m at a distance of 5,000 m and 400 m at a distance of 20,000 m. Due to changes in the current the plume will shift position within a typical range in the order of 5 times larger width than the actual plume width and the plume will shift between northward and southward position.

In the plume surveys performed in 1989 (Refs. 25, 26) sediment concentrations in the plume arising from sand dredging by James Ensor at Sprogø Østrev were measured at up till 20-30 mg/l in a distance downstream of 3-4,000 m. This concentration corresponds fairly well with the calculated concentration of 30-60 mg/l in the plume Case 2.

The suspended sediments will affect the light penetration of the water column. The penetration depends on the suspended concentration as well as on the size of the particles suspended (Refs. 2, 3). From Ref. 3 it can be concluded, that the particle fraction 0.001-0.060 mm is contributing most to the decrease in light intensity, and that the light attenuation for this fraction of clay particles can be estimated (approx.) as $k = 0.1\ m^{-1} * [\text{susp. conc. in mg/l})]$ in the relation:

$$I_z = I_o * \exp(-(k + k_B)z)$$

k_B is the attenuation of the water of Storebælt. According to Ref. 44 this value is 0.34 m^{-1} (median value), ranging from 0.28 to 0.54 m^{-1}. I_o is the light intensity at the surface and I_z the light intensity z meter below the surface. By use of the relation a conservative estimate of light intensity can be worked out (see Chapter 10). The relationship has been used both for clay particles and organic matter, although light penetration is known to be affected differently by clay and organic substances as gyttja/peat. Because of the relatively small amounts of soft sediments compared to clay amounts it is not expected that the assessments in Chapter 10 will be affected significantly by this difference.

6. RELEASE OF NUTRIENTS

6.1 Individual Operations

The bed material in Storebælt contains nutrients. During the marine earth work operations these nutrients will be released to some extent. The release takes place both at dredging, reclamation (ramps, reefs etc.) and from disposal operations (sedimentation basins, dumping etc.).

In Table 6.1 the estimated release rates for the main operations are listed, based on the activities listed in Table 3.1 - 3.3 and the nutrient release specifications of Section 4.3.

Some of the operations have or will take place at the same time and in the same area. For example the Phase 1 operations up till Nov. 1989: "CD, sand dredging (James Ensor)" and "Sprogø east ramps, sand reclamation (James Ensor and Haarlem)". In this case the actual rate of released nutrients at Sprogø Østrev has been the sum of the three individual operations (220-400 kg N/day and 11-24 kg P/day).

The release due to the construction works of Table 6.1 may be compared to other sources of nutrient input to the upper layer of Storebælt. In Table 6.2 point sources and area sources from the area are listed. Nyborg town+catchment area is the largest point source within a distance of 10-15 km from the Link.

The release rates during the construction works are seen to be largest around Sprogø, where it amounts to up till 100% of the size of the inorganic N summer source and about 300% of the P summer source from Nyborg town+catchment area in short periods during Phase 1. The sand extraction from Romsø SE equals 20-30% of the source from Nyborg town+catchment area (or the entrained inorganic-N from lower layer over an area of 20 km^2).

In Phase 2 the nutrient release will only be significant if the excess moraine clay is dredged by a cutter suction dredger, and the slurry is discharged directly at the disposal site. However, in this case the nutrients will mainly be discharged into the lower layer of Storebælt, which normally has a high background concentration of nutrients.

OPERATION	RATE OF NUTRIENT RELEASE		DURATION
	Nitrogen (N)	Phosphorus (P)	
	kg/day		months
<u>Phase 1 up till Nov. 1989</u>			
Romsø SE: sand extraction	250-280	16-20	6
Slettings Grund (Musholm, Romsø): sand extraction	60	2	15
CD: sand dredging (James Ensor)	60	2	3
Sprogø basins: soft infilling	140-450	40-140	3
Sprogø east ramps:			
sand reclamation (James Ensor)	60-140	2-10	7
sand reclamation (Haarlem)	100-200	7-12	2
Knudshoved: sand reclamation	30	1	12
Halsskov: sand reclamation	140	10	1
<u>Remaining Phase 1</u>			
Romsø SE: sand extraction	250-280	16-20	3
Slettings Grund (Musholm): sand extraction	60-160	2-8	4
CD: sand dredging (Leonardo)	14	3	3
Sprogø basins: soft infilling	400-900	140-270	1½
Sprogø east ramps: sand reclamation (Leonardo)	400	25	2
Sprogø west ramp: sand reclamation	30-80	1-4	3
<u>Phase 2</u>			
CD and Route-T:			
clay dredging (mech. dredger)	0.3	0	16
(Leonardo)	3	0	12
Sprogø NW deposition:			
clay dumping (mech. dredged)	8	0	16
clay slurry discharge (Leonardo)	120	0	12

Table 6.1 Estimated rate of nutrient release at main operations in Phase 1 and 2.

NUTRIENT	NUTRIENT SOURCES		REMARKS
	Inorganic-N	Ortho-P	
<u>Area Sources</u>			
Entrainment from lower layer	14 kg/km^2/day	5 kg/km^2/day	Summer average 1975-79
Atmosphere deposit	3 kg/km^2/day	0.04 kg/km^2/day	Yearly average 1978-81
<u>Point Sources</u>			
Nyborg town + catchment area	2,500 kg/day	125 kg/day	Yearly average 1976-85
	900 kg/day	84 kg/day	Summer average 1976-82

Table 6.2 Other nutrient sources of the upper layer in Storebælt (not complete).

6.2 Total Release

The total release of nutrients during the construction works for the Link is listed in Table 6.3.

PHASE	AMOUNT OF RELEASED NUTRIENTS	
	Nitrogen (N)	Phosphorus (P)
	---------- kg	----------
<u>Phase 1</u>		
Up till Nov. 1989	139,000	11,000
Remaining Phase 1	110,000	17,000
Total Phase 1	240,000	29,000
<u>Phase 2</u>		
Mechanical dredged moraine clay	5,000	100
Cutter suction dredged moraine clay	37,000	100
<u>Total Phase 1+2</u>		
Mech. dredged moraine clay (Phase 2)	254,000	29,000
Cutter suction dredged moraine clay (Phase 2)	286,000	29,000

Table 6.3 Estimated released amounts of nutrient during the construction works.

The total release for Phase 1+2 corresponds to less than ½ year's average N-discharge from Nyborg town+catchment area and about ½ year's P-discharge.

6.3 Nutrient Carried to Shallow Areas

The released nutrients can be taken up either by phytoplankton or by benthic macrovegetation. Only if the plume of silt and nutrient is moving over shallow areas a fraction of the nutrient is taken up by the macro vegetation. The following four shallow areas close to sediment operations are considered:

Sprogø north: 7,0 km^2
Sprogø south: 13,0 km^2
Halsskov : 5,4 km^2
Knudshoved : 17,2 km^2

In Table 6.3 an estimate of the portion of nutrients that may be built into local benthic vegetation is given. The estimate is based on a calculated residence time for the water mass containing the nutrient surplus. The amount of nutrient assimilated by the bottom vegetation is assumed to be proportional to the residence time, assuming that all nutrient is assimilated after 16 hours. The residence time is calculated from the fraction of suspended sediments of a corresponding settling velocity, which settles within the area considered according to the System 21 calculations.

OPERATION SITE	MACROVEGETATION				PLANKTON
	Sprogø N	Sprogø S	Knudsh.	Halsskov	
	per cent of total release				
Sprogø, west ramp	5	15			80
Basins, emissions	10	15			75
Sprogø east ramp:					
south current	10	60			30
north current	40	15			45
Compensation dredging	4	9			87
Dumping, Sprogø NW	7	6			87
Knudshoved, land fill			52		48
Halsskov, construction harbour				26	74

Table 6.3 Percentage of released nutrients incorporated into macrovegetation in shallow areas and into phytoplankton.

Table 6.4 lists the estimated amounts of N and P built into macrovegetation and phytoplankton, respectively.

PERIOD	MACROVEGETATION								PLANKTON	
	Sprogø North		Sprogø South		Halsskov		Knudshoved			
	N kg	P kg	N kg	P kg	N kg	P kg	N kg	P kg	N kg	P kg
Phase 1										
1988:	0	0	0	0	0	0	4565	120	21769	573
1989:	12371	1167	15732	3361	1790	99	525	24	82419	6146
1990:	7892	1559	24731	3184	0	0	1333	43	76088	12462
Phase 2, grab and splitbarges										
1991 to 1994:	299	3	336	8	0	0	0	0	4610	86
Phase 2, cutter suction dredger and pipe										
1991 to 1993:	2794	3	2475	8	0	0	0	0	37616	86

Table 6.4 Amount of N and P incorporated into macrovegetation and planktonic algae.

The emissions of nutrient in 1989 and 1990 are the highest. Between 25-30% of these are expected to be incorporated into the macrovegetation. The areas south and north of Sprogø are expected to be the most affected.

Two alternatives for disposal of clay from the compensation area during Phase 2 are presented. The first estimate is based on the use of mechanical dredger (grab), transportation by splitbarges and dumping at Sprogø NW. The second is based on the use of a cutter suction dredger with a pipe to the dumping area north of Sprogø. The estimates show that the cutter suction dredger gives about 10 times higher nutrient releases than the use of grabs and barges.

7. EFFECTS ON OXYGEN CONDITIONS

7.1 Potential Effects

The mechanisms affecting the oxygen conditions during dredging and deposition operations are outlined in Fig. 7.1. The mechanisms include:

A. Initial oxygen consumption in the vicinity of the operation position, caused by hydrogen sulphide (H_2S), other sulphur compounds, reduced iron and labile organic compounds. The consumption will reduce the oxygen concentration in the water volume passing the position.

B. Changed oxygen consumption at the sea bed of the dredging position due to exposure of underlying sediments. This may affect the local oxygen concentration of the upper layer and in the diffusive boundary layer just above the sediment surface.

C. Modification in oxygen consumption of the sea bed (primary process), arising from spreading of lost inorganic and organic sediment during the operation which settles eventually. If the sediment has a high oxygen demand this will introduce a risk of increased sea bed oxygen consumption. The increased consumption will reduce the oxygen concentration in the lower layer and in the diffusive boundary layer just above the sediment surface. For sediments with very low oxygen demand the spreading may not increase the sea bed oxygen consumption. It may even reduce the consumption for a limited period due to the diffusion limiting effect of adding a new layer on top of an active oxygen consuming sea bed.

D. Release and spreading of nutrients. During spring and summer the surface layer is nearly devoid of inorganic nutrient compounds as a result of organic production. Additional input of nutrients will lead to an extra organic production. Organic matter settles, and consequently the oxygen consumption of the sea bed is increased (secondary process). Increased consumption will reduce the oxygen concentration in the lower layer as well as in the diffusive boundary layer just above the sediment surface.

These four mechanisms, affecting the oxygen conditions in the Storebælt during dredging and disposal operations, have been evaluated to elucidate to what extent the marine earth work affects oxygen conditions.

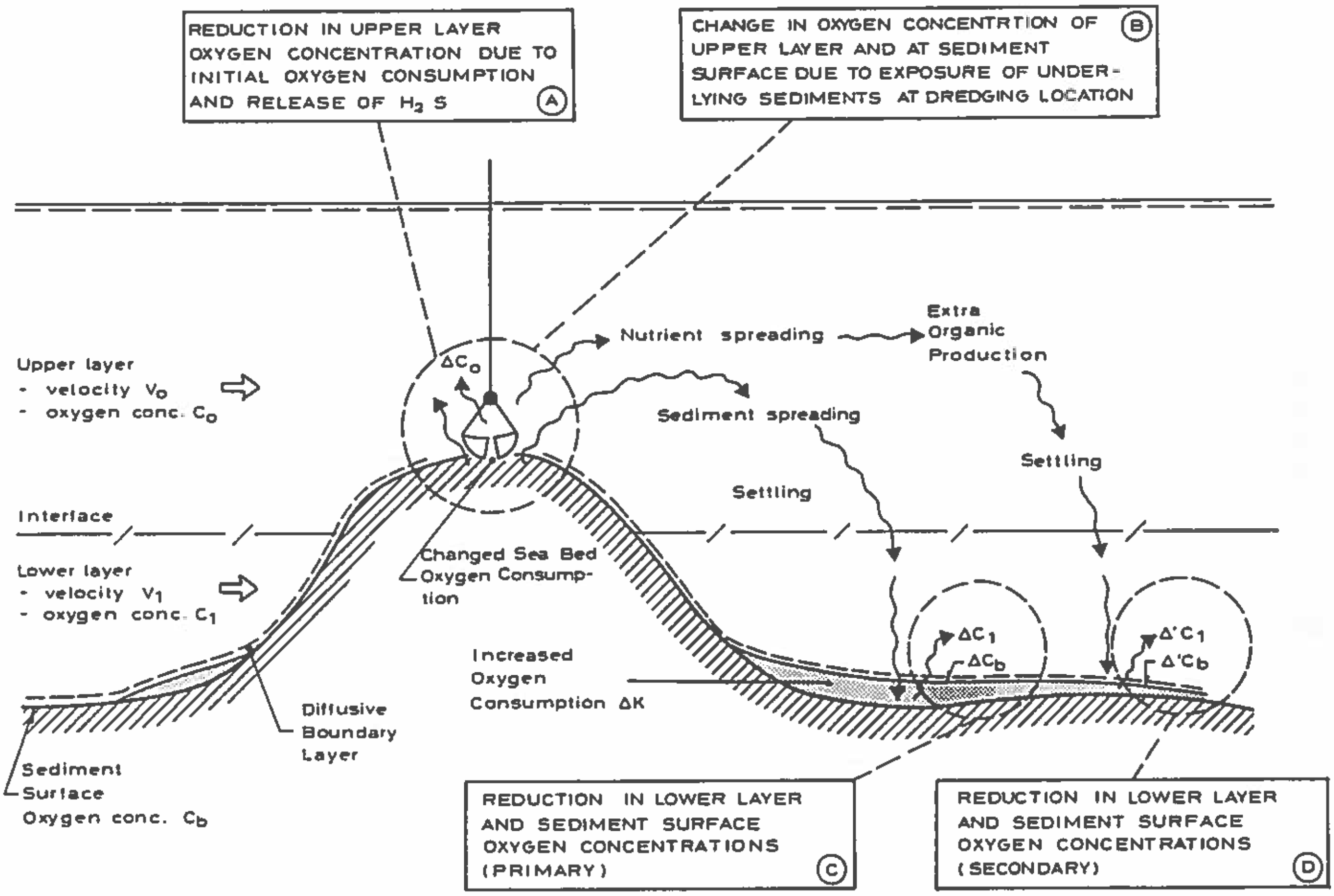


Fig. 7.1 Sketch of the mechanisms affecting oxygen conditions during marine earth work operations.

The hydrographic conditions in Storebælt are well known. Table 7.1 shows the main features concerning the current in the upper layer and lower layer of Storebælt, valid for the alignment in Østerrenden. In the lower layer north and south of Østerrenden the current velocity is approx. 45% of the value given due to the larger cross section area. Upper layer flow will fluctuate much in direction, whereas flow in the lower layer will be more permanently southbound.

UPPER LAYER	Centre of Østerrenden	Sprogø Østrev
	----------- m/s	------------
Velocity statistics:		
50% of time exceeding	0.50	0.40
75% - - -	0.25	0.20
86% - - -	0.15	0.12
~91% - - -	0.10	0.08

LOWER LAYER	Centre of Østerrenden	
	Velocity	Average duration
	m/s	hours
Velocity statistics:		
50% of time exceeding	0.35	80
90% - - -	0.10	37
5% of time stagnant	0.00	40

Table 7.1 Current statistics used for the environmental assessments. Ref. 29.

Oxygen concentrations of the upper and lower layers have been recorded at Station 39 (Halskov Rev) in Østerrenden. Fig. 7.2 shows the recordings taken with approximate intervals of 1 month from the period 1984-89. In the lower layer oxygen concentrations are at a minimum during late summer. The recorded minimum in this period is around 1.9 mg 0_2/l.

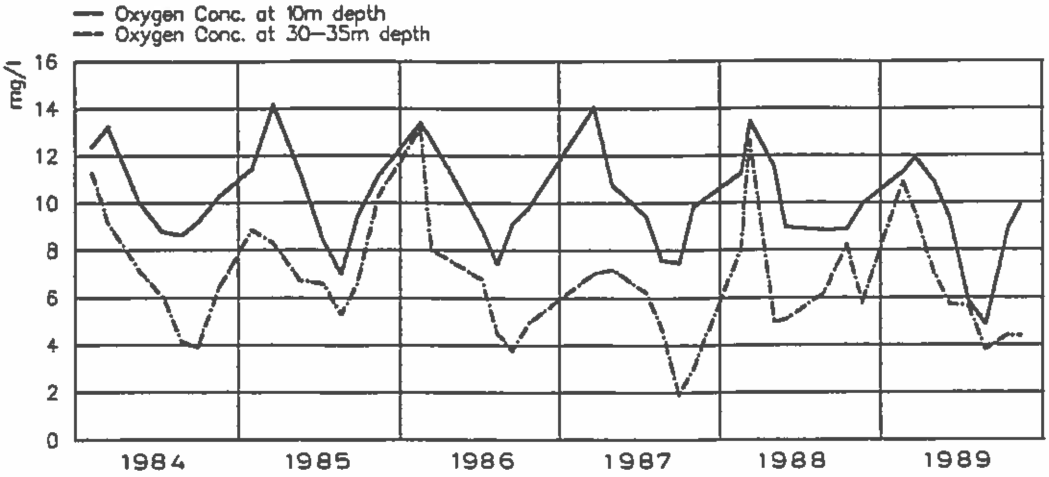


Fig. 7.2 Recorded oxygen concentrations at Station 39 (Halsskov Rev) in Østerrenden.

The upper layer concentration is usually close to saturation (8-14 mg/l). The recorded minimum is 4.9 mg O_2/l for the period 1984-89.

An example of the oxygen profile in Østerrenden as recorded during monitoring in September 1989, Fig. 7.3, demonstrates that the oxygen concentration gradually changes between -7 and -20 m in depth due to mixing between the upper and lower layer (entrainment). Also below -20 m a slight stratification might be found.

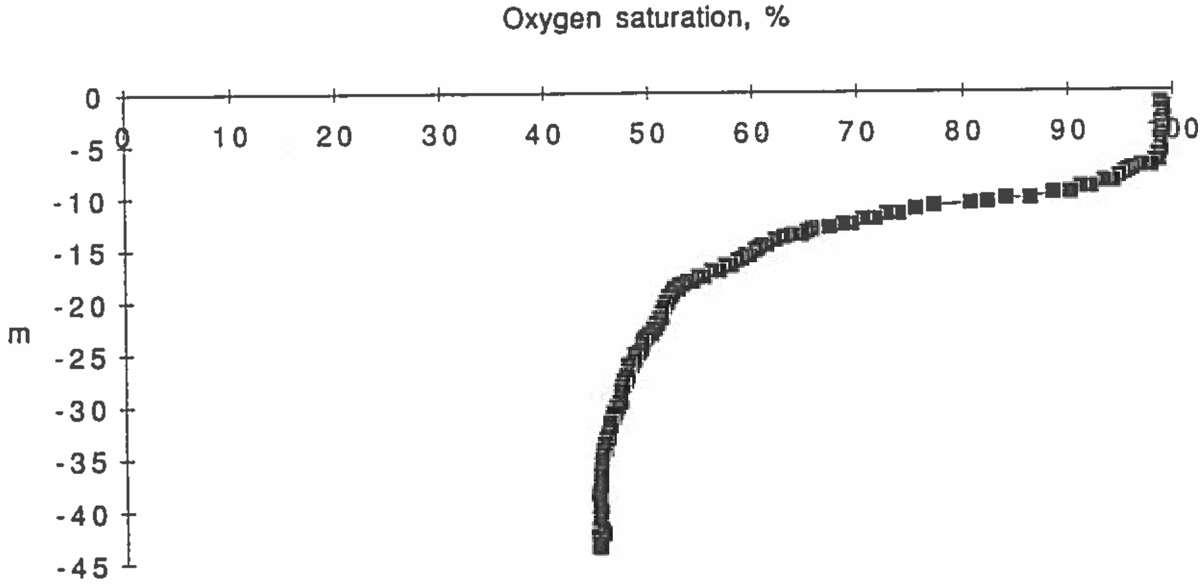


Fig. 7.3 Oxygen saturation profile from Østerrenden. Station F105, 21 September 1989.

The impacts on oxygen concentrations have been based on the dredging/disposal capacities given in Chapter 4. If a larger capacity is used, the impacts during the operation will increase as the impact is intensity related rather than cumulative. At the same time, however, the period of impacts will be shorter for a given dredging volume.

The characteristics of the sediments, affecting the oxygen conditions, have been analysed on sediment samples taken in the dredging area. The sediment characteristics and methods of analysis are described in Appendix A.

The dredging volumes, spillage percentages brought in suspension, knowledge of hydrographic conditions and present knowledge of sediment characteristics form the basis of the present assessments of impacts on oxygen concentrations from the dredging. The precision of the assessments depends primarily on the knowledge of the final operation of dredging procedures and the field behaviour of the sediment processes analyzed in the laboratory.

Simple conservative calculations have been used rather than more sophisticated methods, as long as these calculations indicate a negligible risk of detrimental effects.

7.2 Initial Oxygen Consumption

The initial oxygen consumption affects the oxygen concentrations of the ambient water in the vicinity of the dredging position. For deposition operations the initial oxygen consumption is only expected to be significant for sediments dredged by a cutter suction dredger and transported in a pipe to the disposal position.

Among the sediments to be dredged the soft sediments (gyttja, peat and surface sediments) have the largest oxygen consumption per volume of sediment.

The water affected by initial oxygen consumption will form a plume downstream the operation position. Part of the initial consumption will take place very close to the position, whereas the rest will be activated further downstream.

For the assessment of reduction in oxygen concentration the initial consumption is assumed to affect the oxygen content in a limited current cross section area, specified by the water depth (upper layer depth) and 100 m wide, see Fig. 7.4. The initial consumption is distributed evenly over this cross section. The initial consumption is set at the analyzed SOD_{24} value (Suspended Oxygen Demand within 24 hours) given in Appendix 1. Only a part of the production rate is expected to contribute to the initial consumption, see Table 7.2.

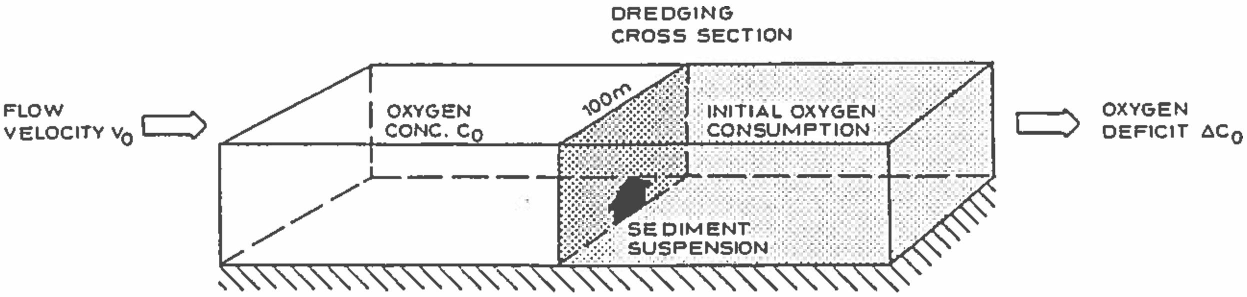


Fig. 7.4 Model for initial oxygen reduction.

Table 7.2 summarizes the initial reduction in oxygen concentrations for six main operations. In Case 1 - 5 the initial reduction affects upper layer, whereas Case 6 may reduce the oxygen concentration in the lower layer due to the discharge of slurry at water depths of about 15 m. Due to variations in the ambient current speed the initial reduction will vary in time.

Downstream the initial cross section the plume will mix with unaffected water. The concentration deficit will thus diminish downstream.

CASE	1	2	3	4	5	6
Area	Romsø SE	CD(east)	CD(east)	CD(west)	CD(East)	Sprogø SW
Equipment	Trailing	Trailing	Cutter	Cutter	Mech.	Slurry Disch
Sediment	Sand	Sand	Sand	Soft	Clay	Clay
Prod. rate	0.66 m^3/s	0.66 m^3/s	0.46 m^3/s	0.23 m^3/s	0.46 m^3/s	0.23 m^3/s
Affected prod.	60%	11%	10%	10%	10%	10%
SOD_{24} $kgO_2/m^2/dag$	0.22	0.22	0.22	0.61	0.30	0.30
Water depth	13 m	6 m	6 m	4 m	6 m	10 m
	---------------------- mg O_2/l --------------------					
Maximum oxygen reduction in						
50% of time	0.2	0.1	0.05	0.1	0.01	0.2
90% of time	1.0	0.5	0.2	0.4	0.05	0.6

Table 7.2 Estimated initial reduction in oxygen concentration for six main cases of marine earth work operations. Case 1-5 affect upper layer, whereas Case 6 affects lower layer.

This simple analysis overestimates the expected oxygen deficit near the dredging location, since it is based on an initial oxygen consumption corresponding to the 24 hours SOD value.

In the overflow from the sedimentation basin low oxygen concentrations may occur depending on the construction of the sedimentation basins (oxygen transfer from the atmosphere) and the overflow.

In the performed surveys in 1989 no measurements of oxygen concentration have been taken in the plume close to the earth work activity. Further away (2-4 km), the measurements have not shown any oxygen reduction.

7.3 Effect of Exposed Underlying Sediments

In the CD area and in sand extraction areas the underlying sea bed will be exposed after the dredging. The new sea bed with different sediments exposed will result in a change in sea bed oxygen consumption. Experiments have shown (Appendix 1) that oxygen consumption of the actual sediment types just after exposure is expected to be 1.0 - 1.4 g $O_2/m^2/day$. This value should be compared to the oxygen consumption of the existing bed of 1.4 - 2.6 g O_2/m^2/day found in the laboratory experiments.

Thus, the effect of exposure of underlying bottom is to reduce the oxygen consumption just after exposure. After some time the effect will vanish due to natural settling of dead organic matter.

7.4 Increased Sea Bed Oxygen Consumption due to Sedimentation for individual Operations

The increase in sea bed oxygen consumption has been based on the sediment spreading calculated in Section 5.2 and the laboratory experiments of increased oxygen consumptions for a range of settled layer thicknesses.

A conservative interpretation of the experiments has been used for the assessments, see Appendix A. Further, since the experiments showed that the increased sea bed oxygen consumption for superposed sediments was undetectable after 3 weeks under laboratory conditions, the used thickness of superposed sediments (H) has been set at the 1 months settling layer thickness.

Resuspension of sediments has not been taken into account in the calculations. Since the time scale for the oxygen consumption process (1 month) is comparable to the interval between resuspension events, situations with 1 month or more of settling without resuspension are likely to appear. Therefore the calculations without resuspension will reflect the maximum increase in sea bed consumption quite well.

The resuspended sediments will eventually settle further away in the natural settling areas of Storebælt, see Fig. 5.3. Since the transfer time will be relatively long, most of the oxygen consumption is likely to have taken place before final settling, and the effect on the local oxygen consumption will be limited.

Fig. 7.5 shows the calculated distributions of increased sea bed oxygen consumption for six main operations. Table 7.3 shows the calculated areas affected by increased oxygen consumptions and the maximum increase in consumption.

The six operations are:

1: Dredging sand at Romsø SE, 12,800 m^3/day (trailing suction: James Ensor)

2: Dredging sand (CD) and reclamation (Sprogø), 12,800 m^3/day (trailing suction: James Ensor)

3: Dredging sand (CD) and reclamation (Sprogø), 40,000 m^3/day (cutter suction: Leonardo)

4: Dredging soft (CD west) and reclamation in basin (Sprogø), 20,000 m^3/day (cutter suction: Leonardo)

5: Dredging moraine clay (CD), 10,000 m^3/day (mechanical dredgers)

5B: Dredging moraine clay (CD) and dumping (Sprogø NW), 10,000 m^3/day (mechanical dredgers/splitbarges)

CASE	INCREASE IN SEA BED OXYGEN CONSUMPTION							DURATION
	Area Affected by Stated Increase (ΔK in g O_2/m^2/day)					Max. Increase		
	>0.5	>0.2	>0.1	>0.05	>0.01	Total	Outside Dredging Area	
	km^2					-g O_2/m^2/day-		months
1: Romsø SE sand dredging (trailing)	2	18	32	57	213	1.4	0.7	8
2: CD sand dredg. and Sprogø recl. (trailing)	0	6	10	16	62	0.46	0.46	3
3: CD sand dredg. and Sprogø recl. (cutter suction)	½	6	11	21	64	1.0	1.0	1-2
4: CD(west) soft and basin depos. (cutter suction)	0	1½	4	10	80	0.49	0.31	~1
5: CD clay dredg. excl. deposition (mech. dredger)	0	0	0	0	0	0.02	0.01	14
5B:CD clay dredg. and dumping at Sprogø NW (mech. dredger)	0	2	5	19	40	0.38	0.28	14

Table 7.3 Areas affected by increased sea bed oxygen consumption due to settling of suspended sediments from six main earth work operations. Natural comsumption about 1.4-2.6 g O_2/m^2/day.

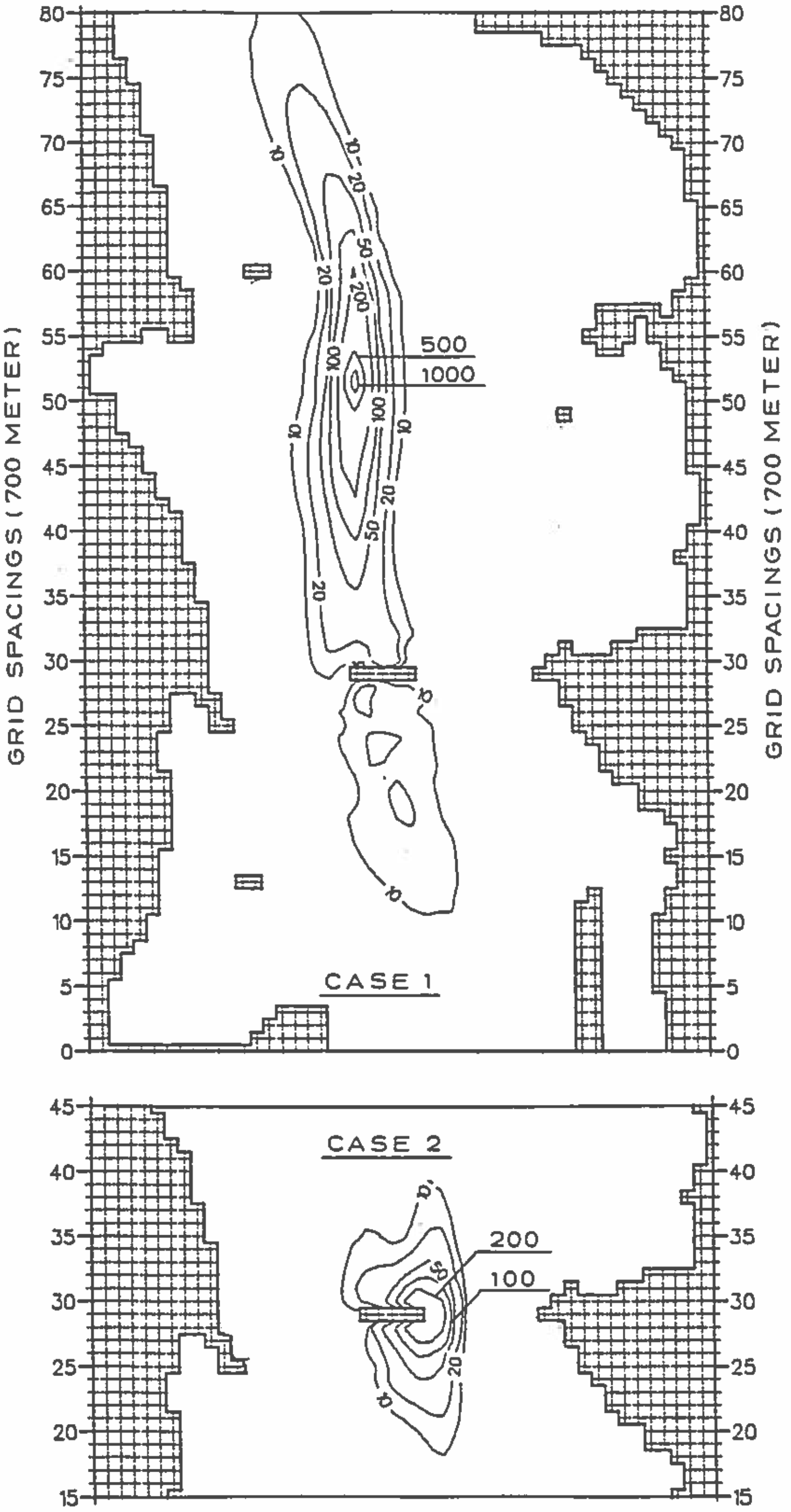


Fig. 7.5a The calculated distributions of increased sea bed oxygen consumption for six main operations (Case 1+2). Unit mg O_2/m^2/day. Natural consumption about 1400-2600 mg O_2/m^2/day.

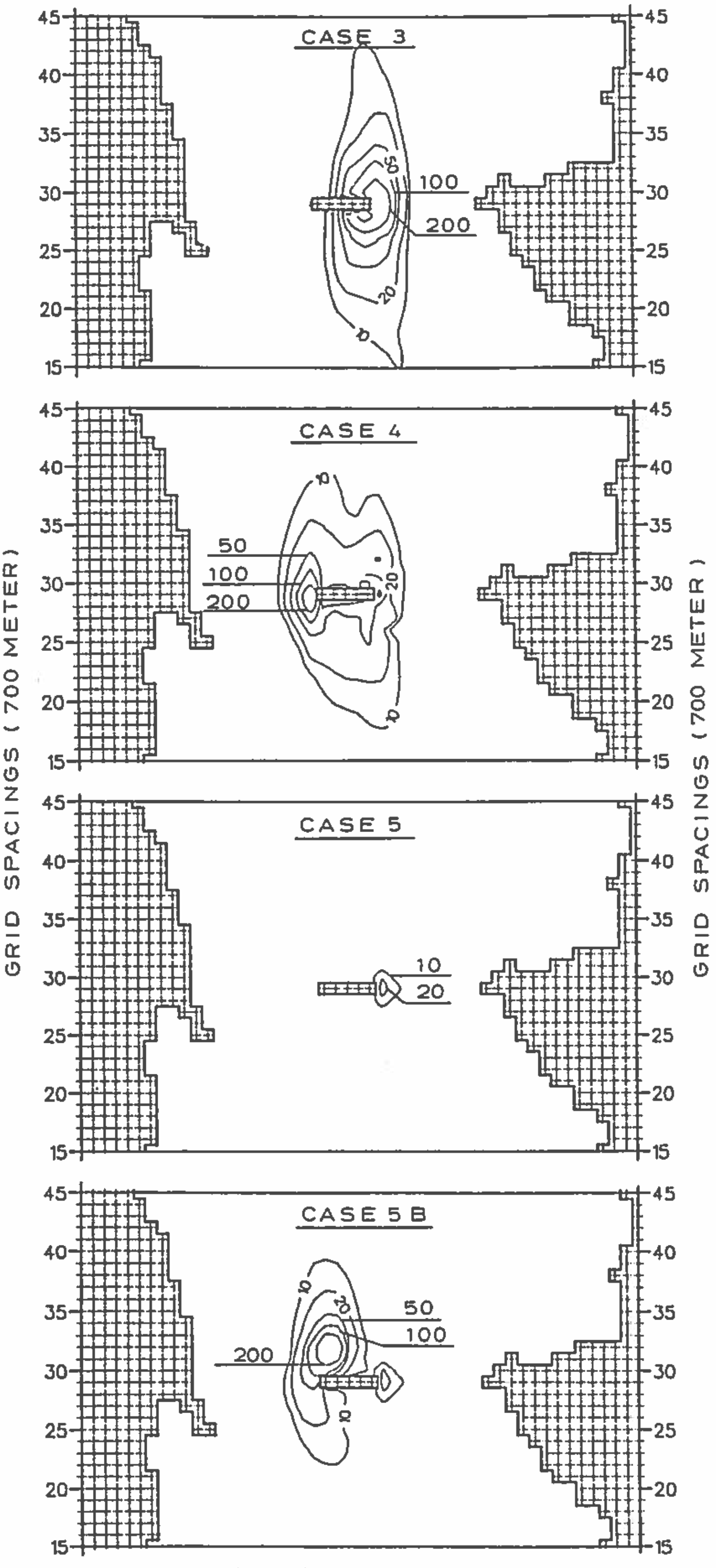


Fig. 7.5b The calculated distributions of increased sea bed oxygen consumption for six main operations (Case 3 - 5B). Unit mg $O_2/m^2/day$. Natural consumption about 1400-2600 mg $O_2/m^2/day$.

7.5 Increased Sea Bed Oxygen Consumption due to Release of Nutrients

The released nutrients become incorporated in phytoplankton and in bottom vegetation on shallow areas near major sediment operations. The affected shallow areas include sea bed north and south of Sprogø and sea bed along the coastline near Knudshoved and Halsskov. This surplus production of organic matter results in an additional oxygen consumption when decomposed.

Estimation of surplus oxygen demand is based on the following assumptions:

- Macro vegetation C:N:P = 142:7:1
- Plankton algae C:N:P = 40:7:1
- O_2/C conversion factor = 3.3 g O_2/g C
- Produced plankton is exported to the lower layer
- No recycling of incorporated nutrient

The nutrients are distributed between macrovegetation and phytoplankton according to Section 6.3.

The produced plankton is assumed to decompose continuously throughout the production period. For the bottom vegetation it is assumed that half of the production is decomposed within one month during fall. The rest of the produced bottom vegetation biomass decomposes continuously throughout the production period due to respiration and secondary consumers.

It is assumed that the produced plankton carbon settles to the lower layer, where it decomposes. The released nitrogen and phosphorous is trapped in the lower layer away from the photic zone. Recycling of nutrient is therefore not included in the calculations.

Referring to the theoretical concept of "regenerated" and "exported" carbon and nutrient cycling (Ref. 44), addition of nutrients is assumed to result in exported production.

Long term registrations of lower layer oxygen and nitrogen concentrations support this assumption as the increased load of nutrient to the Danish waters is followed by a stoichiometric increase in nitrogen and decline in oxygen concentration in the lower layer (Ref. 30).

The possibility of a bloom of rapid regenerating phytoplankton species is discussed in Chapter 10.

The calculated production and the surplus oxygen demand in the lower layer are shown in Tables 7.4 and 7.5.

PERIOD	MACROVEGETATION (Shallow Areas)				PLANKTON
	Sprogø		Halsskov	Knuds-hoved	
	North	South			
Affected area:	7 km^2	13 km^2	5,4 km^2	17,2 km^2	~350 km^2
	g C/m^2/year				g C/m^2/day
Phase 1					
1988:	0.0	0.0	0.0	5.3	0.0017
1989:	35.3	36.7	6.6	0.6	0.0064
1990:	31.6	38.0	0.0	1.5	0.0068
Phase 2. Grab and splitbarges:					
1991-1994	0.2	0.1	0.0	0.0	0.0001
Phase 2. Cutter Suction dredger and pipe:					
1991-1994	$\leq$2.0	$\leq$1.0	0.0	0.0	$\leq$0.0007

Table 7.4 Production of plankton and macrovegetation for impact areas due to nutrient release from sediment operations.

PERIOD	SHALLOW AREAS (Upper Layer)				PLANKTON
	Sprogø		Halsskov	Knuds-hoved	(Lower Layer)
	North	South			
Affected area:	7 km^2	13 km^2	5,4 km^2	17,2 km^2	~350 km^2
	g O_2/m^2/day in autumn				g O_2/m^2/day
Phase 1					
1988:	0.0	0.0	0.0	0.3	0.0056
1989:	2.2	2.3	0.4	0.04	0.0211
1990:	2.0	2.4	0.0	0.1	0.0224
Phase 2. Grab and splitbarges:					
1991-1994	0.01	0.01	0.0	0.0	0.0003
Phase 2. Cutter suction dredger and pipe:					
1991-1994	$\leq$0.1	$\leq$0.05	0.0	0.0	$\leq$0.0024

Table 7.5 Daily increases in sea bed oxygen consumption due to nutrient release from sediment operations.

The daily production and the daily oxygen consumption are both based on a productive period from March to October. The estimated increases in consumption due to nutrient release appear only during this period.

Two alternatives for Phase 2 are discussed. One where material from the compensating area is excavated by grab and dumped from splitbarges at a site Sprogø NW, and another alternative where the sediment is dredged by a cutter suction dredger and boosted to the dumping site in pipes.

Compared with the grab method, use of a cutter suction dredger is expected to release more nutrients. The potential release of nutrients is 10 times higher with the cutter suction dredger, but a part of the nutrient will be trapped in the lower layer, because the sediment water mixture is discharged in the lower layer. Gradually some of the nutrient will be mixed into the upper layer. Tables 7.4 and 7.5 give maximum affects for cutter dredging, assuming that all released nutrients are transferred into the upper layer.

The highest surplus oxygen consumption pr. m^2 is expected during the autumn on areas covered by macrovegetation around Sprogø and near Halsskov and Knudshoved. Degradation of macrovegetation is assumed to happen in the upper layer where reaeration and current transport oxygen to the affected areas. Oxygen depressions caused by degradation of the macrovegetation are only expected to occur locally in sheltered areas with calm waters.

In contrast to the macrovegetation, degradation of planktonic algae are assumed to take place in the lower layer, where vertical transport of oxygen are hampered by the halocline (interface). Therefore, the calculated surplus oxygen consumption is assumed to create a corresponding depression in the oxygen concentration.

7.6 Effect of Increased Sea Bed Consumption on Oxygen Concentrations

The effects of increased sea bed oxygen consumption on oxygen concentrations is only quantified with respect to effects in the lower layer of Storebælt. Usually the upper layer is close to saturation and there will be no risk of critical low oxygen concentrations for the listed surplus sea bed consumptions in Table 7.5. However, in local areas with eelgrass vegetation, reduced oxygen concentrations in the vegetation may occur under low ambient current conditions at nighttime. This is discussed in Chapter 10.

The total increase in sea bed oxygen consumption is found by adding the calculated effect from settling of suspended sediments and the effect of nutrient spreading. Table 7.3 and Table 7.5 show that the maximum increased sea bed consumption (near the operation) is totally dominated by the effect of sediment spreading. Further away the effect of nutrient release may dominate.

The increased sea bed consumption will reduce the oxygen concentrations in the free water layer above the sea bed and in the boundary layer just above the sediment surface as outlined in Fig. 7.6.

The effect of increased sea bed consumption on oxygen concentrations has been quantified for the free water layer (Case A and B of Fig. 7.6). For the boundary layer effects (Case C) the analysis is more qualitative.

The approach of the analyses are:

Case A Reduction in oxygen concentration during flowing conditions

When passing the area of increased sea bed oxygen consumption, a water column of lower layer water flowing northwards or southwards will have its oxygen concentration reduced. As a 'worst case' situation a water column following an artificial trajectory, passing the most affected part of the sea bed on its passage through the belt, is considered. No real current trajectory may follow this path. For this 'worst case' trajectory the reduction in oxygen concentration is calculated.

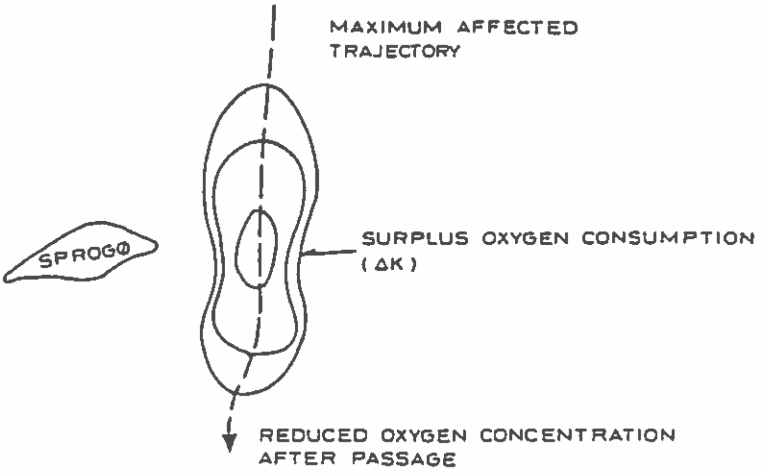
Case B Reduction in oxygen concentration during stagnant conditions

Stagnant situations lasting for more than a few hours may occur in the lower water layer, whereas the tide ensures a minimum current speed in the upper layer. During a stagnant situation the water column of the lower layer above a sea bed area with increased oxygen consumption will have its oxygen concentration reduced.

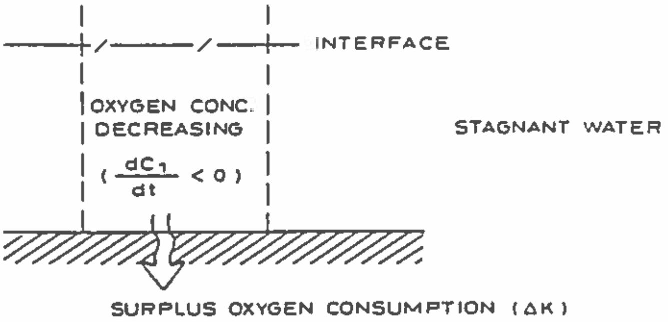
Case C Critical oxygen conditions at sediment surface

The oxygen gradient in the boundary layer depends among others on the oxygen consumption of the sediment. The gradient results in a lower concentration at the sediment surface than in the overlying water mass. Under certain environmental conditions (high sediment oxygen demand, low oxygen concentration in the water mass, low current velocity), the concentration at the sediment surface (C_b) will approach zero. If the sediment oxygen

CASE A Reduction in oxygen concentration during flowing conditions



CASE B Reduction in oxygen concentration for stagnant water



CASE C Critical oxygen conditions of sediment surface

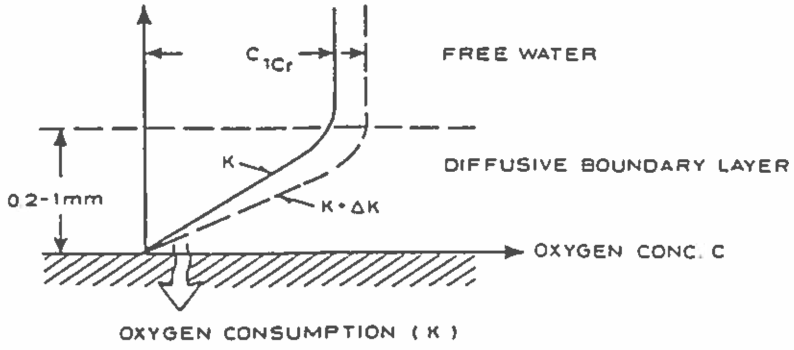


Fig. 7.6 The three main cases of effect on oxygen concentrations in the lower layer of the surrounding sea due to increased sea bed consumption.

> consumption is increased, the zero situation will occur at a higher oxygen concentration in the free water mass (C_1) than previously, i.e. the critical concentration (C_{1Cr}) has increased. Thus, the risk or frequency of critically low oxygen concentrations at the sediment surface increases if the oxygen consumption of the sediment increases.

It should be noted that the mechanisms in Case C and the present baseline situation at the sediment surface are not known in detail. Thus, no oxygen concentrations at the sediment surface are available from field measurements. However, situations with very low oxygen concentrations have been observed, and a carpet of sulphur bacteria have been found recently near Halsskov Rev and Sprogø Østrev. Such a carpet indicates that oxygen concentrations have been close to zero at the sediment surface for some time.

The thickness of the diffusive boundary layer ranges between approx. 1 mm for low current velocities to approx. 0.2 mm for high velocities. Field measurements of near bottom oxygen concentrations are normally recorded 0.1 - 0.3 m above the bottom.

Therefore, Case C calculations can only be taken as an indicator of the magnitude of the effect in the diffusive boundary layer of increased sea bed oxygen consumption.

Case A

The maximum affected trajectory case for the lower layer has been evaluated for the six main earth work operations examined in Section 7.4. The height of the water column of lower layer water following the trajectory has been set at 15 m for the Romsø SE dredging and at 5 m for the other operations examined.

The resulting reduction in oxygen concentration is given in Table 7.6.

CASE	CURRENT CONDITIONS (lower layer)					
	Normal			90% exceeded		
	Sediment Spreading	Nutrient Release	Total	Sediment Spreading	Nutrient Release	Total
	mg O_2/l					
1: Romsø SE sand dredging (trailing)	0.03	0.003	0.03	0.11	0.01	0.12
2: CD sand dredg. and Sprogø recl. (trailing)	0.012	0.006	0.02	0.04	0.02	0.06
3: CD sand dredg. and Sprogø recl. (cutter suction)	0.015	0.012	0.03	0.04	0.04	0.09
4: CD(west) soft and basin depos. (cutter suction)	0.011	0.03	0.04	0.04	0.09	0.13
5: CD clay dredg. excl. deposition (mech. dredger)	0.001	~0	0.001	0.003	~0	0.003
5B:CD clay dredg. and dumping at Sprogø NW (mech. dredger)	0.009	~0	0.01	0.03	0.001	0.03

Table 7.6 Oxygen reduction along the maximum affected trajectory in the lower layer in Storebælt caused by surplus sea bed oxygen consumption from sediment spreading and nutrient spreading.

Case B

The effect of increased sea bed oxygen consumption during stagnant current condition is shown in Table 7.7. The duration of the flow condition is set at 40 hours, which is the average length of stagnant conditions recorded in the lower layer in Østerrenden. The reductions in oxygen concentrations have been calculated for heights of the lower layer column ranging from 1 to 15 m.

SURPLUS SEA BED OXYGEN CONSUMPTION ΔK	LOWER LAYER COLUMN HEIGHT 1 m	2 m	5 m	10 m	15 m
g O_2/m^2/day	mg O_2/l				
0.01	0.017	0.008	0.003	0.002	0.001
0.05	0.08	0.04	0.017	0.008	0.005
0.1	0.17	0.08	0.03	0.02	0.01
0.5	0.8	0.4	0.17	0.08	0.05
1.0	1.7	0.8	0.3	0.2	0.1

Table 7.7 Reduction in oxygen concentration for a water column exposed to a surplus oxygen consumption during stagnant flow conditions for 40 hours.

Among the main earth work operations examined affecting the lower layer the maximum surplus of oxygen consumption is obtained by the sand dredging at Romsø SE (maximum $\Delta K = 0.7$ g O_2/m^2/day, column height 15 m), which according to Table 7.7 will result in less than a 0.1 mg O_2/l reduction in the oxygen concentration.

For the area near Sprogø the maximum surplus oxygen consumption of the lower layer will be 0.1-0.2 g O_2/m^2/day (sand dredging by James Ensor, see Case 2 in Fig. 7.5), which according to Table 7.7 will result in a reduction of 0.2-0.3 mg O_2/l for a 1 m high lower layer and less for higher layers.

Dumping of moraine clay dredged mechanically is estimated to reduce the lower layer oxygen concentrations during stagnant situations outside the dumping area in a hypothetical 1 m high water layer by maximum 0.4 mg O_2/l and less for higher layers (maximum $\Delta K = 0.3$ O_2/m^2/day).

Case C

The assessments are based on a simplified oxygen transport equation for the diffusive boundary layer:

$$C_1 - C_b = R \cdot K$$

where R is the transport resistance for oxygen through the boundary layer and K the sea bed oxygen consumption. The transport resistance is the resulting resistance from turbulent and molecular diffusion and bio-transport of oxygen to the sea bed.

Assuming R unaffected and a situation where the sediment surface oxygen concentration C_b reaches zero, the impact on the critical free water concentration C_{1Cr} of a surplus sea bed oxygen consumption ΔK is:

$$\frac{C_{1Cr}(K + \Delta K)}{C_{1Cr}(K)} = \frac{K + \Delta K}{K}$$

Thus, the relative increase in critical free water oxygen concentration is assumed to be proportional to the relative increase in K. The reference sea bed oxygen consumption (from the bottom core experiments) is 1.4-2.6 g O_2/m^2/day. In Table 7.8 the impact on the critical free water oxygen concentration from surplus bottom oxygen consumptions is shown.

	Surplus Sea Bed Oxygen Consumption ΔK (g O_2/m^2/day)				
	0.5	0.2	0.1	0.05	0.01
Relative increase in free water critical oxygen concentration (C_{1Cr})	20-35%	8-14%	4-7%	2-4%	0.4-0.7%

Table 7.8 The effect of increased sea bed oxygen consumption on the critical free water oxygen concentration. Actual ΔK values given in Fig. 7.5.

No reliable information is available today of the reference critical free water oxygen concentration. The critical value is expected to depend both on the oxygen consumption and the local hydraulic conditions. Thus, no exact impact of the frequency of critical sediment oxygen concentrations can be given.

Fig. 7.7 shows the accumulated frequency of lower layer oxygen concentration from Østerrenden. The figure can be used to demonstrate, conceptually, the impact of increased sea bed oxygen consumption on the frequency of critical sea bed oxygen concentration.

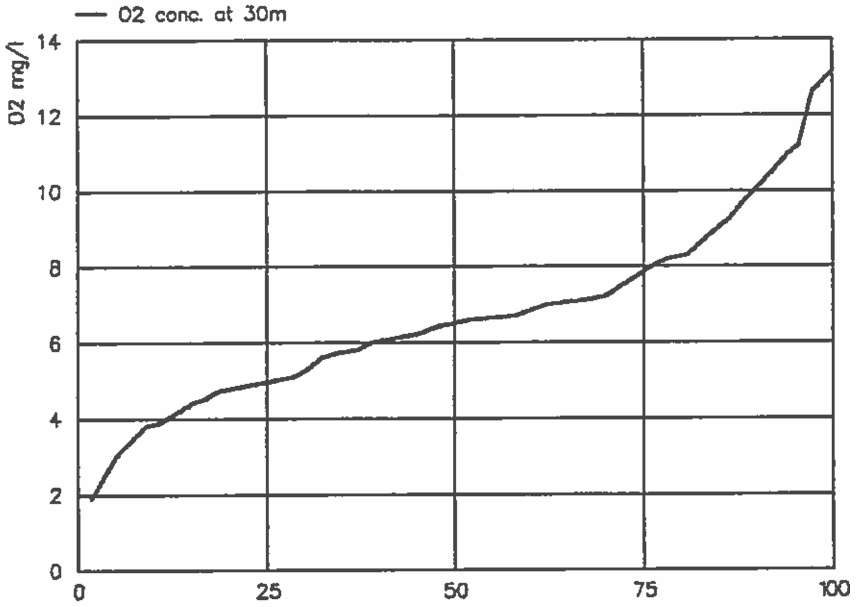


Fig. 7.7 Accumulated frequency distribution of lower layer oxygen concentration in Østerrenden (Station 39, 1984-89).

If one, for example, assumes the reference value of C_{1Cr} = 4.0 mg O_2/l, which according to the figure occurs in less than approx. 11% of the year, the increase of the sea bed consumption by ΔK = 0.1 g O_2/m^2/day (4-7%) results in a new critical free water oxygen concentration of 4.2 mg O_2/l, which is expeced to occur less than 13% of the year.

8. RELEASE OF OTHER SUBSTANCES

Sulphide

Free hydrogen sulphide (H_2S) will be released from spilled materials or extracted if the dredged material is mixed with water during the operation. During the investigations of sediment oxygen demand (Ref. 27), hydrogen sulphide was detected by its smell in numerous samples. However, a detectable amount of extractable H_2S was found only in surface sand samples containing decomposing mussels.

H_2S contributes to the initial oxygen demand as it is oxidized within some hours when exposed to oxygen. Furthermore, H_2S is toxic to the fauna and should not occur in lethal concentrations in the open water.

It has been estimated that maximum initial H_2S concentrations of 0.09-0.4 mg/l may occur in the plume when dredging in mussel beds. When dredging in post- and late glacial sediments, the concentrations will be an order of magnitude lower. In moraine clay the total sulphur content is very low, and a significant release of H_2S is unlikely.

Dissolved H_2S is oxidized within 1 to 24 hours upon exposure to oxygen containing sea water, depending on the conditions (Ref. 31).

Heavy metals

During suspension of sediment, heavy metals may be released to the open water. This release may be enhanced by oxidation of the heavy metal compounds.

The level of heavy metal concentrations in sediments from the Storebælt is known from analysis of 5 samples of surface sediments (Ref. 32) and 9 samples of clay (Ref. 33). The elements analysed are: As, Cd, Cr, Cu, Pb, Hg, Ni, Sn and Zn. The highest metal contents were found in the surface sediments, while the metal contents in clay in general were lower. Positions of sediment samples used for heavy metal analysis and heavy metal concentrations are given in Appendix B.

Metal contents in the surface sediments are of the same level as background concentrations of metals in Danish surface sediments in general (Refs. 4, 34). Further, it is evident from the geological surveys that the glacial and post-glacial layers are unaffected by human activities and therefore represent the local background conditions.

Due to the hydrographic conditions in the Great Belt, the surface deposits may be affected only by extremely diluted loads of heavy metal.

Potentially releasable heavy metals in the sediment can be divided into the following pools:

a) Dissolved in the pore water

b) Adsorbed to the surfaces of clay particles

c) Bound to organic carbon. This is a substantial binding form in marine gyttja and peat

d) Bound as salts of low solubility (sulphides, phosphates). This may be a substantial binding form in sediments of marine origin.

Important environmental factors influencing the release of heavy metals from suspended sediments are the redox potential, the salinity, the acidity and the turbidity of the sea water. Increasing redox potential increases the metal release because of oxidation of sulphides and organic carbon. Increasing salinity and decreasing pH both increase the ion exchange between clay particles and sea water and thereby increase the desorption of heavy metals.

Furthermore, increasing ionic strength of the water may for some elements lead to formation of anions by chlorination, hydroxylation etc., which further may increase the metal release from clay particles and organic carbon. Finally, increasing turbidity increases the metal release, partly because it prolongs the residence time of sediment particles in suspension, and partly because it increases the bulk flow of dissolved heavy metal ions away from the particle surfaces.

These processes will probably not be fast enough to cause release of significant amounts of heavy metals from sediment particles in a mobile suspension in the water column because the suspended particles will settle within some hours (see Fig. 8.1). On the other hand, recently settled sediment particles in stationary suspension may give rise to a release of metals when exposed to oxidizing conditions, as this phase of sedimentation will be of weeks' or months' duration. Thus, a silty clay sediment exposed to oxidized sea water under laboratory conditions was found to release significant amounts of cadmium within two weeks. Reduced and slightly oxidized conditions gave no significant increase in dissolved cadmium (Ref. 35).

Another long-term study of dredged sediments gave only a slight release of sediment-bound cadmium after four months of equilibration in oxidized sea water.

However, the concentration of dissolved cadmium had dropped again after eight months, resulting in a net mass release of essentially zero for the study period (Ref. 36).

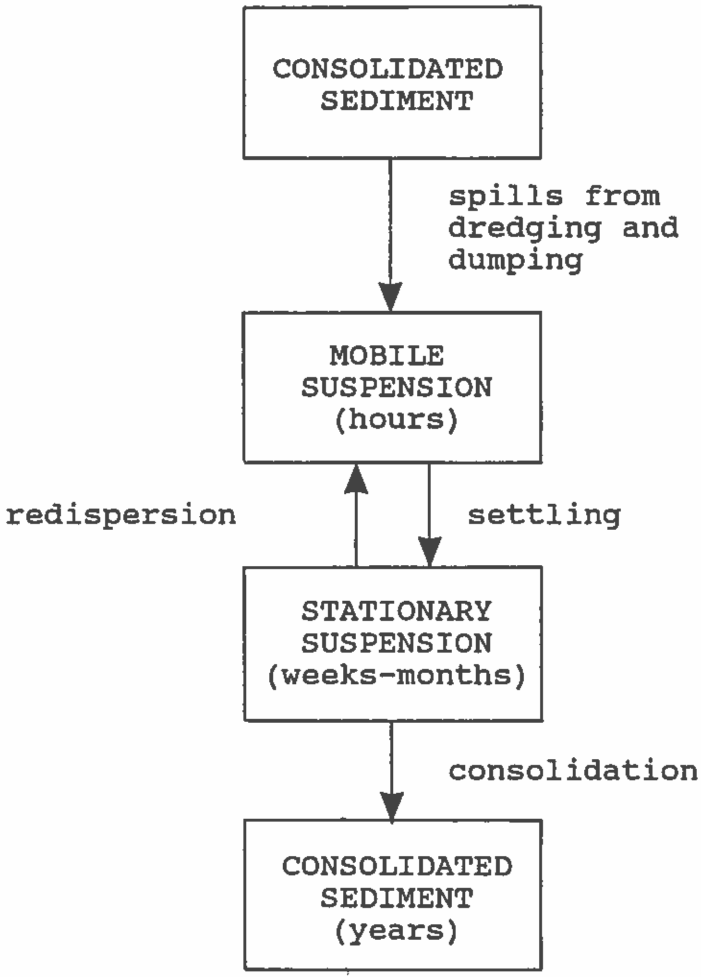


Fig. 8.1 Major pathway of spills from dredging and dumping. The magnitude of residence times is given for each phase.

The experiments with cadmium release are here chosen as examples, because cadmium is one of the most mobile elements among the heavy metals.

Considering the fact that the heavy metal concentrations in the dredged material are low compared to background concentrations in Danish surface sediments, and the fact that dilution is very high due to the hydrographic conditions, the effects of heavy metal release, if any, on water quality and biota are expected to be of short duration only. More detailed information could be obtained by investigations of metal mobility in actual sediment samples exposed to actual sea water from Storebælt.

Non-Natural Substances

Non-natural substances originate from dredged material disposed of previously or from disposed solid waste.

The sea bed area to be dredged is known to include a spoil disposal area east of Knudshoved.

The spoil disposal area is delimited by the positions mentioned below:

55°19'00 N, 10°51'60 E
55°19,00 N, 10°54'20 E
55°17,80 N, 10°53'30 E
55°17,80 N, 10°52'60 E

The dumping operations licensed in this area since 1976 are:

1976: 200,000 m^3, mainly moraine clay from dredging for a ferry berth in Nyborg harbour

1978: 53,000 m^3 clay from dredging for quay works

1979: 60,000 m^3, clay from dredging for quay works

1980 and later: 30-40,000 m^3, harbour sediment, mud, clay and sand from deepening of Nyborg harbour

1985: 360,000 m^3 sand and moraine clay from dredging in Knudshoved ferry harbour

1987: 150,000 m^3 moraine clay from dredging around Lindholm in Nyborg Fjord.

The authorities of the County of Funen and/or the Danish Environmental Protection Agency have in each case assessed that the levels of heavy metals and other polluting substances were not exceeding the general background levels.

According to the authorities of the County of Funen, the dumping permits have not been fully utilized. Thus, the total volumes dumped are somewhat less than the sum of the licensed dumping volumes.

The foundation dredging for the west bridge piers will interfere with the disposal area. Since the concentrations of heavy metals and other polluting substances in the dumped material are estimated not to exceed the background levels, it is not necessary to take the disposal area into special account with respect to spills of sediment from dredging for piers.

Other affected disposal areas are not known.

There are no indications of disposed solid waste of any important kind in the affected sea bed area.

9. CHANGED CURRENT CONDITIONS NEAR SPROGØ

The extension of Sprogø by the east ramps and the west ramp will affect the local current conditions, as the current lee areas north and south of Sprogø will be enlarged. Further, the compensation dredging at Sprogø Østrev (and Vestrev) will affect the local current in the dredging areas.

The construction works on Sprogø Østrev started in early 1989, and the total blocking from the east ramps was obtained from October 1989, where the northern bund of the east ramps was completed (see Fig. 3.4).

The construction works at the west ramp are planned for initiation early 1990, and the total blocking effect is expected to be obtained in May 1990.

The CD started in August 1989 and is planned to continue until 1994.

The effects on the current near Sprogø will persist after the completion of the Link construction works.

A preliminary presentation of the effects on the current due to the ramps and the CD is given below. The basis for the assessment is:

- System 22 model (2 layer) simulations of currents for a 5 days period in a 250 m grid resolution,
- a preliminary layout of the reference topography and the topography after the end of the construction works (total CD volume 8.7 mio. m^3)

In Fig. 9.1 the distribution of the mean current speed in the vicinity of Sprogø before the construction works started (reference) and after termination of the works are shown. In Fig. 9.2 the relative changes in mean current speed are shown. The results are summarized in Table 9.1.

Fig. 9.3 shows the corresponding distributions for the frequency of current speed below 0.1 m/s.

AREA WITH CHANGED MEAN CURRENT SPEED									
Current after termination relative to reference									
0-50%	60%	70%	80%	90%	100%	110%	120%	130%	140-160%
km^2									
1.2	0.5	1.2	2.3	18.8	-	12.5	2.6	1.6	1.4

Table 9.1 Current speed effects of Link constructions in the vicinity of Sprogø (preliminary results).

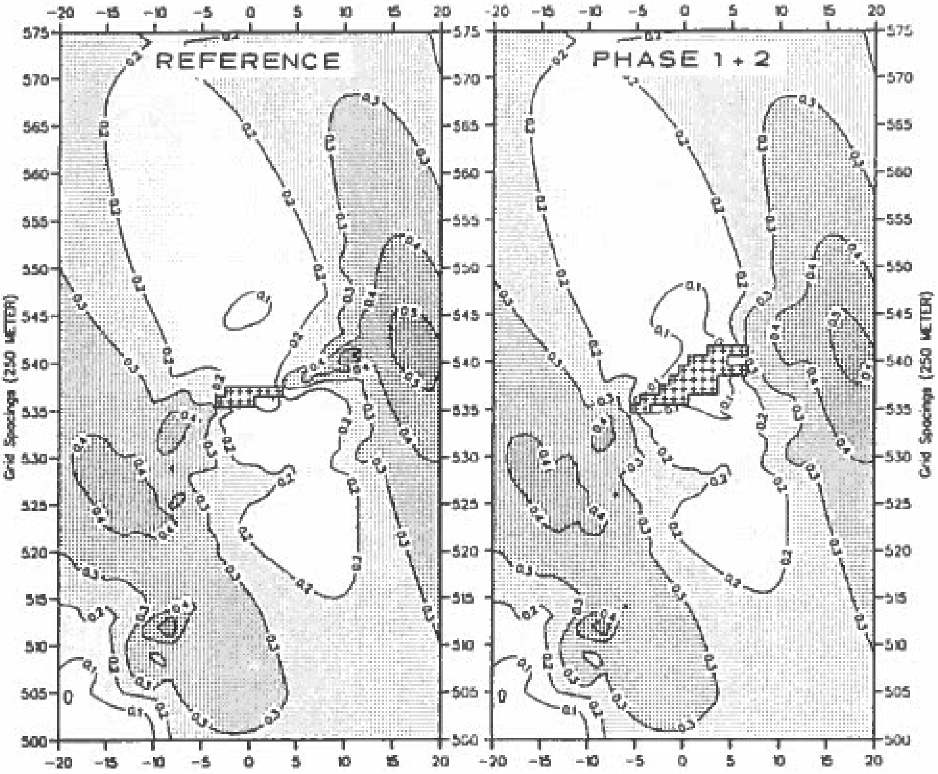


Fig. 9.1 Distribution of mean current speed (m/s) in the vicinity of Sprogø for the reference situation and after termination of the construction works (preliminary results).

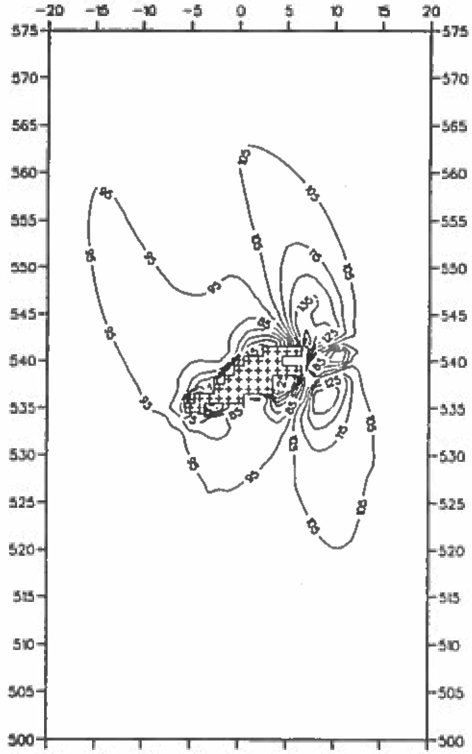


Fig. 9.2 Mean current speed in the vicinity of Sprogø after termination of the construction works relative to the reference situation (percent, preliminary results).

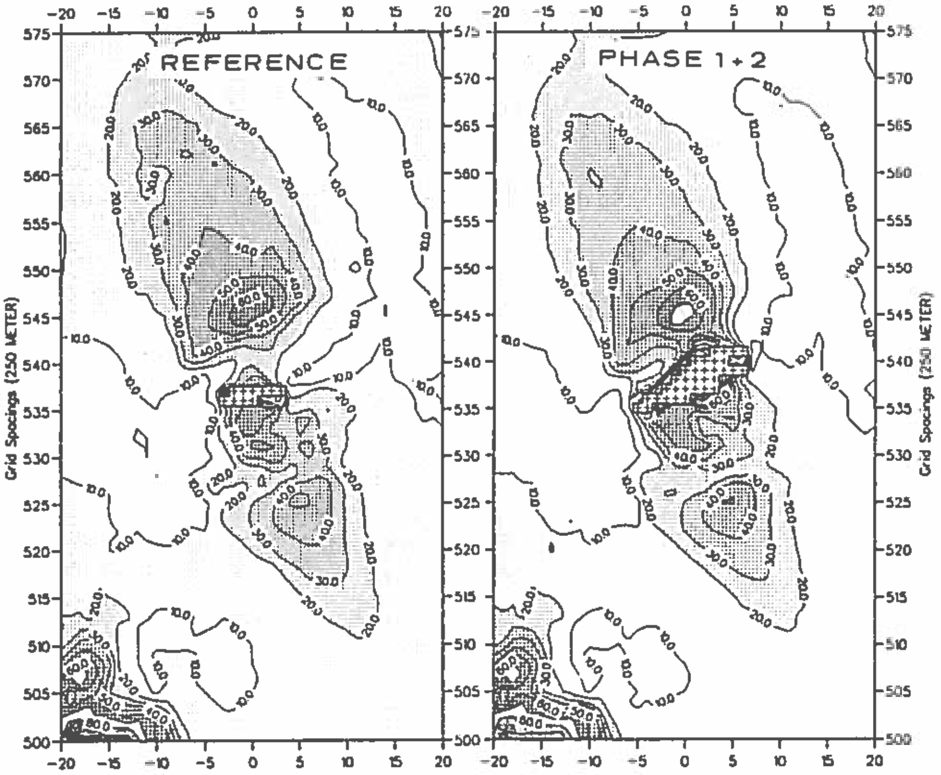


Fig. 9.3 Distribution of frequency (percent) of current speed below 0.1 m/s in the vicinity of Sprogø for the reference situation and after termination of the construction works (preliminary results).

The area where the mean current is reduced is seen to be limited to an area within up till 1000 m from the new coastline of Sprogø and a narrow area where the top of the Sprogø Østrev has been removed (for reduced speed less than 85% of reference speed). Increased speeds are expected to occur up to about 3 km north and south of the CD area of Sprogø Østrev.

10. ECOLOGICAL IMPACT

This chapter addresses the ecological effects of construction activities of the Fixed Link across Storebælt, including direct effects of changes in the currents around Sprogø.

The present assessment does not address ecological effects of changed wave exposure and changed sedimentation or erosion conditions due to the presence of ramps etc. Further, it does not address permanent effects of the Route-T realignment or permanent effects of ramps in the Knudshoved or Halsskov areas.

The ecological assessment is based on

- Calculations presented in Chapters 5 to 9 in this report.
- Ecological mapping of Storebælt (Ref. 5).
- Previous environmental impact assessments (Refs. 1, 20).
- Preliminary results from the biological monitoring programme (Refs. 37, 38, 39).

In general, the ecological impact is discussed for the project as a whole (Phases 1 and 2). The impacts of activities completed on 30 November 1989, and of Phase 1 as a whole, are discussed shortly at the end of this Chapter (Sections 10.5 and 10.6).

10.1 Preliminary Results of the Biological Monitoring Programme

The biological monitoring programme was initiated on a preliminary basis in June 1989. The programme is described in Ref. 40. The following section summarizes results which have been obtained during 1989. Due to the late initiation of the technical implementation of the programme, the data coverage for 1989 is not complete.

Mussels/eiders

The biomass of mussels around Sprogø and Halsskov Rev has been estimated in November 1988 before the arrival of the wintering eider ducks and in April 1989 after their departure.

The investigation showed that the biomass of mussels in the Sprogø/Halsskov area was reduced by approximately 40% due to predation by eiders and starfish.

Furthermore, the investigation indicated that almost all the mussel biomass was turned over in one year.

The almost total turnover of mussel biomass indicates that the number of eiders feeding in the waters around Sprogø is limited by the amount of food. Therefore, the destruction of mussel beds may therefore affect the fouraging possibilities for eiders in the area.

Video inspection of the sea bed was carried out on different biotopes near the reclamation and dredging areas around Sprogø on 1 November 1989 and on 3 January 1990. 15 locations were visited.

No immediate sign of sedimentated fine particles was observed on the sea bed at any of the locations visited, except in a deep ditch southeast of Sprogø dredged by the cutter suction dredger Haarlem. The observations indicate that any material sedimented in the area had been suspended and carried away by the currents.

Vegetation and mussels seemed unaffected by the reclamation and dredging activities, even mussels observed in or near dredging areas (Ref. 37).

Growth rate of mussels

In situ growth experiments with mussels have been carried out in the area in September 1989. High contents of suspended matter in the water column from dredging activities were measured in the experimental period. The experiments demonstrated that the mussel growth rate was not affected by exposure to increased levels of suspended matter for a growth period of 22 days (Ref. 38).

Oxygen balance

The oxygen concentration in the lower layer of Southern Kattegat and Storebælt remained low during a prolonged period of summer and autumn 1989.

Recorded oxygen profiles from September 1989 indicate that oxygen concentrations are strongly affected by vertical mixing and therefore variable, between -7 and -20 m depth (see Fig. 7.3). Minimum values were about 45% saturation (3.9 mg O_2/l). (Ref. 25).

Further profiling and data analyses are required in order to assess possible interactions between the regional oxygen deficiency and possible effects of dredging and deposition.

Algal Blooms

In May-June 1988, before the construction works started, a severe bloom of Chrysochromulina polylepis caused fauna kill along the Swedish and Norwegian coast in Kattegat.

In spring 1989 the National Environmental Protection Agency recorded the algae in Kattegat. A succeeding cruise made by the County of Funen confirmed the presence of a minor bloom (Ref. 43). The algae were recorded in an area north of Funen in Storebælt and in the Langelands Bælt between 30 May and 13 June. Like the situation in 1988 the bloom was vertically restricted to a few meters just above the interface. At all stations the concentration in this band was over 2 million cells per litre.

The highest concentrations were found at stations near Sprogø (7.4 million cells/l) and north of Romsø (4.8 million cells/l).

During cruises in late June and September 1989 with the Great Belt Link survey vessel no sign of such a bloom was found. There have been no reports of fish kill or other malconditions.

Before and after the bloom, hopper dredgers were excavating sand near Romsø to be unloaded at Sprogø. When operating near Romsø a concentration of 1,8 g N/m^3 was measured in the overflow, giving a daily load of 250 kg N. The N load at Sprogø during unloading was estimated at 140 kg/day. Together these sources correspond to 40% of the input from the Nyborg catchment area.

The coincidence of this bloom and the nutrient load from dredging indicates that this load is likely to have contributed locally to the bloom, though the main nutrient source for the bloom, on the regional scale, has been entrainment of nutrients from below the interface.

Spreading of Sediments and Nutrient Release

Measurements of the load from dredgers and sedimentation basins were performed during major operations in 1989. The spreading of sediments was followed by tracing of plumes from dredgers and from unloading in the near field (Refs. 23, 24, 25, 26).

The results of these activities have been included in the calculations presented in Chapters 4-7.

10.2 Impact Area

10.2.1 Definition of Criteria

As in the previous versions of the EIA (Refs. 1, 20) the criterion for the impact area has been defined as an increase in primary sedimentation of 0.5 mm or more during the construction period. In order to locate and estimate areas of more intensive sedimentation, a criterion of 5 mm sedimentation has been used.

The general impact area is to be understood as an area of potential impact. The type of impact and the risk of its occurrence depend on the ecological community and is discussed separately for each community.

In general, the occurrence of an effect may depend either on the intensity of sediment spreading during restricted periods, or on the cumulative impact.

Oxygen consumption is a characteristic example of an intensity dependent effect. Also, possible effects of primary sedimentation on stone reefs, mussel beds and eelgrass areas are largely intensity dependent, as the primary sedimentation is resuspended and removed from these areas, typically within several months. Cumulative effects may occur in soft bottom areas.

Effects of shading are mainly depending on intensity and duration of the events. Effects of nutrient release, especially on bottom vegetation, are cumulative within an annual cycle.

The impact from nutrient release, shading on bottom vegetation and increased sea bed oxygen consumption are mainly within the above defined area. However, these effects have been assessed by use of individual impact criteria defined in Section 10.3.

10.2.2 Ecological Communities

In the impact area five categories of ecological communities on the sea bed have been identified (Ref. 5):

- Stone reefs with dense growth of algae and/or sponge colonies and sea anemones (four communities of this category have been identified)

- Mussel beds

- Soft bottom communities (five communities of this category have been identified)

- Eelgrass beds

- Herring spawning grounds.

10.2.3 Assessment of Impact Area

Table 10.1 shows the estimated impact areas based on the sedimentation definition for the whole construction period (Phases 1 and 2). The calculated sedimentation does not include sediments derived from the erosion of the new bottom of the compensation dredging area.

	Stone Reefs	Mussel Beds*	Soft and Sand Bottom	Eelgrass Beds Ground**	Herring Spawning Area	Total Impact
	km^2					
Phase 2 dredging by mechanical dredger						
> 0.5 mm	21.6	9.8	262	1.3	29.6	295
> 5 mm	4.3	4.1	37	0.6	11.8	46
Alternative dredging by cutter suction dredger in Phase 2						
> 0.5 mm	25.4	10.4	315	1.3	29.6	352
> 5 mm	8.6	6.7	48	1.3	20.4	65

* Areas with more than 20% of the bottom covered with mussels

** The herring spawning ground includes mainly stone reefs and mussel beds. For this reason the total impact area is not equal to the sum of subareas.

Table 10.1 Impact areas for the total construction period. Impact areas around Knudshoved and Halsskov are included.

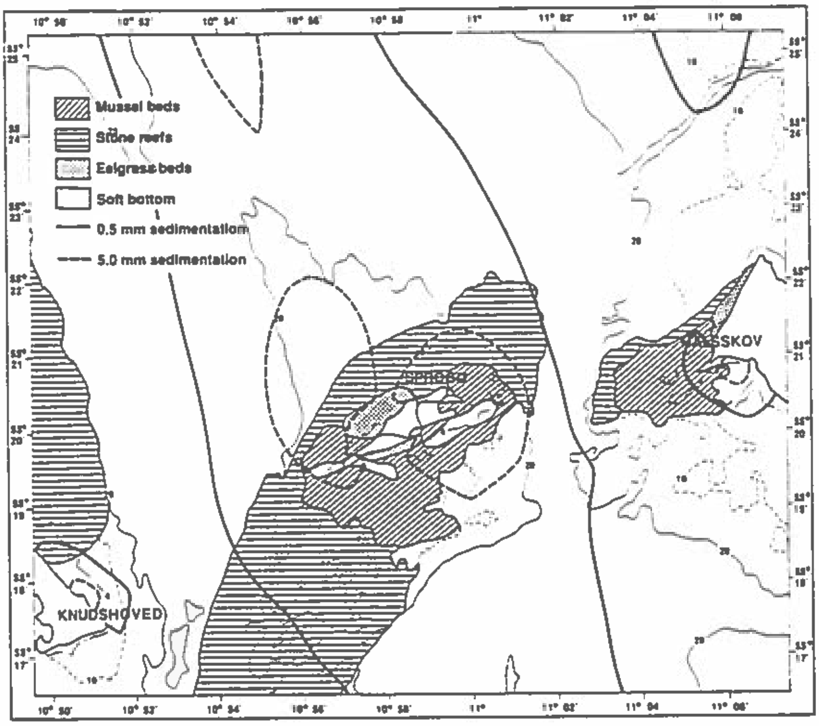


Fig. 10.1 Impact area and bottom biotopes (mechanical dredging in Phase 2). Isolines for 0.5 and 5 mm sedimentation are shown.

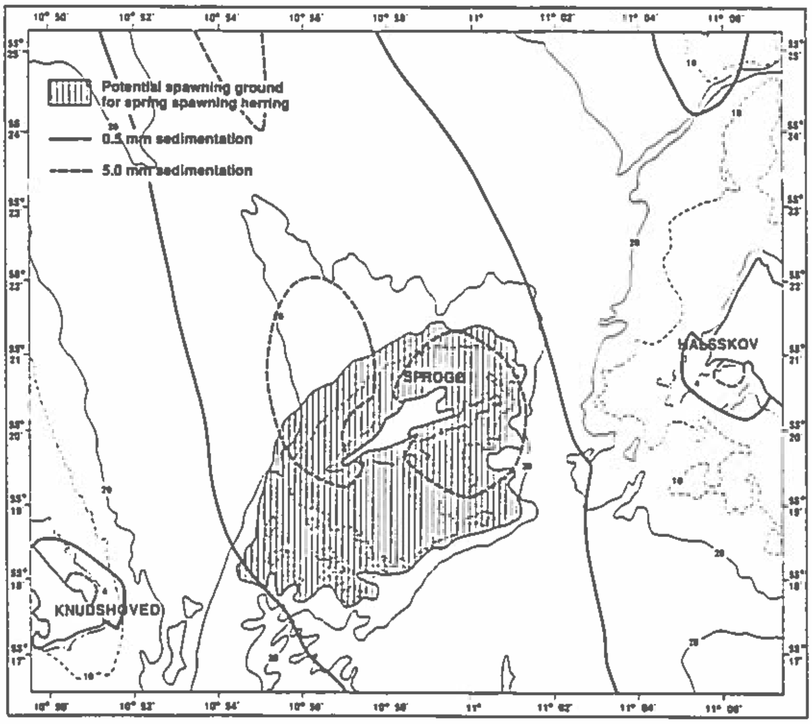


Fig. 10.2 Impact area and potential herring spawning grounds around Sprogø (mechanical dredging in Phase 2). Isolines for 0.5 and 5 mm sedimentation are shown.

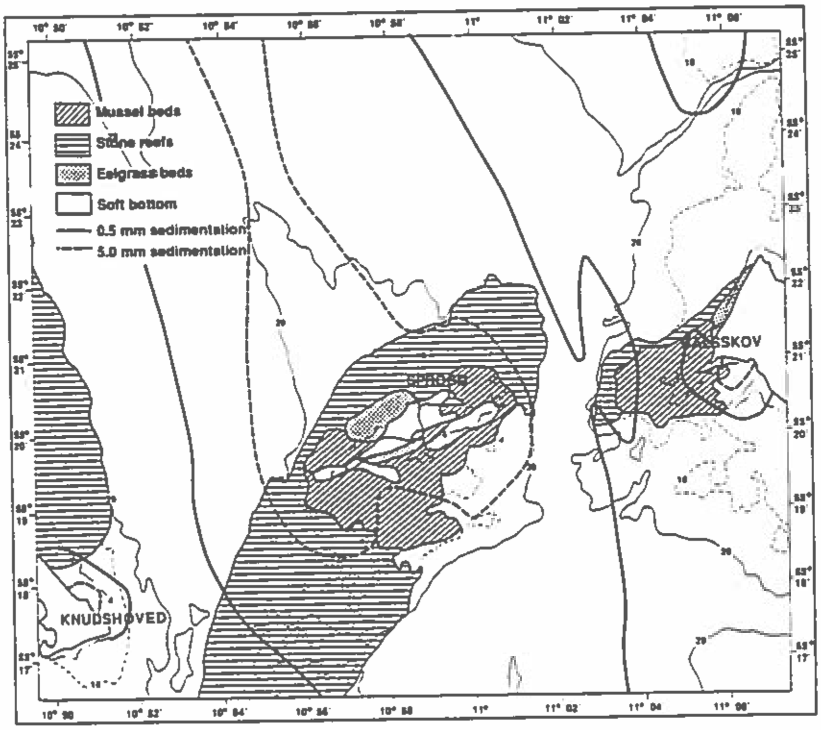


Fig. 10.3 Impact area and bottom biotopes (cutter suction dredging in Phase 2). Isolines for 0.5 and 5 mm sedimentation are shown.

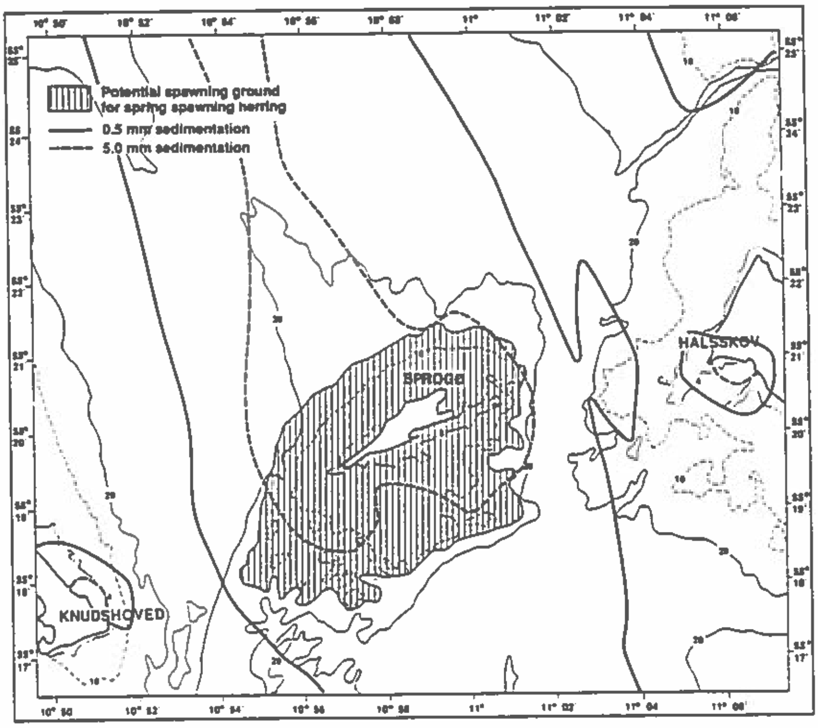


Fig. 10.4 Impact area and potential herring spawning grounds around Sprogø (cutter suction dredging in Phase 2). Isolines for 0.5 and 5 mm sedimentation are shown.

Figs. 10.1 and 10.2 show the potential impact areas together with the different biotopes assuming mechanical dredging in Phase 2. Figs. 10.3 and 10.4 show the corresponding impact areas, assuming cutter suction dredging in Phase 2.

The major part of the impact area consists of areas with soft bottom sediments (sand or mud). The main part of the primary sedimentation will take place on more coarse sediment bottom, but the soft bottom is likely to act as final sink for most of the suspended material after resuspension and transfer from other primary sedimentation areas. Also, soft bottom areas outside the impact area will be affected by final sedimentation. The size of this final sedimentation cannot be quantified. Since resuspension occurs during high-current events, the sediments are likely to spread to a large area which will only be affected to a small degree.

10.3 Short-Term Effects

10.3.1 The Water Column

Nutrients

As described in Section 6.3 the released nutrients will either be taken up by phytoplankton in the water column or be built into the benthic vegetation. In both cases it will give rise to an increase in primary production.

The released nutrients may accelerate exceptional blooms of algae or affect the environment by creating an oxygen deficit when the dead algae are degrading.

Because of the strong currents the generated plankton surplus is spread over large areas. The plankton production is estimated to increase by less than 0.007 g C/m^2/day, see Section 7.5. Compared to a normal primary production of 0.5-0.8 g C/m^2/day the estimated effects on the oxygen concentration in the lower layer are insignificant.

Shading

The plume of silt (and clay) will be up to approximately 400 m wide within a distance of 20 km downstream. At the same time the plume will meander. Within and beneath the plume there will be a temporary shading effect on the growth of phytoplankton.

Because of the limited duration of the shading, the reduction in phytoplankton growth will not have significant ecological effects.

Oxygen Conditions

The oxygen concentration in the water column is affected by the initial oxygen consumption of suspended materials in the plume, by the increased oxygen consumption of the sea bed caused by settled sediments, and by decomposition of produced vegetation (phytoplankton and bottom vegetation) due to release of nutrients.

From the calculations presented in Chapter 7 it can be concluded that:

- The oxygen concentration of the upper layer can in no cases be expected to approach critical levels due to the dredging and disposal of sediments.
- The decrease in oxygen concentration in the lower water layer of the water column may be detectable. However, this may only occur in cases of stagnant lower layer, and only at sites recently affected by intense settling of oxygen demanding sediments in the impact area or local sedimentation of released bottom vegetation. The effect can be described as a slight intensification of otherwise critical oxygen conditions; oxygen consumption from spilled material will not elicit such situations by itself.
- Dumping of moraine clay during Phase 2 is expected to have a similar effect as described above for other operations. However, the extent of this impact depends on the dredging capacity applied and on the location and type of discharge. As the effects on oxygen concentrations are of short duration, and the dumping operations are not planned to coincide with other major impacts to the lower layer, the effects are not expected to interfere with each other.

10.3.2 Soft Bottom Biotopes

It is estimated that a soft bottom area of 262-315 km^2 will be exposed to an increase in primary sedimentation of 0.5 mm or more during the dredging period, of which 37-48 km^2 are expected to be exposed to more than 5 mm of sedimentation.

At depths of 10-20 m the bottom fauna can be characterized mainly as an Abra alba community on sand. At greater depths (>20 m), the fauna can be characterized as Abra alba community on sandy mud and a Haploops community on mud, respectively (Ref. 5).

North of Sprogø at a depth of 16-18 m an area of approximately 15 km^2 has been described as a Ciona community on muddy sand. An area considered for dumping is located within the Ciona community which is the only biotope of this kind in the investigated area (Ref. 5).

Settling particles will affect the bottom fauna by burial or by changing the sediment characteristics. Furthermore, suspension feeders may decrease in abundance due to temporary increase in concentrations of suspended matter in the bottom water due to primary sedimentation and resuspension of unconsolidated sediment. However, possible direct effects are expected to be of short duration only. In general, soft bottom fauna is adapted to sedimentation of the magnitude calculated for the Great Belt Project. Regeneration of soft bottom communities after intense sedimentation has been reported from similar situations (Refs. 7, 8).

On the basis of considerations presented in Section 7.6, the potential effect of the dredging operations on the <u>oxygen balance</u> of soft bottom areas can be defined as an increased risk or frequency of anoxic conditions at the sediment surface for a given site.

The gradual decrease in oxygen concentrations by depth in the lower layer (see Fig. 7.4) indicates a higher risk of anoxic conditions in the deepest areas. However, recent experience from intensive monitoring in other Danish marine areas indicates that large flat bottom areas having a restricted layer of bottom water have a high risk of oxygen deficiency (B. Kruse, pers. comm.). This observation is consistent with the calculations of Section 7.6 of this report (Case B). During investigations before the initiation of the construction activities, several cases of bottom oxygen deficiency were observed at depths between 13 and 20 m.

For activities along the Link alignment the potential effects on the oxygen balance are essentially confined to soft bottom areas closely north and south of the compensation dredging area. The sand dredging at Romsø SE affects sand and mud areas in the northern part of Storebælt at depths between 20 and 30 m.

Surplus oxygen demand caused by degradation of phytoplankton produced by the released nutrient is low in relation to the background sediment oxygen demand.

In the autumn, released bottom vegetation can be transported to soft bottom areas where the decomposition can cause local reduction in oxygen concentrations at the sediment surface. Identification of areas which may be affected is not possible on the existing background.

The oxygen calculations of settled sediment effects (Section 7.4) represent the upper range interpretation of experimental results with a high degree of uncertainty. The lower range interpretation of the data would give an insignificant effect on the oxygen balance. Therefore, it remains uncertain whether the dredging and disposal operations can result in any case of oxygen deficiency at the bottom.

The effects of oxygen deficiency, if it occurs, are detectable in terms of changes in the bottom fauna as tolerant or opportunistic species will be favoured.

Studies of recovery potential of bottom fauna from dredging areas in shallow waters of the Baltic Sea showed recovery times of up to five years (Refs. 7, 8). Other studies (cited in Ref. 9) have shown recovery times of 0.5 to 2 years.

Changes in bottom fauna composition may favour dab at the expence of plaice (Refs. 10, 11, 12). Both plaice, flounder and dab feed on bottom fauna. Especially plaice and dab will be in natural competition for food such as small bivalves and polychaetes. Invertebrate species tolerant to low oxygen concentrations (for instance brittle stars) are in general better food for dab than for plaice.

10.3.3 Herring Spawning Grounds

It is estimated that an area of approximately 30 km^2 of potential spawning ground for spring spawning herring will be exposed to increased sedimentation due to the dredging and disposal operations (Fig. 10.4). 12-20 km^2 of the impact area are estimated to be exposed to sedimentation of 5 mm or more.

The total spawning area for spring spawning herring in Storebælt is approximately 150 km^2. This means that approximately 20% of the spawning area in Storebælt may be influenced by the operations.

Herring spawn around Sprogø from the end of March till the beginning of June, the peak spawning period depending on hydrographical and meteorological conditions (Ref. 5). The adhesive eggs are deposited on the bottom in more or less dense "mats" on sand, gravel, stones or vegetation.

Sedimentation of fine grained material may affect herring spawning as follows:

- Sedimentated particles may adhere to egg masses in the spawning period and thereby hamper egg respiration causing reduced survival and development of the eggs (Ref. 13).
- Sedimentated particles may alter the composition of the sediment. This effect may alter the suitability of the area for spawning as herring is choosing particularly suitable spawning substrates. It has been suggested that herring recognize spawning grounds by auditory sensation. A suitable ground has its own acoustic image, created by current and wave actions, the sound frequencies being

> dependent on depth, sediment texture, sea bed topography etc. If topography and sediment composition change due to sedimentation the acoustic image may change accordingly, so that the herring may not recognize the spawning ground (Ref. 10).

Even a total destruction of eggs deposited at the grounds around Sprogø in the spawning season during the construction period due to primary sedimentation will probably not significantly affect the standing stock of herring in Storebælt. The stock of spring spawning herring has increased in recent years, and probably produces a large surplus of eggs. This implies that the number of recruits entering the stock is independent of the number of eggs spawned around Sprogø.

Changes in sediment composition are considered to be the main threat as these may cause herring to abandon the spawning grounds, temporarily or permanently. Preliminary results of the monitoring programme indicate that sedimented material on the spawning grounds is rapidly resuspended and carried away by the current (Ref. 5). However, if the sediment composition is changed repeatedly each spawning season, the herring may abandon the spawning grounds. The occurrence of spawning herring around Sprogø is monitored during the construction phase in order to assess if herring continues to use the spawning grounds.

10.3.4 Stone Reefs

It is estimated that a stone reef area of 22-25 km^2 will be exposed to increased primary sedimentation during the operation period. Areas of approximately 4-9 km^2 have been estimated to receive sedimentation of more than 5 mm due to the operations.

Stone reefs around Sprogø have a distinctive and diverse macrophyte vegetation and epifauna (animals living on stones and plants), and serve as spawning and nursery grounds for several fish species. These reefs are considered the most vulnerable areas with respect to sedimentation of fine particles. The composition of vegetation and fauna on stone reefs around Sprogø changes with depth to a great extent.

If affected, vegetation of macroalgae will probably recover if a stony bottom suitable for colonization is preserved. However, full development of a vegetation of perennial algae, like Laminaria or Delesseria may take several years. In certain areas a change in the species composition from large algal species (e.g. Laminaria sp.) to smaller annual species may be observed.

Based on video observations during the ecological survey (Ref. 5) on the stone reefs around Sprogø it is rendered probable that from seashore to depths of about 15 m fine grained sediments are not accumulated. Fine grained material settling during the operations (primary sedimentation) will most likely be resuspended and ultimately carried away from this area. Thus, in the major part of the stone reefs the most important impacts on the macroalgae probably are the shading due to materials in suspension, and changes from perrenial to annual species together with an increased epiphyte growth due to nutrient release. At greater depths (>15 m) resuspension may occur more seldom, which means that flora and fauna may be affected more severely by settled materials.

From released nutrients (Section 6.3) the increased production of macrovegetation has been calculated (Section 7.5) for the shallow areas north and south of Sprogø and for the areas around Knudshoved and Halsskov. Production of macrovegetation at the deeper part of the reefs (below the interface level of approximately 10-15 metres) would not be affected by the released nutrients. The reasons for this are that nutrients in this water mass already exist in surplus and that the released nutrients are only to a small extent brought down through the interface.

Table 10.2 shows the estimated production of macrovegetation caused by released nutrient in case cutter suction or mechanical dredgers (grab) are used.

Typical biomasses in such areas are in the range of 2-30 g C/m^2 for red algae communities (as Delesseria biotope) and 5-50 g C/m^2 for brown/red algae communities (as Laminaria/Delesseria-biotope) (Ref. 14).

Compared to these biomasses the increased production from Phase 1 1989-90 in the areas around Sprogø mentioned in Table 10.2 will be of significance. It is expected that the main part of the calculated production will be in the group of annual species (including epiphyte production). As a consequence, the perennial species will most likely be succeeded by the annuals.

Period	Sprogø North (7 km^2)	Sprogø South (13 km^2)	Halsskov (5.7 km^2)	Knudshoved (17 km^2)
Phase 1				
1988	0	0	0	5
1989	35	37	6	0.6
1990 (remaining)	32	38	0	1.6
Phase 2				
1991-94, grab	0.2	0.1	0	0
1991-94, cutter suction	$\leq$ 2	$\leq$ 1	0	0

Table 10.2 Estimated increase in macrovegetation production (g C/m^2/day) assumed that compensation dredging in Phase 2 is done by grab or cutter suction.

The increased production and a possible change from perennial to annual species in the areas around Knudshoved (1988), Halsskov (1989) and north and south of Sprogø in Phase 1 are expected to be detectable. However, because of the limited period at Halsskov and Knudshoved (one year) it is not expected to have severe ecological consequences.

From Table 10.2 it can be seen that the use of cutter suction instead of grab may give rise to about 10 times greater increase of production. However, in both cases the increases during Phase 2 are considerably lower than the corresponding increases during Phase 1. Because these increases are expected to spread over at least a two-year period they are not expected to have any severe ecological consequences.

Assuming that the extra bottom vegetation production is decomposed within the vegetation areas in the autumn, a surplus oxygen demand of maximum 2.4 g O_2/m^2/day has been estimated in the area around Sprogø for the last part of Phase 1, 1990 (Table 7.5). If this coincides with critically low oxygen contents in the water, it may have a negative effect on the bottom-dwelling fauna between the stones. In the autumn parts of this production can be released and transported to calm or deep waters where it will decompose. Effects from this are discussed in Section 10.3.2.

Stone reef areas which are situated below the interface are sensitive to oxygen deficiency, and sulphur bacteria have been observed on the bottom during the baseline investigations. Such areas were found within the impact area to the north of the dredging area.

The shading effects can be discussed according to light intensities at different depths. The depth limit for growth of bottom macro vegetation is related to the average light intensity in relation to surface intensity. The maximum depth limit of the described Delesseria-biotope around Sprogø is 10 m and for the Laminaria/Delesseria-biotope 15 m. For the background concentration of suspended matter (about 2 mg/l), this corresponds to light intensities at the bottom of 13.5% and 5% of surface light, respectively. From literature a light limit of 1% and even lower had been reported (Ref. 15). The 1% limit is implied in the following as the absolute depth limit of the vegetation type on stone reefs around Sprogø.

Shading effect can be caused directly by the plume or indirectly by a generally increased concentration of suspended material in the area. From the calculation of sedimentation a general increment in concentration of suspended matter around Sprogø of 0.2-0.4 mg/l can be expected. Compared to the background concentration of approximately 2 mg/l the general increment is insignificant.

The effects of the various activities mentioned in Chapters 3 and 5 are estimated in the following. Only the most important activities, related to spill and duration, are estimated.

Dredging at Romsø SE

During the sand dredging at Romsø SE in the period May to September 1989 by James Ensor a significant spill occurred.

The plume from this dredging area mainly moved north or south depending on the direction of current. When going north, the centre of the plume only rarely reached shallow water areas (water depth less than 10-15 m), where bottom vegetation exists. When going south the plume reached the reef area with bottom vegetation around Sprogø within a distance of 20 km. The plume was expected to spread in the top layer of the halocline (7-12 m), and bend eastwards where it reached the bottom at this depth north of Sprogø. From the calculations in Chapter 5 (Fig. 5.8) it can be concluded that the concentration of suspended matter in the centre of the plume at this distance is at the order of 60 mg/l.

From the equation mentioned in Chapter 5, it can be calculated that 10% of the light can penetrate about 40 cm down in the centre of the plume.

The plume width at this distance is in the order of 400 m and fluctuates over a section of approximately 2 km. The plume width is defined as an area with concentrations greater than 20% of the centre concentration. Each part of the vegetation area will be covered by this part of the plume in approximately 10% of the time the dredging is going on. At the edge of the plume centre at a distance of 20 km, the concentration is around 10 mg/l. 10% of the light can here penetrate 2 m through the plume and 1% of the light 4 m through.

The light under the plume at the part of the reef where macrovegetation (Laminaria and Delesseria biotopes) is present (7-15 m) is reduced to an extent where the photosynthesis processes are almost totally inhibited. As this occurs approximately 10% of the time, a reduction of the production of around 10% can be expected.

With regard to stimulation of growth (caused by release of dredged sediments) no compensating effect is expected at depths greater than 10 m. The reason for this is that the vegetation in question is situated in the lower water layer where nutrients are generally in excess. Furthermore, the nutrient level in this water mass is only slightly affected by the induced release.

The production of the reef vegetation at 5-10 m's depth could be stimulated by the above-mentioned increase in released nutrients. This effect will not necessarily compensate for the reduction due to shading, because the increased growth and the shading together change the growth time and stimulate the fast growing annual species and the epiphytes.

Compensation Dredging

From the compensation dredging activities, the suspended plume will reach areas with bottom vegetation mainly when the current is going north. It will reach the stone reef north of the compensation dredging area within 0-3 km depending on which part of the area that is dredged.

The concentration of suspended matter in the plume depends on the type of dredger being used, and the type of material, see Table 10.2. The depth of 1% and 10% light under the plume centre is also calculated in the Table.

ACTIVITY	m^3/m^3	mg/l	1% light m	10% light m
Leonardo, clay	10^{-6}-10^{-5}	2-20	2,3-23	1,1-11
Leonardo, sand	10^{-5}-10^{-4}	20-200	0,2-2,3	0,1-1,1
James Ensor,sand	10^{-4}-10^{-3}	200-2000	0,02-0,2	0,1-0,01

Table 10.3 Estimated sediment concentration in plume centre within 3 km from compensation dredging and depth of 1% and 10% light intensity.

Only half of the time the plume is going north. At a distance of 3 km the plume width (concentration greater than 20% of the centre concentration) is approximately 200 m and it covers a band of approximately 1,000 metres. The plume covers each part of the effected band 10% of the time.

The depth of the affected reef is 10-15 metres. If dredging clay by Leonardo da Vinci, the reef will only be affected to a significant extent by shading if dredging occurs within a distance of less than 2 km. It is not expected that this will have severe effects on the reef vegetation.

When dredging sand, the light penetration under the plume is decreased to an extent where the photosynthesis processes of the bottom vegetation at the reef will be affected significantly. Under the centre of the plume the photosynthesis processes will be almost totally inhibited. Because the plume only covers an area approximately 10% of time the effect will be a reduced growth of the benthic vegetation in the period of dredging of maximum 10%.

Sedimentation Basin A

The runoff from basin A opens to the east of Sprogø. The plume is going north or south depending on current direction. Only when going north, the plume will reach reef areas with bottom vegetation. The distance from the outlet point to that part of the reef which is not destructed by the compensation dredging is approximately 2 km.

At this distance the concentration of suspended matter in the centre of the plume is calculated to approximately 80 mg/l. At this concentration, 10% light penetrates 30 cm and 1% light 60 cm through the plume. At the edge of the plume (20% of centre concentration) 10% light penetrates 1.5 m and 1% penetrates 3 m water column. The photosynthesis processes of the bottom vegetation (at a depth of 10-15 m) will be almost totally inhibited under the plume.

The plume covers each point of the affected area 10% of the time. On this background it is expected that the outlet from basin A results in approximately a 10% reduction of the algal production on the reef north of the compensation dredging area in the working period.

Bund Construction

During construction of the northern bund, the plume could both go north and south depending on direction of current. The northern bund was constructed by interval pumping by James Ensor. During the periods of pumping the concentration of suspended matter in the plume centre was equal to the calculation for Leonardo working at the southern road-bund. The plume reaches the reef areas after 2 km. At this distance the plume width was approximately 100 metres and it fluctuated over a section of 500 m. If the plume had been continuous it would have covered each part of the fluctuating section 10% of the time. Because of the interval pumping of James Ensor it is estimated that each part was covered less than 5% of the time.

The concentration at a distance of 2 km was approximately 100 mg/l at the plume centre. This corresponds to a penetration of 10% and 1% light through 20 and 50 cm water column, respectively. Because of the very low intensity with which each area was covered, the shading had only very restricted effect on the reef vegetation.

The most intensive plume that will occur due to construction of the southern road-bund is estimated to be a 2-3 months period in 1990 caused by the works of Leonardo da Vinci.

This plume will not to any significant extent reach reef areas with vegetation when it is southgoing.

When the current in Storebælt goes north, the spill from the construction will be pressed towards east by the already constructed railway ramp and then towards north. Here it will reach the reefs which have not been destructed by the compensation dredging.

10% of the time it will cover each part of the reef with a concentration of 60-80 mg/l. Through this, 10% of the light will penetrate approximately 30 cm of the water column.

The effect of this is comparable to the effect of the emissions from Basin A and the compensation dredging.

In case a spill occurs simultaneously from bund construction, basin A and compensation dredging, the plumes over the northern reefs will overlap and almost form one plume with a higher concentration. But light below the plume has already decreased to a level where photosynthesis is totally inhibited so that no further effects can be seen.

Dumping

It is planned to dump surplus material at a dumping site just northwest of Sprogø reef. The spill from this dumping depends on the method of dredging/dumping.

Fig. 5.8 shows the concentration of suspended matter in the plume from dumping of material dredged by grab and dumped from splitbarges. The concentrations when cutter suction dredger is used and material pumped to the dumping site can be expected to be five times that of grab and splitbarges.

When the current is northgoing only marginal or no effects can be expected on vegetation. When the plume is southgoing (50% of the time) it will cover areas of the reefs with Laminaria and Delesseria biotopes. These vegetation types are found at distances of 0-20 km along the main current line in southern direction.

From Fig. 5.8 it can be estimated that 1% of the light penetrates to a depth of approximately 2.3 m at a distance of 2 km when grabs and splitbarges are used. At a distance of 20 km 1% of the light penetrates to 23 m depth. The reef vegetation grows at a depth of 7-15 m in this area. Each part of the reef will be covered about maximum 10% of the dumping time.

A maximum of 10% reduction in the production of the reef algae population can be expected. The dumping will go on for approximately 400-500 days over two to four years.

Due to the long duration of the activity, changes in species composition and a change toward smaller depth limit of some algae species can be expected. Fast growing annual algae species are expected to be favoured on expense of perennial species.

Shading from this activity affects the same area as was affected in 1989 by the dredging activities at Romsø SE. This can amplify the above effects, especially with respect to changes in species composition. Planned dredging west of Sprogø will further affect part of the same areas although this activity will result in smaller effects than those already mentioned, especially as the duration is shorter.

10.3.5 Eelgrass Beds

The eelgrass beds north and south of Sprogø are fully covered by the impact area. They are estimated to cover an area of approximately 1 to 1.5 km^2. It has been estimated that an area of 0.6-1.3 km^2 of the impact area will be exposed to sedimentation of 5 mm or more.

Eelgrass beds are known for their ability to increase the sedimentation of suspended particles and reduce the current velocity. This has resulted in enhanced sedimentation at the marginal areas of the beds and in some cases actual rises of the outermost portion of the bed (Refs. 16, 17). Field experiments have shown that eelgrass covered areas accumulated up to 2.5 cm sediment over a period of 53 days from August to October. In the same period an erosion of up to 1.5 cm occurred in denuded areas (Ref. 18).

The released nutrients will increase the total production of bottom vegetation in the eelgrass beds. It is estimated that in the vegetation area north of Sprogø the increase will be as shown in Table 10.2.

It is expected that this production will mainly occur in the group of annual bottom living macroalgae or epiphytes on the eelgrass. This will result in a shading effect on the eelgrass and reduce its growth. The whole eelgrass bed north of Sprogø will be affected, though most pronounced near the dumping site northwest of the reef.

The eelgrass beds north of Sprogø can be affected by shading caused by spills from the construction of railway ramps and northern bunds and from the dumping of surplus material just outside the northwestern limit of the stone reef at Sprogø.

The mechanisms are similar as for macroalgae, but the depth limit occurs at about 15% light (Ref. 19).

The plumes from the construction of the northern bunds affected the eelgrass beds within the first two kilometres from the outlet point. As mentioned under stone reefs (Section 10.3.4) each part of the affected area was estimated to be covered less than 5% of the time. Despite sufficient light cannot penetrate through the centre of the plume, it is not expected to have had severe effects on that part of the eelgrass population which has not been affected directly by construction works. The reason for this is the low frequency (5% of time) by which each part is covered by the plume.

According to the hydraulic description, the main direction of the plume from the dumping site will not be towards the eelgrass bed north of Sprogø. But, during southbond current and strong western wind, the plume may cover part of the eelgrass beds at Sprogø. The distance from the dumping site to eelgrass beds is approximately 1-2 km. From the calculations mentioned in Section 5.3 it can be estimated that there will not be sufficient light for the eelgrass production under the plume. This means that some part of the eelgrass bed can, to some extent, be affected by shading of the plume from the dumping site. But because this effect will only occur for few per cent of the time, it is estimated that this will only have marginal effect on the eelgrass vegetation north of Sprogø.

Eelgrass vegetation has a good ability to recover as long as the roots and rhizones are preserved. If, however, the vegetation has been affected severely, recolonization may be slow. Once the eelgrass has vanished the location will be more subject to erosion which may hamper or prevent recolonization.

The eelgrass beds are not sensitive to changes in the oxygen balance of the magnitude calculated. The eelgrass beds are all located above the interface and therefore not exposed to critical oxygen concentrations. Further, the natural oxygen turnover is high relative to the changes due to the dredging and disposal activities.

It has been calculated that the produced bottom vegetation can cause an excess oxygen demand of max. 2.4 g O_2/m^2/day in 1990 from last part of Phase 1 activities. Such oxygen demands may locally have negative effects for the fauna living in the bottom between the eelgrass.

The current velocities in the eelgrass beds are reduced by 10 to 50% due to the land reclamations. These changes are unlikely to restrict the occurrence of eelgrass, as this plant is common in less exposed ares. Rather the reduced current may give eelgrass an advantage in marginal areas where it competes with macroalgae.

10.3.6 Mussel Beds and Eiders

The waters around Sprogø and Halsskov have been designated an EEC bird protection area because of the large flocks of eiders (Somateria molissima) which concentrate on the rich mussel (Mytilus edulis) beds in the area during the winter period.

The potential impact area of mussel beds is 10 km^2, which includes all mussel beds east, south and west of Sprogø, as well as part of the mussel beds at Halsskov. 4-7 km^2 has been estimated to be exposed to more than 5 mm sedimentation.

Based on the ecological mapping (Ref. 5), the total area of mussel beds around Sprogø and at Halsskov Reef is approximately 15 km^2.

Approximately 2 km^2 of these mussel beds is situated within the area of compensation dredging. Compensation dredging will remove mussels from the area. However, preliminary results from the biological monitoring programme indicate that a considerable amount of healthy mussels is left after dredging in a mussel bed area (Ref. 37). Furthermore, mussels may recolonize the area again if the water depth is less than 10 m after dredging. Based on the ecological mapping (Ref. 5) it has been concluded that the optimum water depth of occurrence of mussels in the areas is 5-7 m. However, dense mussel beds are found at depths of 8 m, while 10 m seems to be the depth limit for occurrence of mussels.

At first glance, a total destruction of 2 km^2 of mussel beds out of a total of 15 km^2 may seem insignificant. However, preliminary results from the biological monitoring programme indicate that almost all the mussel biomass in the Sprogø/-Halsskov area is turned over in one year, due to predation from eiders and starfish, indicating that the number of eiders feeding in the waters around sprogø is limited by the amount of food (Ref. 39). The mussel beds in the dredging area is heavily exploited by eiders. It has been estimated that a total removal of all mussels within the dredging area will result in a missing food supply for approximately 8000 eiders in a 3 month period. On the other hand this food may be found in an area southwest of Sprogø, not exploited by eiders. It has been argued that this area is not exploited because the water depth is larger (7-9 m) than at the heavily exploited areas where the water depth is less than 6 m. If the eiders have no choise they may exploit the area southwest of Sprogø. They feed heavily at the Elephant ground in the northern part of Storebælt at a water depth of 7-9 m (Ref. 39). The occurrence of eiders is monitored during the construction phase in order to detect any effect of the dredging and reclamation activities (Refs. 37, 38).

Significant effects on the oxygen balance of mussel beds are not expected, because the mussel beds are located above the interface, where critically low oxygen concentrations are unlikely to occur. Further, the potential effect of the sediment spreading is insignificant in relation to the natural oxygen turnover of mussel beds, which is several times higher than the oxygen turnover of the bottom outside the mussel beds (Ref. 5).

Changes in current conditions may affect mussel beds as feeding depends on the water exchange. Thus reduced current may reduce growth and vice versa.

A major part of the present mussel beds is situated in the area affected by current reductions between 5 and 15%, while only insignificant areas are affected by reductions exceeding 15% (see Chapter 9). In the compensation dredging area the current is calculated to increase by 15-40%.

In the worst case a reduction in growth proportional to the current reduction may occur in the mussel beds affected by reduced currents. In the compensation dredging area the future current velocities in most of the area are comparable to currents in some of the present mussel beds. Possible effects of current will probably be impossible to distinguish from other factors in this changed area.

10.4 Long-Term Effects

10.4 Long-Term Effects

As a basis for this assessment, long-term effects are defined as effects which can be observed 10 years or more after the completion of dredging operations in 1994.
Based on the discussion of effects and recovery times in Section 10.3, the following effects may persist after 10 years:

- Reduction in herring spawning areas around Sprogø:

  The local herring stock may avoid the part of the spawning ground around Sprogø when the sediment surface is changed due to settling. Recovery of the physical sediment characteristics to pre-impact conditions is expected to take place within the 10 years' period, but it is not known whether herring will return to these areas for spawning.

  Based on the fact that the affected spawning area is small (20%) compared to the total area in Storebælt, this long-term effect is considered to have limited impact on the local Storebælt herring stock.

  The Storebælt herring stock is of very little importance for the commercial fishery.

- Changes in the eelgrass beds:

  Approximately 0.5 km^2 of eelgrass bed has been destroyed by land reclamation at Sprogø. The remaining eelgrass areas and part of the macro algal vegetations are situated in the zone of reduced currents immediately around Sprogø. Reduced current will not restrict the eelgrass vegetation. Rather, the current effect may cause the eelgrass vegetation to spread into areas presently covered by macro algae. This effect partly depends on possible changes in sedimentation patterns around Sprogø, which have not yet been assessed.

  A damage of eelgrass beds north of Sprogø will have significant local effect including increased coastal erosion in the area.

- Changes in the macroalgal vegetation of stone reefs:

  Minor stone reef areas have been destroyed by land reclamation at Sprogø (< 0,5 km^2). As presently planned, the compensation dredging area will not include significant stone reef areas with macro algal vegetation.

  Effects of suspended sediments and nutrients (restricted depth limits, increase of annual and epihytic species) will recover within the first years after the dredging activities. However, similar effects may occur during the following years due to increased nutrient load from other sources.

Due to the long recovery time for these biotopes, recovery after short-term effects may not be complete after 10 years. However, the risk of affects requiring long-term recovery is low.

The effect areas are small compared to the total area of those biotopes in Storebælt. In the regional perspective the possible long-term effects are therefore considered not to be significant.

- Decrease in population size of wintering eiders and other diving ducks which feed on mussels:

  If the mussel population is a limiting factor for the size of the diving duck population in Storebælt, the stock may be reduced for a period of time extending beyond 10 years from the stop of the dredging and disposal operations. This aspect is currently being addressed in a field study.

It should be noted, however, that many of the potential effects of the construction activities as described above, are similar to potential effects of increased land-based nutrient load. This is true for the risk of abnormal phytoplankton blooms and oxygen deficiency, for effects on macroalgae and eelgrass, such as restricted depth of occurrence and increase of annual and epiphytic species, and for the favourisation of dab instead of plaice.

Such effects have been reported with an increasing frequency during the recent years, from localities affected only by remote sources of nutrient load. Potential long-term effects of the Great Belt Link must be evaluated against this regional development. As the basic conditions and tendency for this development is poorly quantified as yet, it may become difficult to distinguish possible long-term effects of the Link from regional development due to land-based nutrient load.

10.5 Status for Ecological Impacts as per 30 November 1989

Figures 10.5 and 10.6 show impact areas near the Link alignment for construction activities carried out until 30 November 1989. As major sand dredging operations have been carried out at Romsø SE, a major area in the northern part of Storebælt is affected. The bottom in this area consists of sand or mud and has not been mapped in detail. A total area of 180 km^2 has received more than 0.5 mm sedimentation; 25 km^2 has received more than 5 mm.

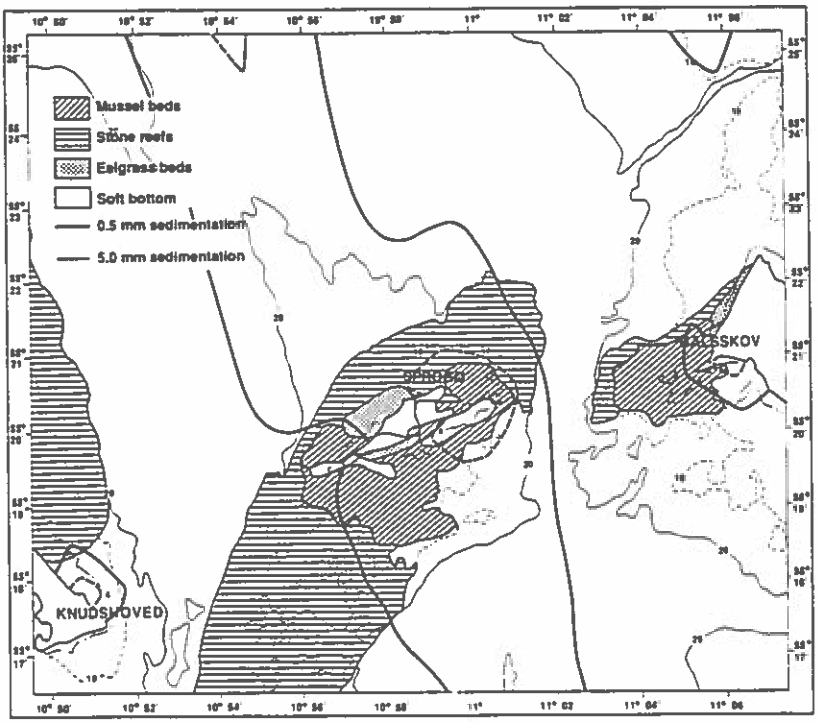


Fig. 10.5 Impact area of construction activities before ultimo November 1989, and bottom biotopes near the link alignment. Isolines for 0.5 and 5 mm primary sedimentation are shown.

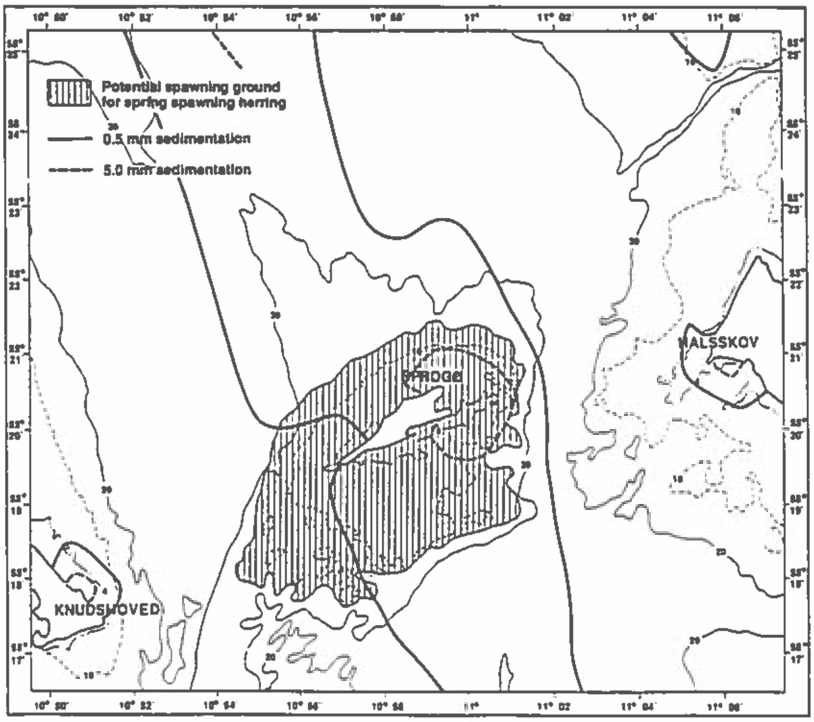


Fig. 10.6 Impact area of construction activities before ultimo November 1989 and herring spawning grounds around Sprogø. Isolines for 0.5 and 5 mm primary sedimentation are shown.

Nutrients and Shading

An increase in phytoplankton production of less than 1% was expected from the released nutrients (see Section 7.3).

The shading from suspended materials and the mentioned increase in phytoplankton production had no severe ecologicl effects (see Section 10.3.1). Acceleration of exceptional plankton blooms cannot be excluded as a possible effect.

Oxygen conditions

Two major cases of potential impacts on oxygen conditions occurred during 1989.

- Dredging by James Ensor at Romsø SE (see Fig. 7.4).
- Compensation dredging east of Sprogø by James Ensor.

During the summer of 1989 oxygen concentrations of the lower layer in Southern Kattegat and in Storebælt remained low and gradually decreased to minimum values of about 3 mg O_2/l in September. This oxygen deficiency was part of a continuous oxygen deficient water mass in the lower layer stretching through Southern Kattegat and Storebælt. (DMU cruise data, communicated by G. Ærtebjerg).

This regional oxygen deficiency implies a risk of local death of fish and other bottom fauna and occurrence of white sulphur bacteria on the bottom, in areas with an unfavourable combination of high bottom oxygen consumption and low water exchange. From the increases in bottom oxygen consumption calculated in Table 7.2, it is concluded that the risk of critical oxygen conditions has been increased during the sand dredging at Sprogø SE.

The sand dredging in the CD area affected more restricted areas, and the areas receiving the highest load of oxygen consuming sediments were located above the interface. Field measurements during this dredging operation have demonstrated that the oxygen concentration was elevated down to about -20 m, including most of the soft bottom areas affected by the CD operations.

Bottom Biotopes

The impact on the various bottom communities until ultimo November 1989 may be summarized as follows:

- The land reclamation east of Sprogø has been carried out reducing the area of eelgrass beds by approximately 0.5 km^2.

- The mussel beds east of Sprogø have been reduced by land reclamation and compensation dredging. Furthermore, the most intensive loads of sedimentation have reached the mussel beds. Most of this sedimentation had disappeared by resuspension by the end of the period, and the mussels were found to be in good condition, except for certain localities, which are likely to be affected by starfish predation.

- Soft bottom areas, mainly near the Romsø SE and Musholm, have been exposed to increased sedimentation and an increased risk of oxygen deficiency.

- Major spreading of sediments around Sprogø started about the end of the spawning period for spring spawning herring (14 May 1989).

- Stone reefs and eelgrass areas around Sprogø have been subject to a load of suspended sediments and nutrients which is typical for the impact during the construction period.

  Shading of suspended particles from work until 30 Nov 1989 has had its most significant effects on the algal vegetation of the reef north of the compensation dredging area, and the reef west and south west of Sprogø (from Romsø SE dredging). Further the eelgrass beds north of Sprogø had been affected. The effects are expected to be a slight decrease in production and a stimulation of annual species and epiphytes at the expense of perennials. From estimation of nutrient release it is expected that the increase in production of annual and epiphytic species was in the order of 30-40 mg C/m^2/year which is significant in relation to the expected benthic plant biomass in the area. No monitoring activities have been carried out for control of the above estimated effects with respect to shading and nutrient releases.

10.6 Status of Ecological Impact after Phase 1

Figures 10.7 and 10.8 show impact areas near the link alignment for the whole Phase 1. Major areas in the northern part of Storebælt are likewise affected. These areas consist of sand or mud bottom and have not been mapped in detail. A total of 260 km^2 receives more than 0.5 mm sedimentation during Phase 1, while 36 km^2 receive more than 5 mm.

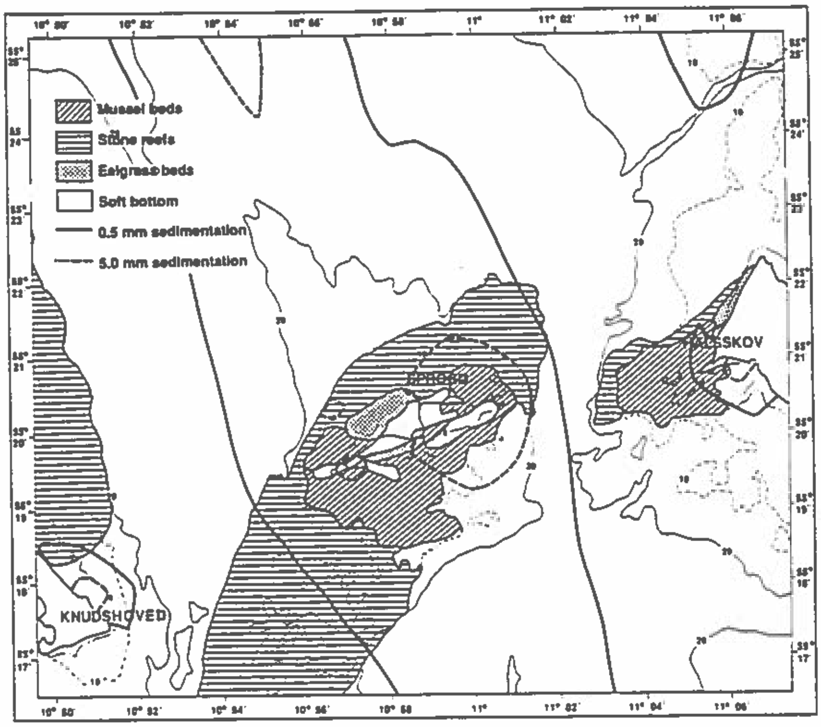


Fig. 10.7 Impact area of construction activities of Phase 1 and bottom biotopes near the Link alignment. Iso lines for 0.5 and 5 mm primary sedimentation are shown.

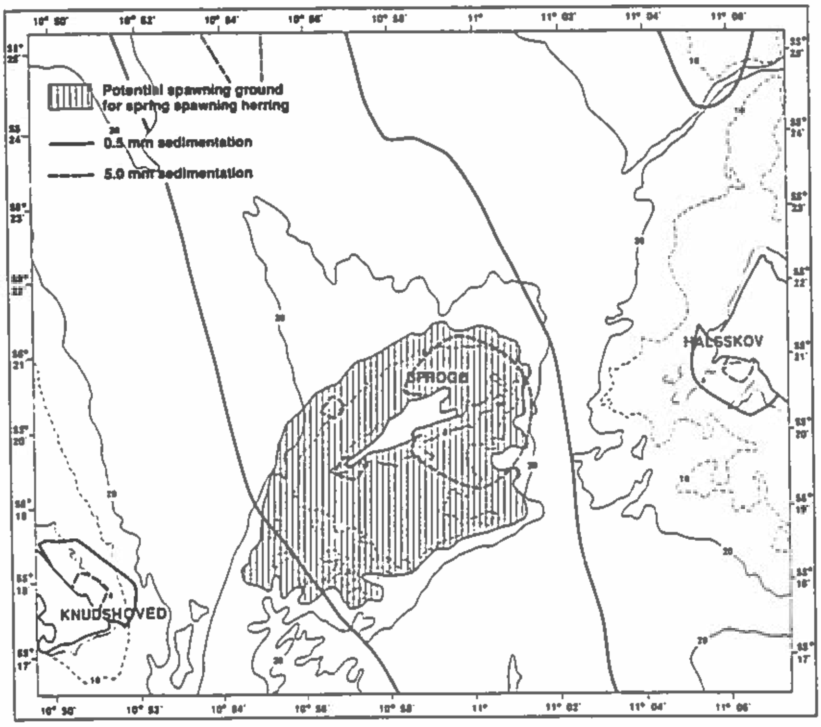


Fig. 10.8 Impact area of construction activities during Phase 1 and herring spawning grounds around Sprogø. Iso lines for 0.5 and 5 mm primary sedimentation are shown.

Most of the remaining Phase 1 activities are planned to be carried out during 1990. The estimated release of suspended sediments around Sprogø is of the same order of magnitude as in 1989, though the western side of Sprogø will be affected to a higher degree than previously. The remaining release at Romsø SE is about 30% of the release during 1989.

Nutrients and Shading

The nutrient release and shading after Phase 1 have effects on phytoplankton similar to that mentioned for the first part of Phase 1 (end November 1989).

The increase in phytoplankton production after Phase 1 is still expected to be less than 1% of background production. This increase is not expected to give any severe ecological effects. Acceleration of exceptional plankton blooms cannot be excluded as a possible effect.

Oxygen Conditions

Like the situation in 1989, the major cases of potential impact on oxygen conditions are:

- Sand dredging by James Ensor at Romsø SE
- Compensation dredging east of Sprogø.

The impact of sand dredging at Romsø SE will be similar to the impact described in Section 10.5, but of shorter duration.

Depending on the final choice of dredging method for compensation dredging in 1990, the impact on the oxygen balance around Sprogø may be similar or slightly higher than the impact in 1989 (see Table 7.2).

Bottom biotopes

Apart from the increased impact on the western side of Sprogø, the impact on bottom biotopes may be described as a continuation of the impact during 1989 (see Section 10.5).

The effect after Phase 1 will have lasted much longer than up till the end of November 1989. Therefore, the effects could be expected to become more pronounced.

11. EFFECTS OF EROSION

Erosion of the new sea bed surface will take place both from the CD area and Route-T re-alignment, from the shaping of anchor blocks by deposition of moraine clay and from the dumping site.

As the sea bed surface of the CD area today consists of sand, gravel and stones, erosion of the new moraine clay surface here will continue until a new stable surface has been established with erosion protecting sand and gravel at the top.

The dumping site at Sprogø NW is less exposed to erosion as the water depth is larger (12-20 m). The sea bed surface of this area today consists of sand, gravel and stones out to approx. 15 m water depth and muddy sand below 15 m.

The thickness of the sea bed layer affected by erosion and the erosion velocity will depend among others on the sediment type left as surface. For the moraine clay in the CD area and the Route-T re-alignment about 15 cm of mainly silt and clay is estimated to have to be eroded before the surface becomes stable. For the shaping reefs about 10% of the clay volume is assumed eroded before the surface becomes stable.

References on process velocity are very few and not related to the moraine clay in Storebælt.

Table 11.1 lists the erosion volumes together with the volumes of sediments brought in suspension during the dredging and disposal operations.

The suspension volumes from the erosion is seen to amount to 30-40% of the suspension volume during the marine earth work operations.

CASE	EROSION AREA	SUSPENSION VOLUME
	km^2	m^3
Erosion		
Compensation dredging	about 3.0	about 450.000
Route-T alignment	0.2-0.4	45.000
Shaping reefs	0.08	60.000
Dumping site (Sprogø NW)	about. 1.5	225.000

Sum erosion		about 800.000
Earth Work Activities Phase 1+2 (Section 5.1)		
Moraine clay dredged by mechanical dredger or		2,000,000
Moraine clay dredged by cutter suction dredger		2,600,000

Table 11.1 Suspension volumes due to erosion compared to suspension volumes from dredging and disposal operations.

Ecological impacts of this sediment spreading has not been assessed. Compared to the sediment spreading from dredging and disposal, this sediment spreading will take place during a few storm events per year, however probably lasting for many years. The sediments will be diluted and spread over a large area due to the very dynamic hydrographic conditions during the stormy weather.

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APPENDIX A

CHARACTERIZATION OF SEDIMENT

In this appendix the characteristics of sediment types known to be present in the compensation dredging area are summerized on basis of an analytical programme carried out during May-August 1988 (Refs. 27, 42).

Sampling

Samples representing the different sediment types were selected by subsampling from 13 vibrocorings taken in May 1988. Positions for vibrocoring were selected to cover the major domains of organic deposits, on the basis of preliminary isopach maps derived from seismic data and borings. Surface sediments were sampled manually as Kajak cores in two campaigns in May and July 1988. The positions of the sampling stations are shown in Fig. A.1.

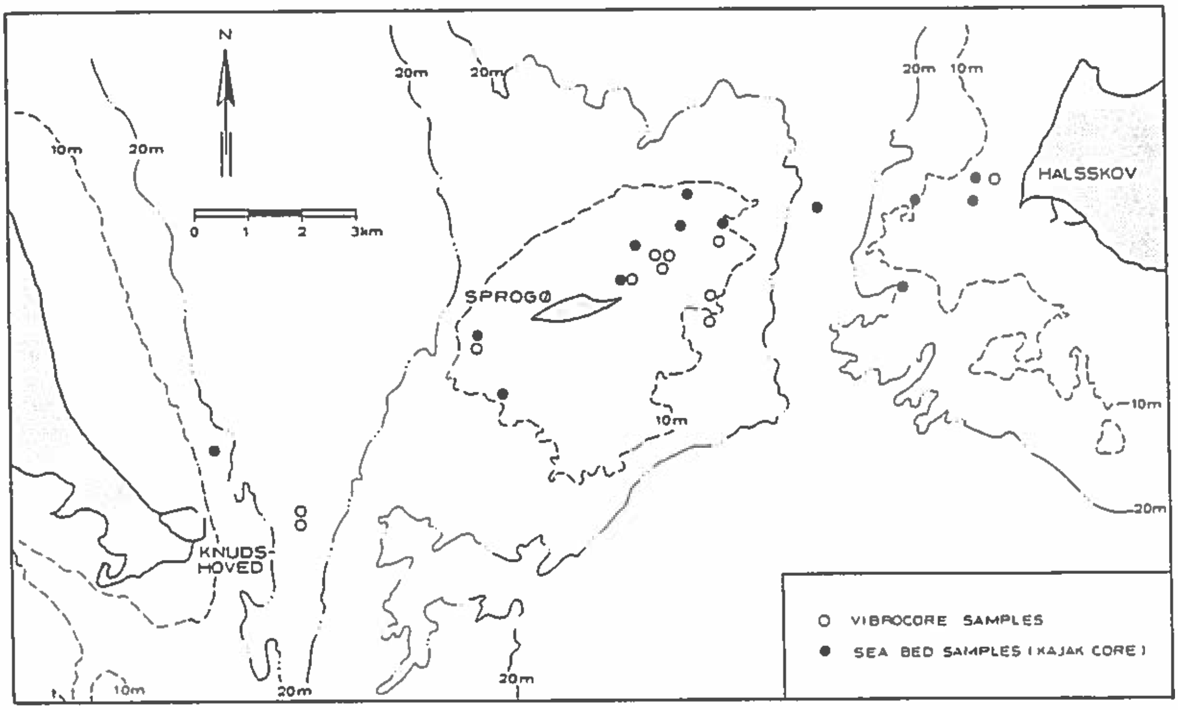

Fig. A.1 Positions of sampling stations for vibrocorings and Kajak core samples. Some of the vibrocoring stations were covered by more than one core.

Sediment Settling Velocity

The settling velocity of peat and gyttja sediments was measured in the laboratory using a Braystock SK 110 settling tube (Ref. 27).

The samples were dispersed in 8.8 o/oo filtered salt water. For dispersion heavy mechanical stirring was used together with treatment in an ultrasonic bath. The breakdown of the samples was continued for 30 minutes to ensure complete dispersion.

The applied mechanical breakdown of the sediment in the laboratory is much more violent than the one expected during excavation, transport and deposition. The grain size of the dispersed sediment in the experiments is consequently finer and the mean settling velocity is lower than what can be expected during removal of the sediment.

Based on experimental results it can be concluded that the peat sediments in question have median settling velocities in the range 0.0015 - 0.0056 m/s and that the finest 10% of these sediments will have settling velocities smaller than about 0.00015 m/s.

For the gyttja sediments median settling velocities are in the range 0.00079 - 0.0036 m/s. The finest 10% have settling velocities smaller than 0.00043 m/s (average for the 5 gyttja samples).

The observed settling velocities, which are very high for fine-grained materials, can be explained by

- Flocculation of particles into larger aggregates due to the high ionic strength of the water.
- A content of very fine-grained sand in many of the samples. However, the sand content does not affect the settling velocity of the finest part of the samples.

Sediment Oxygen Demand

A total of 33 samples from the vibrocorings, representing the main types of sediments encountered, have been analysed for total iron, total sulfur and loss on ignition (550°C). The total potential oxygen demand (total-POD) was calculated stoichiometrically, assuming total oxidation of iron, sulfur and organic compounds.

The actual oxygen demand of 16 of the samples was measured by incubation in suspension. All samples were measured for 22-24 hours, and several samples were subsequently kept oxidized for 5 days before repeated measurement of oxygen consumption.

The oxygen comsumption rate was highest during the first few hours after suspension after which it decreased somewhat to reach a level which changed little during the period 12-24 hours. After 5 days oxygen consumption had decreased markedly and approached the detection limit of the experiment. The results of the experiments were expressed by two parameters:

- The oxygen demand of the first 24 hours: SOD_{24} (Suspended Oxygen Demand).
- The oxygen consumption rate as estimated from the period 12-24 hours (partly stabilized): SOD_{rate}.

The results of the measurements are summarized in Table A.1, which shows median and range of the oxygen demand parameters for the various types of sediments encountered in the compensation dredging area.

	SOD_{rate}		SOD_{24}		Total-POD	
MATERIAL	Median	Range	Median	Range	Median	Range
	- kg O_2/m^3/day -		kg O_2/m^3			
Surface sand/gravel	0.23	0.16-0.39	0.45	0.31-1.3	56	13-87
Gyttja	0.42	0.41-0.54	0.61	0.56-0.65	153	99-182
Peat	0.34	0.12-0.54	0.61	0.28-0.66	355	125-482
Other materials						
All	0.20	0.02-0.38	0.29	0.056-0.38	67	23-118
Sand	0.20	0.02-0.38	0.22	0.056-0.38	29	23-54
Moraine clay	0.25	0.20-0.29	0.30	0.29-0.31	100	81-118

Table A.1 Oxygen demand in suspension (SOD_{24} and SOD_{rate}), and potential oxygen demand (total POD), expressed per unit volume of sediment.

There is no simple relation between total POD and the oxygen demand measured in suspension for the material as a whole. The organic fraction, which dominates the POD in most samples, often consists of very refractory compounds, especially in the glacial and early postglacial deposits. Within each class of sediments, however, total POD may be assumed to indicate the level of oxygen demand of a given sample.

The short duration of the initial oxygen demand indicates that, for most samples, it is mainly the result of oxidation of reduced iron and, for some samples, hydrogen sulphide.

The following comments apply to the different classes of sediment:

Surface sand and gravel have the highest SOD values relative to POD. These sediments contain undecomposed as well as old decomposed (refractory) organic matter, and the sediments encountered in the field may be even more variable than those investigated, as the Storebælt area is very heterogenous.

Gyttja and peat are early postglacial deposits, and the main part of the organic matter is refractory.

Sand sediments are very variable in terms of oxygen demand. Marine as well as freshwater deposits are found in the area (Ref. 28). They contain variable amounts and types of organic compounds, iron and sulphur, depending on the conditions at the time of deposition.

The moraine clay seems to be less variable. Its oxygen demand is relatively high, but is likely to derive from its high iron content.

Oxygen Demand after Deposition

Deposition of sediment on the sea bed was simulated experimentally by incubation in the laboratory of intact cores of surface sediment from the near field with and without suspended sediment settled on top of the natural surface.

The cores were taken from 3 stations above and one station below the interface. The respiration before deposition of suspended sediment was measured for all samples (period I). The mean consumption rate for each station ranged between 1.4 and 2.6 g O_2/m^2/day. These are fairly high consumption rates, which may in part be due to the high stirring applied to the water phase during the experiment.

Two sediment samples were selected for deposition, see Table A.2. The surface sediment from station B was chosen to show the effect of a sediment with a relatively high oxygen demand, whereas sample 9A-5 shows the effect of a sediment with low oxygen demand.

Sample	Water depth	Type	SOD_{rate}	SOD_{24}	Total-POD
			kg O_2/m^3/day	—— kg O_2/m^3 ——	
Station B	3 m	Surface sand	0.29	0.35	18
9A-5	6.6 m	Medium sand depth 0.5 m	0.02	0.06	29

Table A.2 Characteristics of sediment material used for deposition, expressed per unit volume of sediment.

The station B sediment was applied in layers of 1, 5 and 10 mm, while sample 9A-5 was applied only as a 5 mm treatment. Each treatment was applied to a core from each station, while one core served as control. Oxygen consumption was measured daily during the first and the third week after application of suspended sediment (periods II and III).

The results were analyzed statistically by analysis of variance, using consumption of period I (before application of sediment) as cofactor to eliminate variation between individual cores.

By this analysis it was found that the effect of deposition was similar for all 4 stations, and consequently the results are presented as (geometric) means for the stations.

Period		DEPOSITED SEDIMENTS				
		Station B				9A-5
	Layer depth:	0 mm	1 mm	5 mm	10 mm	5 mm
		—— g O_2/m^2/day ——				
II: 0-7 days after deposition		2.18	2.06	2.39	2.55	1.83
III: 15-22 days after deposition		2.01	1.90	1.68	2.00	1.64

Table A.3 Sea bed oxygen consumption rates without and with deposited sediments. Mean values based on pooled experiments with intact surface sediments from 4 different positions.

The oxygen consumption rates for the different treatments are shown in Table A.3. In period II the variation between treatments was found to be statistically significant. Thus the increase in consumption with increasing amounts of Station B sediment can be interpreted as the result of the deposition. However the natural variability of the material does not permit a more detailed evaluation. Thus the decrease found at 1 mm deposition cannot be distinguished from natural variability. The same applies for the decrease measured after deposition of the 9A-5 sediment.

In period III no significant difference was found between treatments. Thus the possible effect of the treatments cannot be distinguished from natural variability.

It may then be concluded that deposition of an oxygen-consuming sediment gives rise to a measureable increase in oxygen consumption rate of the sediment at the settling site, but that the effect decreases below the limit of detection within a few weeks after deposition.

Oxygen Demand of Newly Exposed Sediment Surfaces

The new sediment surface exposed after dredging was simulated by packing material from vibrocores into Kajak tubes and incubating these at the same conditions as the sediment cores used in the deposition experiments described above. Oxygen consumption was measured during the first and third week after exposure.

Three samples were selected among the most oxygen-consuming types encountered, representing gyttja, peat, and sand with high organic content. The characteristics of the samples are shown in Table A.4.

Sample	Sediment depth	Type	SOD_{rate}	SOD_{24}	Total POD
	m		kg O_2/m^3/day	kg O_2/m^3	kg O_2/m^3
a	1.4-1.6	Gyttja	0.54	0.61	173
b	3.95-4.10	Peat	0.26	0.60	428
c	7.55-7.75	Fine sand (with org. matter)	0.38	0.38	54

Table A.4 Characteristics of sediment samples from Sprogø Østrev used to simulate oxygen consumption of newly exposed underlying sediments. Expressed per unit volume of sediment.

The oxygen consumption rates of the newly exposed sediments are shown in Table A.5. These rates were lower than the oxygen consumption rates measured for the undisturbed sediments from the same area, already during the first week after exposure, and oxygen consumption decreased further between the first and the third week.

Sample	Type	Oxygen consumptions rate Period 1 Day 0-3 Mean	St.dev.	Period 2 Day 13-17 Mean	St.dev.
		g O_2/m^2/day			
a	Gyttja	1.27	0.61	0.85	0.51
b	Peat	1.40	1.19	1.01	0.34
c	Fine sand (with organic matter)	1.04	0.66	0.82	0.29

Table A.5 Sea bed oxygen oxygen consumption rates of newly exposed underlying sediments measured after the first and third week after exposure.

Since these samples represent the upper range of oxygen demand found among sediments in the area, it can be concluded that the exposure of underlying sediments will not increase the oxygen demand relative to the existing conditions. The experiment does not include the effect of suspended sediments settling on the new sea bed.

Generalization of Oxygen Demand

In order to estimate the overall effect of the dredging operations on oxygen conditions, the effect on oxygen consumption of the sediment materials after settling has to be estimated for all sediment types on the basis of the deposition experiments and the otherwise known characteristics of the sediments (see Table A.1).

It is assumed that oxygen consumption in suspension is a better predictor of the behaviour of individual sediment types than potential oxygen demand. This assumption is supported by the fact that oxygen demand in suspension, like the effect on oxygen consumption after settlement, decreases after a period with oxidizing conditions.

Among the two parameters of oxygen demand in suspension (SOD_{24} and SOD_{rate}), the latter is assumed to be most relevant, considering the duration of the effect after settlement.

The uncertainty of the generalization is largely due to two points:

- Generalizing from one sample of suspended sediment.
- Generalizing from a laboratory experiment to field conditions.

Because of these uncertainties the relation between increase in oxygen consumption after settlement (ΔK), sediment oxygen demand of the superposed sediment (SOD_{rate}), and height of the superposed layer (H) has been modelled on the basis of a conservative interpretation of the experimental results.

The model is based on the follwoing considerations:

The most conservative model would be assuming that the oxygen demand after settling is equal to the value measured in suspension, which would give $\Delta K = SOD_{rate} * H$. This model would, however, give oxygen consumption rates far higher than those measured. The reduction of the effect after settling is likely to be due to the fact that oxygen consumption of sediments is limited by diffusion in the sediment and the boundary layer.

If, however, it is assumed that the oxygen demand of the first millimeter of deposited sediment contributes fully to ΔK, while further deposition contributes only by 20% of its oxygen demand the predicted oxygen demand coincides roughly with the upper confidence limits of the experimental results (see Fig. A.2). Thus the model represents a conservative, but realistic interpretation of the experimental results. It is given by the following expression:

$$\Delta K = \begin{cases} H \cdot SOD_{rate} & \text{for } H \le 10^{-3} \text{ m} \\ (0.0008 \text{ m} + 0.2 H) \cdot SOD_{rate} & \text{for } H > 10^{-3} \text{ m} \end{cases}$$

where H is the thickness of the settled out layer and SODrate is the suspended oxygen consumption rate of the inspected sediment types which are being dredged.

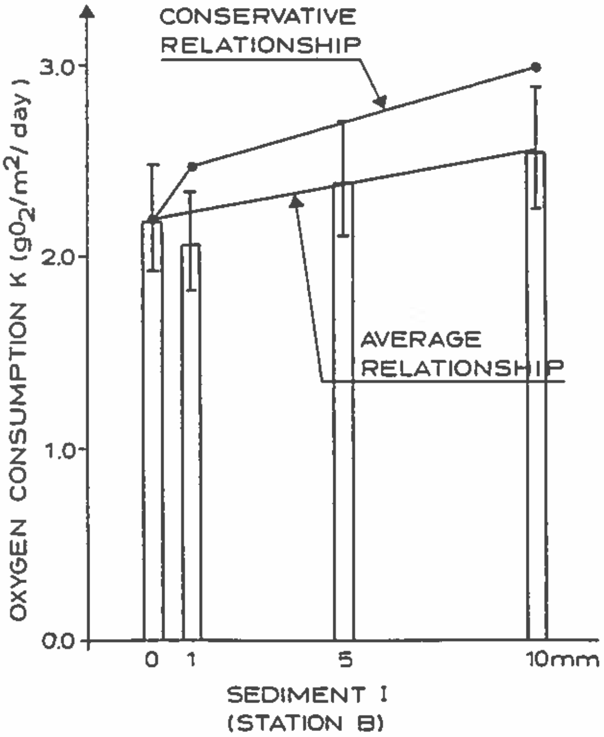

Fig. A3.2 Relationship between oxygen consumption and settled sediment layer thickness tested on experimental results.

Nutrient Contents

Estimates of release and pools of exchangeable nitrogen (N) and phosphorus (P) are based on experiments with anoxic suspensions of sediments. Aerobic experiments underestimate the release because of the nitrification-denitrification processes.

The pools of exchangeable nutrients were determined as the accumulated release during the entire experiment, i.e. 52 days. The highest release was recorded at the start of the experiment. During the following 7 weeks the release in most suspensions decreased to zero.

The greatest pools of N and P were found in the sea bed surface layer (0-20 m), where the fauna and flora are situated, and where the sediment receives fresh organic matter with N and P, see Table A.6. The sediments without gyttja and peat had lower pools of N and P than the surface layer. The range of pools appeared to be lower, too.

Material	N-pool Median	N-pool Range	P-pool Median	P-pool Range
	g N/m^3		g P/m^3	
Surface sand/gravel	58	14-219	24	3-56
Gyttja	55	24-86	16	11-20
Peat	12	11-12	6	3-8
Other materials				
All	31	14-65	4	-2-12
Sand	36	29-65	7	5-12
Moraine clay	15	14-33	0	-2-2

Table A.6 Pools of nitrogen (N) and phosphorus (P) in sediment samples. Based on analysis after 52 days in the test set-up. Ref. 27.

Two samples with gyttja were examined. The pools of the samples differed by a factor three to four. On average the size and the range of the pools is between what was found in the surface layer and in the sediments without peat and gyttja.

The initial release rates of nutrients were determined as the release during the first 12 hours of experiment. The highest initial release rates were recorded in the sediments containing gyttja, see Table A.7.

Sediments with peat had a negative inital release rate of N, meaning that N was absorbed from the sea water, while the release rate of P was positive, but low. Surface sediments and sub-surface sediments without gyttja and peat had similar N-release rates. The level was between what was found in the gyttja and in the peat.

The P-release rate was higher in the surface sediment, though less than in the sediments with gyttja, while the P-release rate of sub-surface sediment without gyttja and peat was close to zero.

Material	N-release, 12 h Median	N-release, 12 h Range	P-release, 12 h Median	P-release, 12 h Range
	g N/m^3		g P/m^3	
Surface sand/gravel	12	-6-52	7	0-23
Gyttja	26	9-43	9	4-14
Peat	-14	-16-(-13)	3	2-3
Other materials				
All	16	-1-41	1	-2-4
Sand	15	-1-41	1	0-4
Moraine clay	17	11-23	0	-2-2

Table A.7 Initial release rates of nitrogen (N) and phosphorus (P) in sediment samples. Based on analysis after 12 hours in the test set-up. Ref. 27.

Generally, the range of initial N-release rates were of a similar magnitude in the different groups of sediments, except that no positive values were recorded in the sediments with peat. Concerning initial P-release rates, surface sediments and sediments containing gyttja had wider ranges than the other sediments.

APPENDIX B

DATA ON HEAVY METAL CONCENTRATIONS IN SURFACE SEDIMENTS AND CLAY AND MARL SAMPLES FROM STOREBÆLT.

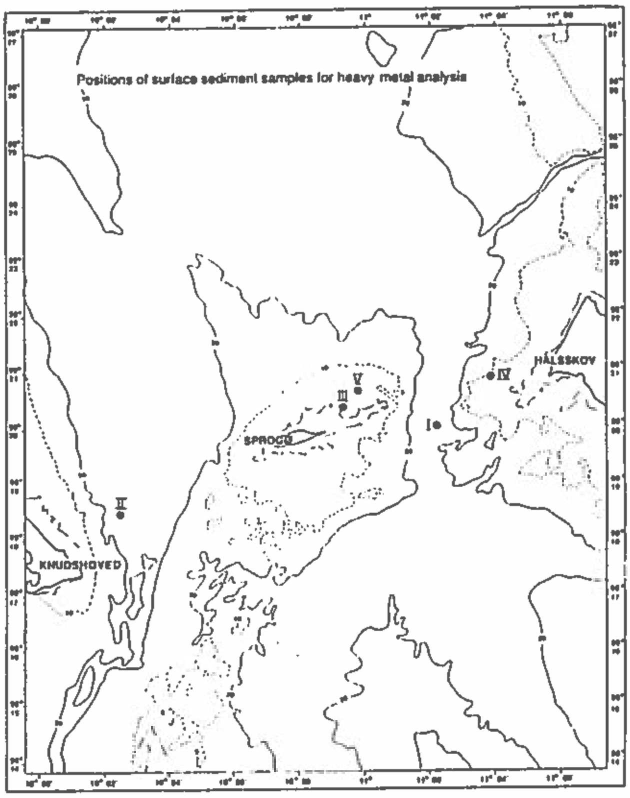

Fig. B.1 Sampling positions of surface sediment samples for heavy metal analysis.

	mg/kg loss of ignition								
	As	Cd	Cr	Cu	Pb	Hg	Ni	Sn	Zn
St. I	317	14	825	870	1261	2.5	696	74	3304
St. II	160	6.5	500	500	462	0.7	846	38	1462
St. III	47	4.5	362	271	163	0.2	316	11	714
St. IV	207	11	634	427	866	1.3	364	66	2439
St. V	136	7.4	420	333	506	0.6	346	43	1852
Mean	175	8.7	548	480	652	1.1	568	46	1954
S.D.	99	3.4	235	235	422	0.9	230	25	98

Table B.1 Heavy metal contents in surface sediment samples from Storebælt related to per cent loss of ignition.

	Depth below sediment surface m	Concentrations in mg/kg DM As	Ca	Cr	Cu	Pb	Hg	Ni	Sn	Zn	Ref No
						Surface sediments					
Station I	0	7.3	0.33	19	20	29	0.058	16	1.7	76	32
Station II	0	4.4	0.17	13	13	12	0.018	22	1.0	38	32
Station III	0	5.2	0.5	40	30	18	0.018	35	1.2	79	32
Station IV	0	1.7	0.09	5.2	3.5	7.1	0.011	5.2	0.54	20	32
Station V	0	1.1	0.06	3.4	2.7	4.10	0.005	2.80	0.35	15	32
Mean		3.9	0.23	16	14	14	0.022	16	0.96	46	
S.D.		2.6	0.18	15	12	10	0.021	13	0.54	30	
					Samples from geotechnical investigations						
Station 8712	7.7	1.6	0.059	13	5.8	4.2	0.0045	10	<0.2	22	33
Station 8712	18.6	1.2	0.09	14	5.2	3.4	0.0035	11	<0.2	20	33
Station 8713	2.0	0.8	0.26	10	3.7	2.3	0.0036	11	<0.2	14	33
Station 8713	21.1	1.0	0.10	11	7.5	3.9	0.0035	7.3	<0.02	19	33
Station 8714	7.1	1.5	0.16	11	5.5	4.0	0.0049	9.0	<0.2	23	33
Station 8714	16.0	1.4	0.17	8	5.7	3.1	0.0042	8.4	<0.2	21	33
Station 8714	22.2	1.1	0.08	13	4.3	3.1	0.0034	11	<0.2	16	33
Station 8715	19.6	1.2	0.08	8	8.0	3.6	0.0035	7.9	<0.2	22	33
Station 8716	37.0	1.1	0.10	13	5.4	3.5	0.0030	12	<0.2	22	33
Mean		1.2	0.12	11	5.7	3.5	0.0038	9.7	<0.2	20	
S.D.		0.3	0.06	2	1.4	0.6	0.0006	1.6	-	3	

Table B.2 Heavy metal contents in sediment samples from Storebælt related to dry matter.

12. DANSK RESUME

Denne undersøgelse omfatter de mulige miljøeffekter af de marine jordarbejder i forbindelse med anlægsarbejderne for den faste forbindelse over Storebælt.

Undersøgelsen er en opdatering af to tidligere undersøgelser (ref. 1, 20). Opdateringen er bl.a. baseret på:

- mere specifikke informationer om planlagte og gennemførte marine jordarbejder,
- konkrete målinger af spildmængder fra anlægsarbejdet fra måletogter i 1989.

Undersøgelsen er baseret på foreliggende informationer pr. januar 1990. På dette tidspunkt var fase 1 af anlægsarbejderne fastlagt:

- lavbroen over Vesterrenden og opfyldning ved Knudshoved,
- udbygningen af Sprogø med ramper mod øst og vest,
- togtunnel i Østerrenden,
- arbejdshavnene ved Lindholm og Halsskov,
- første del af kompensationsafgravningerne (CD).

Boringen af jernbanetunnelen (tør boring) i fase 1 og fremtidig bortledning af dræningsvand fra denne er ikke medtaget i undersøgelsen af de marine effekter.

Fase 2 af Storebæltsforbindelsen er endnu ikke endeligt fastlagt. I denne vurdering af de marine effekter er fase 2 forudsat at omfatte:

- en hængebro med 1400 m gennemsejlingsfag og beton-tilslutningsfag,
- del 2 af CD (sat til 4 mio. m^3 moræneler),
- udretning af dybskibsruten gennem Østerrenden (T-ruten, ca 0.6 mio. m^3 moræneler),
- opbygning af strømlignende rev ved broens ankerblokke (ca. 0,6 mio. m^3 moræneler).

Følgende forhold er omfattet af undersøgelsen af effekter fra de marine jordarbejder:

- Sediment spredning:
  Mængde, koncentration af suspenderet sediment i fanen nedstrøms aktiviteten, og område påvirket af sedimentation.

- Næringssalt frigivelse:
  Mængde og effekter på makroalgevegetation og fytoplankton produktion.

- Iltforhold:
  Iltsænkning i fanen nedstrøms for aktiviteten, påvirkning af bundens iltforbrug fra sedimentation af suspenderet

materiale og frigivelsen af næringssalt, samt effekten heraf på iltkoncentrationerne.

- Frigivelse af andre stoffer:
  Svovlbrinte, tungmetaller og andre stoffer.

- Økologiske effekter:
  Effekter på stenrev, muslingebanker, blødbundsområder, ålegræsområder og sildegydeområder langs linieføringen for Storebæltsforbindelsen.

Endvidere omfatter undersøgelsen en foreløbig vurdering af ændringen i strømforhold omkring Sprogø som følge af udbygningen med ramper, samt omfanget af erosion fra blotlagte morænelersoverflader.

Nedenfor er resumeret hovedresultaterne af undersøgelsen.

Omfanget af marint jordarbejde

Fase 1 af de marine jordarbejder vil ialt omfatte ca. 10 mio. m^3 (tabel 3.2) af sen- og postglaciale aflejringer (sand samt blødbund). Indtil slutningen af november 1989 har jordarbejderne omfattet ca. 5,5 mio. m^3 (tabel 3.1).

I fase 2 forventes ca. 5 mio. m^3 flyttet (hovedsageligt moræneler, se tabel 3.3). Mængden i fase 2 er dog usikker, da den endelige dimensionering endnu ikke er foretaget.

Fase 2 forventes at resultere i et overskud af moræneler, som enten skal deponeres på land, bruges til konstruktionsformål eller deponeres marint. Undersøgelsen indeholder en foreløbig diskussion af effekterne af de forskellige deponerings alternativer. Det anbefales på baggrund af miljøhensyn at gennemføre en nøjere undersøgelse af alternativerne med klapning ved Romsø SE og med direkte udledning af moræneleret i opslemning (gravet med skæresugemaskine) til nedre lag i Østerrenden.

Spild af sediment

På baggrund af måletogter i 1989 er foretaget en revision af spildspecifikationerne fra jordarbejderne (tabel 4.1 - 4.3).

Herefter er opgjort de forventede mængder af sediment, der under jordarbejderne bringes i suspension og spredes i Storebælt. Indtil udgangen af november 1989 er tabet bestemt til 1,2 mio. m^3 (tabel 5.1). Totalt for fase 1 forventes spredt 1,7 mio. m^3 sediment. I fase 2 forventes spredt 0,3 - 0,9 mio. m^3 afhængigt af om der anvendes mekaniske uddybningsmetoder (spandkæde- eller grabmaskiner) eller skæresugemaskiner.

Hovedparten af sedimenttabet sker i sandressourceområdet ved Romsø SE (ca. 64%, fig. 3.2). Omkring 6% af det samlede sedimenttab skyldes gravning i CD området.

Den primære spredning og sedimentation af suspenderet materiale er beregnet med System 21. Den primære sedimentation vil overskride 0,5 mm i et område på omkring 300 km^2, og 5 mm i et område på 46-65 km^2 (tabel 5.2 og fig. 5.4 - 5.7). Den maksimale akkumulerede primære sedimentation er ca. 100 mm uden for graveområderne.

Det endelige sedimentationsområde efter resuspension af sedimentet er Storebælts naturlige sedimentationsområder (blødbundsområder, se fig. 5.3).

De højeste suspenderede stofkoncentrationer vil forekomme i sedimentfanen nedstrøms for aktiviteten (fig. 5.8) og vil hæmme lysnedtrængningen.

Næringssalt frigivelse

Frigivelsen af næringssalt for de individuelle jordarbejder vil normalt ligge i intervallet 30-300 kg N/dag og 1-25 kg P/dag (tabel 6.1). Dette svarer til op til 30% af tilledningen af næringssalt om sommeren fra Nyborg by og opland.

I kortvarige perioder under indpumpning af blødbund i bassinerne på Sprogø kan forventes frigivelser på op til 900 kg N/dag og 270 kg P/dag. For jordarbejderne i moræneler vil frigivelserne være meget små, pånær for direkte udpumpning af morænelers-opslemning gravet med en skæresugemaskine.

Samlet udgør den forventede frigivelse af næringssalt ca. 260 ton N og 29 ton P (tabel 6.3), svarende til i størrelsesordenen ½ års tilledning fra Nyborg by og opland.

Hovedparten af de friggivne næringsalte vil blive indbygget i fytoplankton, mens 25-30% vil blive indbygget i makroalgevegetation på de lavvandede områder ved Sprogø, Knudshoved og Halsskov (tabel 6.4).

Iltforhold

Iltforholdenen i Storebælt kan påvirkes af jordarbejderne gennem:

- iltsænkning i sedimentfanen lige nedstrøms for graveaktiviteten,
- generel påvirkning af iltkoncentrationen i vandmasserne som følge af forøget bundiltforbrug.

Iltsænkningen i sedimentfanen er blevet vurderet for de største jordarbejder (tabel 7.2). Sandindvinding ved Romsø SE giver den største iltsænkning (iltsænkning mindre end 1 mg O_2/l i 90% af tiden). De fleste sedimentfaner vil kun påvirke øvre lag, hvor iltforholdene normalt er gode. Endvidere vil iltsænkningen aftage i nedstrøms retning, idet fanen iblandes upåvirket vand.

Deponeringsalternativet med udpumpning af opslemmet moræneler i nedre lag under skillefladen til øvre lag vil imidlertid medføre, at iltsænkningen i sedimentfanen forløber i nedre lag (iltstænkning mindre end 0.6 mg O_2/l i 90% af tiden).

Omfanget af generel iltsænkning i vandmassen som følge af ændret bundiltforbrug er vurderet på baggrund af:

- iltoptagelsen fra den fritlagte overflade på gravepositionen,
- effekten af sedimentation af suspenderet materiale fra jordarbejderne,
- frigivelsen af næringssalte.

Laboratorieforsøg har vist, at iltoptagelsen fra den fritlagte overflade ikke overstiger forbruget fra den eksisterende overflade, og dermed ikke bidrager til forværrede iltforhold. Den største del af graveområderne er placeret i øvre lag.

Effekten af sedimentation af suspenderet materiale er blevet baseret på en konservativ tolkning af laboratorieforsøg med pålejring af sediment på intakte bundprøver. Effekten er bestemt for 6 hovedtilfælde af jordarbejder (fig. 7.5). Det største bidrag til forøgelsen af bundiltforbruget er beregnet til 35-70% tæt på aktiviteten. Arealet med 10% forøgelse i bundiltforbruget er for de 6 hovedtilfælde beregnet til 2-32 km^2 (tabel 7.3).

Frigivelse af næringssalt vil hovedsageligt påvirke iltforbruget på de lavvandede områder ved Sprogø, Halsskov og Knudshoved. Her vil næringssaltene forøge makroralge produktionen, hvilket resulterer i et ekstra iltforbrug ved nedbrydningen i efteråret (table 7.5). Da disse områder imidlertid er placeret i øvre lag, hvor iltforholdene generelt er gode, forventes effekten på iltkoncentrationerne at være begrænset. Forøgelsen i bundens iltforbrug for nedre lag som følge af forøget produktion af fytoplankton, som til sidst sedimenterer ud på bunden, er beregnet til maksimalt 1% af baggrundsværdien for bunden.

Effekten på iltkoncentrationerne i nedre lag af de ovenfor nævnte ændringer i bundens iltforbrug er analyseret:

- I tilfælde med strøm i nedre lag vil reduktionen i iltkoncentration i nedre lag maksimalt nå 0,1 mg O_2/l.

- I tilfælde uden nettostrøm i 40 timer vil reduktionen i iltkoncentration i nedre lag maksimalt blive 0,4 mg O_2/l under klapning af moræneler, mere for direkte udledning af morænelers opslemning til nedre lag og mindre for andre graveaktiviteter.

De beregnede reduktioner i iltkoncentrationen kan sammenholdes med de målte iltkoncentrationer på 30-35 m dybde ved Halsskov Rev (fig. 7.2), som viser en minimal iltkoncentration på 1,9 mg O_2/l i 1987.

Samlet kan konkluderes, at effekter på iltkoncentrationerne under jordarbejderne kun forventes at være målelige under større jordarbejder som tidsmæssigt falder sammen med meget rolige strømforhold i Storebælt. Endvidere er mulige økologiske effekter af reducerede iltkoncentrationer begrænset til perioden juli-oktober, hvor iltkoncentrationen i nedre lag i Storebælt generelt er lav (se endvidere under omtalen af de økologiske påvirkninger nedenfor).

Frigivelse af andre stoffer

I fanen nedstrøms graveaktiviteten kan koncentrationen af fri svovlbrinte (H_2S) nå op på ca. 0.09-0.4 mg/l under gravning i muslingebanker. Ved gravning i andre materialer vil koncentrationen være mindst 10 gange mindre. De forventede koncentrationer er ikke kritiske for fisk ved korte exponeringer.

Der forventes kun ringe frigivelse af tungmetaller fra gravematerialet, som ikke vil have signifikant effekt på marint liv. Dette skyldes, at koncentrationerne i grave-materialet er lave (Appendix 2) og upåvirket af menneskelig aktivitet. Endvidere er frigivelsesprocesserne langsomme sammenlignet med varigheden af en sedimentpartikel i suspension, og fortyndingen er høj.

Der er ingen informationer om deponeringer af affald eller andre stoffer af betydning, som kan spredes under jordarbejderne.

Ændrede strømforhold ved Sprogø

Der er gennemført en foreløbig analyse af effekterne på strømforholdene omkring Sprogø fra udbygningen af Sprogø med ramper. Analysen er gennemført med den hydrodynamiske model System 21-HD. Strømsimuleringerne viser en reduktion i strømhastigheden i et bælte på op til 1000 m omkring den udvidede Sprogø, samt hen over den bortgravede top af Sprogø Østrev. Nord og syd for den bortgravede top af revet forøges strømhastigheden.

Resultaterne af det biologiske overvågningsprogram for 1989

Foruden emissionsovervågningen af sediment- og næringssaltfaner, som udgør grundlaget for den foregående kildestyrkevurdering, blev der i 1989 også påbegyndt en overvågning af virkningerne af de marine jordarbejder på vigtige dele af økosystemerne i Storebælt. Denne overvågning omfattede en såkaldt feedback overvågning og en overvågning af væsentlige biologiske fænomener.

På grundlag af den overvågning, som er foretaget indtil videre, kan visse spørgsmål besvares med <u>en høj grad af sikkerhed</u>; det drejer sig om følgende spørgsmål:

> Vil den blivende og midlertidige ødelæggelse af muslingebankerne påvirke bestanden af overvintrende edderfugle omkring Sprogø ?
>
> > Da det er påvist:
> >
> > - at biomassen af muslinger omsættes fuldstændigt i løbet af et år (fortæret og misted ved gydning), hvilket viser, at bestanden af edderfugle er begrænset af fødemængden, og
> > - at der sandsynligvis ikke findes alternative fødekilder tæt på Sprogø med undtagelse af områder med større vanddybder sydvest for Sprogø
> >
> > er svaret på dette spørgsmål bekræftende.
>
> Hvor stor er den mængde af muslinger, som vil blive permanent ødelagt ved kompensationsafgravninger og landindvinding ?
>
> > Kortlægningen af muslingebankerne har vist, at omfanget af ødelæggelsen svarer til fødegrundlaget for ca. 8.000 overvintrende edderfugle.

Da overvågningsprogrammet kun har fungeret i et kort tidsrum, og fordi mange aktiviteter endnu ikke er igangsat, kan visse spørgsmål kun besvares med <u>nogen usikkerhed</u>; det drejer sig om følgende spøgsmål:

> Har udledningen af næringssalte i forbindelse med sandsugning og sedimentopfyldning bidraget til algeopblomstringer i 1989 ?

Overvågningen af udledningerne sammenholdt med oplysninger, som er indhentet fra andre overvågningsprogrammer i Storebælt, tyder på et bekræftende svar.

Vil forøget sedimentation føre til, at muslingernes væksthastighed falder ?

Den første undersøgelse af muslingernes vækst tyder på, at dette ikke er tilfældet med hensyn til virkningen af sediment i det bundnære vandlag. En videooptagelse på nogle få udvalgte stationer, tydede ikke på en kraftig påvirkning af muslingerne. Sedimentfældeundersøgelse viste imidlertid tykke lag af bundfældet materiale, som vil begrave muslingerne og kan nedsætte deres vækst. Der er behov for yderligere undersøgelser for at besvare dette spørgsmål.

Forekommer der forøgede koncentrationer af planktonalger eller formindskede iltkoncentrationer i sedimentfanen ?

Der er ikke fundet tegn på den slags effekter, men fanesporingen i forbindelse med sandsugning har ikke været tilstrækkeligt dækkende til at give et fuldstændigt svar på dette spørgsmål.

Af samme grund som nævnt ovenfor kan nogle spørgsmål vedrørende miljøeffekter kun besvares meget usikkert; det drejer sig om:

Har anlægsarbejderne ført til en nedgang i bestanden af overvintrende edderfugle i Storebælt ?

Flytællinger viste en nedgang i antallet af edderfugle i Storebælt i december 1989 sammenlignet med både november 1989 og december 1988. Der kræves mere end én optælling for at spørgsmålet kan besvares bekræftende.

Der har været rejst to spørgsmål om plantevæksten: Vil en forøget sedimentation føre til en nedgang i væksten hos brunalger (Laminaria), og vil der ske en forøgelse af væksten af epifytiske alger på brunalgerne ?

Den dag videooptagelsen blev foretaget, var der intet sedimentlag at se på brunalgerne, og der kunne ikke iagttages nogen drastisk forandring i laget af epifytiske alger eller i sammensætningen af brunalgerne. Da andre undersøgelser imidlertid har vist lejlighedsvis men betydelig sedimentation, er flere målinger påkrævet, før dette spørgsmål kan besvares.

En hel række af spørgsmål, som ligger inplicit i beskrivelsen af det biologiske overvågningsprogram, kan stadig ikke besvares, enten fordi der er foretaget for få observationer, eller fordi de pågældende dele af overvågningsprogrammet endnu ikke er blevet igangssat. Disse spørgsmål behandles i årsberetningen for det biologiske overvågningsprogram (ref. 46).

Økologiske konsekvenser

Det område, som påvirkes af de marine jordarbejder, er i almindelighed defineret ved en 0,5 mm tilvækst i den primære sedimentation. Hovedparten af det således definerede område på mellem 300-350 km^2 for fase 1 og 2 er blødbund (tabel 10.1). Andre påvirkede områder er sildegydepladser, stenrev, muslingebanker og ålegræsenge (figur 10.1-10.4).

Følgende konsekvenser af de samlede fase 1 og 2 arbejder påpeges:

- Frigivelse af næringssalte kan accelere en algeopblomstring. Frigjorte næringssalte kan endvidere bidrage med ca. 1% til den generelle produktion af planktonalger i et område af størrelsesordenen 350 km^2.

- Sedimentfanens skyggevirkning vil ikke have nogen væsentlig effekt på væksten af planktonalgerne.

- Der forventes ingen økologiske effekter i de øvre eller nedre vandlag på grund af de mindre forandringer i iltforholdene.

- Sammensætningen af blødbundsfaunaen kan ændres lokalt på grund af bundfældning og resuspension af ukonsolideret sediment. Sådanne effekter formodes imidlertid kun at være kortvarige.

- Kraftigt påvirkede blødbundsområder vil have en forøget risiko eller hyppighed for iltmangel ved sedimentoverfladen. Hvis der opstår iltmangel, vil den økologiske konsekvens blive forandringer i bundfaunaen til fordel for tolerante eller opportunistiske arter. Sådanne forandringer kan tænkes at favorisere ising på bekostning af rødspætter.

- 20% af sildegydepladserne i Storebælt påvirkes af anlægsarbejderne. Forandringerne i sedimentsammensætningerne på gydepladserne kan få sildene til at forlade gydepladserne omkring Sprogø midlertidigt eller permanent. Undersøgelser i 1989 viste imidlertid en hurtig resuspension af bundfældet sediment. Da der findes andre gydepladser i Storebælt, må man forvente, at en fuldstændig ødelæggelse af sildeæg, som er lagt omkring Sprogø, ikke vil medføre nogen væsentlig påvirkning af den samlede sildebestand i bæltet.

- Stenrevene er blevet udpeget som potentielt sårbare områder for bundfældning af små partikler. Undersøgelserne har imidlertid vist, at det bundfældede sediment vil blive resuspenderet ned til en dybde af 15 m. De væsentligste konsekvenser for de lavvandede dele af revene vil derfor være skyggevirkningen og frigørelsen af næringssalte. Disse konsekvenser vil favorisere enårige arter på bekostning af flerårige. Der forventes ikke påviselige effekter omkring Halsskov og Knudshoved på grund af anlægsarbejdernes korte varighed.

- Der forventes en nedgang i størrelsesorden 10% af produktionen af plantevæksten på stenrevene nord for Sprogø. Denne nedgang skyldes skyggevirkninger i løbet af anlægsperioden.

- Ålegræsengene omkring Sprogø ligger helt inden for det påvirkede område. Frigørelsen af næringssalte vil forøge ålegræsengenes totale produktion (tabel 10.2), men vil formindske ålegræssets vækst på grund af skyggevirkninger af epifytter og store alger på bunden. Der forudses ikke alvorlige skyggevirkninger på ålegræsenge på grund af fanens sedimentindhold, idet hver enkelt del af området kun forventes at blive skygget mindre end 5% af tiden. Ålegræsengene har endvidere let ved at komme sig.

- Muslingebankerne forventes ikke at blive påvirket af forandringerne i iltforholdene, da muslingerne er placeret oven over skillefladen med høj "genluftning".

- Det kan ikke udelukkes, at ødelæggelse af muslingebankerne på grund af kompensationsafgravninger og landindvinding vil reducere antallet af fødesøgende og overvintrende edderfugle i farvandede omkring Sprogø. Hovedparten af muslingebankerne befinder sig i læområdet med 5-15% nedsat strømhastighed. Dette kan beskære muslingebankerne, da muslingernes fødeoptagelse afhænger af vandtilførslen, men størrelsen af beskæringen er ukendt.

De <u>langtidsvirkninger</u>, som vil kunne iagttages 10 eller flere år efter afslutningen af de marine jordarbejder, forudses at være begrænset til:

- En mulig formindskelse af sildegydepladsernes areal omkring Sprogø.

- En forøgelse af ålegræsengenes areal på grund af læeffekter omkring Sprogø.

- En ufuldstændig tilbagevenden af flerårige algearter på stenrevene og i ålegræsengene (epifytreduktion).

- En mulig nedgang i bestandstørrelsen af overvintrende edderfugle og andre dykænder, som lever af muslinger.

Det er værd at lægge mærke til, at visse af langtidsvirkningerne vanskeligt vil kunne skelnes fra en regional udvikling på grund af tilførslen af næringssalte fra land såvel som andre menneskeskabte aktiviteter, såsom trafik, fiskeri og jagt.

Erosion

Efter afslutningen af anlægsarbejdet vil der ske erosion af den nye morænelers overflade i CD området, i området med opretning af T-ruten, fra de strømlignende rev ved broens ankerblokke og fra klapningspladsen for det overskydende ler, indtil overfladen er blevet selv-armeret med sand og grus. Erosionen vil ske i stormsituationer, hvor den fine fraktion af materialet bliver suspenderet. Etableringan af den erosionsbeskyttede overflade vil sandsynligvis strække sig over mange år.

Erosionsmængden er vurderet til ca. 0.8 mio. m^3 totalt over den længere årrække. Til sammenligning svarer erosionsmængden til 30-40% af det totale sedimentspild fra de marine jordarbejder, som strækker sig over 5-6 år.

EXAMPLES OF PROJECTS WITH SIGNIFICANT ENVIRONMENTAL IMPACT AND WITH COMPLICATED WATER EXCHANGE AND SALT EXTRACTION PROCESSES.

by David M. Farmer

a) Beaufort Environmental Monitoring Project
b) Deep Water Exchange in Rupert-Holberg Inlets

BEAUFORT ENVIRONMENTAL MONITORING PROJECT

1983-1984 FINAL REPORT

Prepared by

LGL Limited
ESL Environmental Sciences Limited
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For

NORTHERN ENVIRONMENT PROTECTION BRANCH
INDIAN AND NORTHERN AFFAIRS CANADA

Scientific Authority: David P. Stone

Funds for this study were provided by the Unsolicited Proposal Program of the Department of Supply and Services, Indian and Northern Affairs Canada, and Environment Canada.

BEAUFORT ENVIRONMENTAL MONITORING PROJECT
1983-1984 FINAL REPORT

This report has not undergone detailed technical review by Indian and Northern Affairs Canada and the content does not necessarily reflect the Department's views and policies.

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SUMMARY

Introduction

There is considerable concern that hydrocarbon development activities in the Beaufort Sea may result in adverse environmental impacts. Because of these concerns and the recognized uncertainties associated with environmental impact assessment, there is a clear need for an environmental research and monitoring program that is fully integrated with future exploration and development plans. In response to this need, Indian and Northern Affairs Canada (INAC) and Environment Canada have initiated a program called the Beaufort Environmental Monitoring Project (BEMP).

The long-term objective of BEMP is to provide INAC and Environment Canada with the technical basis for design, operation and evaluation of a comprehensive and defensible environmental research and monitoring program to accompany phased hydrocarbon development in the Beaufort Sea. This report is the product of a series of steps aimed at meeting the immediate objective of providing INAC and Environment Canada with a research and monitoring plan that:

1) addresses those impacts that could be most significant if they occurred;

2) is based on the best current understanding of industrial development scenarios and ecological processes;

3) has the capability to respond to changing industrial development scenarios and new information regarding ecological processes in the region; and

4) represents the majority viewpoint of a broad range of disciplinary specialists with the necessary experience in research and environmental management in the Beaufort Sea.

During 1983-84, BEMP proceeded through an initial workshop, a series of technical meetings and a second workshop. Development of a simulation model was initiated in the first workshop (May 16-20, 1983). The model was later refined during several discipline-specific technical meetings. A series of impact hypotheses were generated through the process of refinement, and later evaluated at a second workshop held from November 28 to December 2, 1983. Participants at these workshops and technical meetings included experts from industry, government, universities and the consulting community.

Definition of Monitoring

Monitoring was defined as the repetitive measurement of variables to detect changes directly or indirectly attributable to a specific development activity. The primary purpose of monitoring is to determine causal relationships between development activities and environmental effects. Understanding of the causes of these effects can then be used to plan appropriate mitigative responses. In the context of BEMP, monitoring is <u>not</u> surveillance or a part of the regulatory process used to ensure that industry meets the environmental terms and conditions of its operating permits. Monitoring is a scientific process, designed to test specific hypotheses linking sources of environmental impact (actions) to their expression in the biophysical environment.

Research is a test of a system process hypothesis, or baseline measurements. In BEMP, research will only be proposed if the existing level of understanding is inadequate to: (1) differentiate issues from non-issues; or (2) predict the direction of change.

Valued Ecosystem Components

The Valued Ecosystem Component (VEC) concept described by Beanlands and Duinker (1983) was adopted in BEMP to aid in the definition of impact signficance. VECs were defined as resources or environmental features that are: (1) important to local human populations; or (2) have national or inter- national profiles; and (3) if altered from their existing status, will be important in evaluating the impacts of development and in focusing management or regulatory policy.

Approach

Development of the research and monitoring plans described in this report was accomplished by proceeding through the following steps:

1) identification of Valued Ecosystem Components;
2) review of probable industrial development scenarios;
3) definition of the study area;
4) definition of the temporal horizon for monitoring;
5) identification of impact hypotheses that relate development activities to VECs;
6) preliminary screening of impact hypotheses for validity, relevance, and credibility;
7) evaluation of impact hypotheses; and
8) definition of research and monitoring programs necessary to test valid impact hypotheses.

Completion of these steps was accomplished through the use of the techniques and methods of Adaptive Environmental Assessment and Management (AEAM). This approach involves development of a simulation model describing relationships between development activities and the biophysical environment. The process forces workshop participants to think in inter-disciplinary, quantitative, dynamic terms about the possible interactions between the development and the environment.

The simulation model is composed of numerous linkages that connect the development activities to the VECs (see flowchart in back cover pocket). An impact hypothesis can be defined by tracing through a set of linkages from development activities to a VEC. Some hypotheses are straightforward and involve only one or two linkages, while others must encompass complex food web interactions. Each hypothesis was critically evaluated by a working group, and a monitoring/research strategy was proposed in those cases where the hypothesis was considered both valid and worth testing.

Recommended Research and Monitoring

A summary of the recommended research and monitoring related to the 19 hypotheses that were evaluated in detail during the second BEMP workshop is provided below. At present, new research programs are recommended for five of these hypotheses, with all of these research needs relating to marine mammal populations in the Beaufort Sea. Most of these research programs are aimed at providing a better understanding of the factors affecting the distribution of whales and seals in this region. Support of existing research on polar bear detection and deterrents is also recommended. Other research activities are considered necessary if future industrial development scenarios include the construction of major solid-fill causeways along the Yukon coast and/or Tuktoyaktuk Peninsula.

The initiation of new monitoring programs is recommended in relation to four of the 19 hypotheses evaluated during the second workshop. These monitoring programs are directed at hypotheses dealing with the potential impacts of industry facilities and activities on bowhead whales and the white whale harvest, the effects of chronic oil releases on bird populations, and the potential uptake of hydrocarbons and tainting of fish within Tuktoyaktuk harbour. Continuation and revision of existing white whale and polar bear monitoring programs is also encouraged, while other monitoring would be dependent on the results of recommended research programs.

Hypothesis 1:	Ship traffic, seismic programs and active offshore platforms/artificial islands will cause a reduction in the western Arctic population of bowhead whales.
VEC:	Bowhead whale
Conclusion:	The hypothesis is valid and testable.
Research:	Summer/winter energy balance dynamics; distribution of food supply; acoustical behaviour monitoring methods.
Monitoring:	Annual distribution of bowheads and behavioural responses to industry activities/facilities; reproductive success; ambient noise monitoring.

Hypothesis 2:

(a) Offshore structures will reduce the white whale harvest;
(b) Frequent icebreaker traffic in the landfast ice will increase harvest;
(c) Open water ship traffic in the Mackenzie estuary will alter white whale distribution and lead to changes in harvest levels; and
(d) Inuit employment in the industry will change the white whale harvest.

VEC: White whale

Conclusion: The hypothesis is:
(a) Unlikely
(b) Unlikely
(c) Valid and testable
(d) Valid and testable

Research: Factors controlling distribution of white whales in Niakunak and Kugmallit bays.

Monitoring: Annual monitoring of regional landfast ice extent, distribution and breakup; continuation and revision of existing white whale monitoring program.

Hypothesis 3: Marine vessel activities, seismic activities, dredging operations, aircraft overflights and active offshore platforms/ islands will reduce the size of ringed and bearded seal populations.

VEC: Ringed and bearded seals

Conclusion: The hypothesis is valid, but would either be hard to detect or not worth testing (see text).

Research: None

Monitoring: None

Hypothesis 4: Increased frequency of icebreaker traffic (a) through landfast ice and (b) through Amundsen Gulf will reduce ringed seal pup production.

VEC: Ringed seal

Conclusion: The hypothesis is (a) unlikely and not worth testing and (b) valid and testable.

Research: Further analysis of seal samples collected near Holman Island (1971-1982) in relation to Amundsen Gulf ice conditions; ice stability research.

Monitoring: Dependent on research results: aerial photography of icebreaker traffic/ice regime in Amundsen Gulf; possible remote sensing of ringed seal birth lairs.

Hypothesis 5: Icebreaker traffic in the transition (shear) zone will reduce bearded seal pup production.

VEC: Bearded seal

Conclusion: The hypothesis is valid, but would be too hard to detect.

Research: Bearded seal vocalization rates in control area and area exposed to icebreaker traffic (low priority).

Monitoring: None

Hypothesis 6: Icebreaker traffic in Amundsen Gulf will affect the ringed seal and polar bear populations.

VEC: Ringed seal, polar bear

Conclusion: The hypothesis is unlikely.

Research: Data on ice cover and seal (prey) populations (1971-1983) should be examined for correlations between population parameters and annual ice conditions.

Monitoring: Not at present time; pending evaluation of research results.

Hypothesis 7: The presence of active facilities will result in increased polar bear mortality.

VEC: Polar bear

Conclusion: The hypothesis is valid.

Research: None

Monitoring: Existing polar bear monitoring and deterrent programs should be supported and improved.

Hypothesis 8: Offshore hydrocarbon development activities will reduce the harvest of polar bears.

VEC: Polar bear (harvest)

Conclusion: The hypothesis is unlikely.

Research: None

Monitoring: None

Hypothesis 9: Chronic (episodic) oil spills resulting from normal petroleum hydrocarbon development activities will cause localized mortality of polar bears.

VEC: Polar bear

Conclusion: The hypothesis is valid.

Research: Support of existing research on polar bear detection and deterrents.

Monitoring: None

Hypothesis 10: Chronic (episodic) oil spills resulting from normal petroleum development activities will cause localized bird mortality.

VEC: Birds

Conclusion: The hypothesis is valid.

Research: None.

Monitoring: Regular observation of bird abundance, distribution and mortality at shorebases and offshore islands by trained on-site personnel.

Hypothesis 11: Oil slicks in open water areas around offshore structures during periods of ice cover will cause increased mortality of eiders and diving ducks.

VEC: Eiders and diving ducks

Conclusion: The hypothesis is valid, but not worth testing.

Research: None

Monitoring: None

Hypothesis 12: Frequent low level aircraft flights over staging brant will cause increased overwinter mortality.

VEC: Brant

Conclusion: The hypothesis is invalid.

Research: None

Monitoring: None

Hypothesis 13: Shorebases and shallow water production facilities will release (a) hydrocarbons and (b) heavy metals at sufficient levels such that fish harvest will be reduced through tainting and heavy metal accumulations.

VEC: Fish (harvest)

Conclusion: The hypothesis is (a) valid and testable and (b) unlikely.

Research: None unless monitoring shows tainting, and then research would be required to identify source.

Monitoring: Time-series measurements of hydrocarbons in fish from Tuktoyaktuk harbour; possible taste testing and caged fish programs.

Hypothesis 14: Nearshore structures will disrupt the nearshore band of warm brackish water and reduce the broad whitefish population.

VEC: Broad whitefish

Conclusion: The hypothesis is valid and testable.

Research: If a major nearshore structure is proposed: development of a numerical model of nearshore temperature variability; laboratory and modelling studies of fish growth and fecundity.

Monitoring: If a major nearshore structure is proposed: measurements of temperature, salinity, currents and wind; possible tagging of broad whitefish.

Hypothesis 15: Nearshore structures will disrupt the nearshore band of warm brackish water and reduce the Alaskan population of Arctic cisco.

VEC: Arctic cisco

Conclusion: The hypothesis is valid and testable.

Research: If a major nearshore structure is proposed: research defining the migratory habitats of Mackenzie River stocks of Arctic cisco, and their contribution to the Alaskan stock; other research identified in relation to Hypothesis 14.

Monitoring: Same as Hypothesis 14.

Hypothesis 16: The construction of shorebases and shallow production fields will result in a decrease in the population of Arctic cisco.

VEC: Arctic cisco

Conclusion: The hypothesis is unlikely and not worth testing.

Research: None

Monitoring: None

Hypothesis 17: Water intakes will reduce populations of broad whitefish and Arctic cisco.

VEC: Broad whitefish, Arctic cisco

Conclusion: The hypothesis is unlikely and not worth testing.

Research: None

Monitoring: None

Hypothesis 18: Air emissions associated with aircraft and marine traffic; and operation of drill rigs, offshore platforms and shore-bases will adversely affect air quality.

VEC: Air quality

Conclusion: The hypothesis is unlikely.

Research: None

Monitoring: None (see text)

Hypothesis 19: Dredging and deposition of spoils will reduce benthic invertebrate, fish and bearded seal populations.

VEC: Bearded seal

Conclusion: The hypothesis is valid and testable.

Research: None

Monitoring: Site-specific monitoring is recommended in areas of potential concern (see text).

INTRODUCTION

There is considerable concern that adverse environmental impacts may occur in the Beaufort Sea as a result of hydrocarbon development activities. While there has been a large expenditure of time and money in the production and review of the Beaufort Sea - Mackenzie Delta Environmental Impact Statement (Dome Petroleum et al. 1982), many concerns persist because of the recognized difficulties and uncertainties associated with environmental impact assessment. In the Beaufort, these difficulties are compounded by the lack of experience with some of the innovative technologies proposed, and the limited experience of the petroleum industry in the offshore Arctic. Due to these remaining concerns and uncertainties, particularly in the context of Beaufort Sea hydrocarbon development, there is a clear need for an environmental research and monitoring program that is fully integrated with the exploration and development scenario. In response to this need, Indian and Northern Affairs Canada (INAC) and Environment Canada have initiated a program called the Beaufort Environmental Monitoring Project (BEMP).

Long-Term Objective

The long-term objective of BEMP is to provide Indian and Northern Affairs Canada and Environment Canada with the technical basis for design, operation and evaluation of a comprehensive and defensible environmental research and monitoring program to accompany hydrocarbon development activities in the Beaufort Sea region.

To meet this objective adequately, the monitoring program must include the following features:

1) determination of the most significant environmental resources and features likely to be affected by development;

2) formulation and testing of impact hypotheses and predictions;

3) recommendation of mitigative measures and continual evaluation of their success; and

4) adaptability of future research and monitoring to reflect new information, identified data gaps, and changes in the development scenario.

Immediate Objective

This report is the product of a series of steps aimed at meeting the immediate objective of providing INAC and Environment Canada with a plan for initiating research and monitoring activities. Therefore, most of this report consists of descriptions of the elements of a defensible approach to research and monitoring. Prior to considering those elements, we have included a detailed description of the methods used throughout this program, since the nature of our recommendations have been heavily influenced by these methods.

To date, BEMP has proceeded through an initial workshop, a series of technical meetings and a second workshop. During the first workshop (May 16 to 20, 1983), development of a simulation model was initiated. The model was later refined during a series of technical meetings which followed the first workshop. A series of impact hypotheses was generated through the refinement process, and later evaluated at the second workshop held from November 28 to December 2, 1983. Since the focus of this project is monitoring, strategies employed for industrial developments elsewhere in the world, such as the use of "Biological Early Warning Systems", were also briefly discussed and evaluated at the second workshop. The advantages, disadvantages and principles behind these other approaches to environmental monitoring are summarized in Appendix I of this report. The names, affiliations and research interests of workshop participants are identified in Appendix II.

METHODS

Definitions

Impact Hypotheses

Fundamental to the methods used in this project is the concept of an impact hypothesis. Simply stated, an impact hypothesis is a statement that links development activities with their potential environmental effects. Without a statement of relevant impact hypotheses to guide it, a monitoring program may become a directionless effort in data collection.

Monitoring and Research

In BEMP, monitoring is defined as a test of an impact hypothesis designed to:

(a) measure environmental impacts; and
(b) analyze cause-effect relationships.

Research is a test of a system process hypothesis, or baseline measurements. In the context of BEMP, research will only be proposed if the existing level of understanding is inadequate to:

(a) differentiate issues from non-issues; or
(b) predict the direction of change.

Monitoring in this context is the repetitive measurement of variables to detect changes directly or indirectly attributable to a specific development activity. The primary purpose of monitoring is to determine causal relationships between development activities and environmental effects. Understanding the causes of these effects can then be used to plan appropriate mitigative responses. In the context of BEMP, monitoring is <u>not</u> surveillance or a part of the regulatory process used to ensure that industry meets the environmental terms and conditions of its operating permits. Monitoring is a scientific process, designed to test specific hypotheses linking actions (sources of environmental impact) to their expression in the biophysical environment.

Valued Ecosystem Component

Following the approach described by Beanlands and Duinker (1983), the Valued Ecosystem Component (VEC) concept was adopted in this project to aid in definition of impact significance. VECs were defined as resources or environmental features that:

a) are important to local human populations; or
b) have national or international profiles; and
c) if altered from their existing status, will be important in evaluating the impacts of development and in focusing management or regulatory policy.

Tasks

Development of the research and monitoring plans described in this report was accomplished by proceeding through the following steps:

1) identification of Valued Ecosystem Components;

2) identification of development activities;

3) identification of spatial extent and resolution of the model;

4) identification of temporal horizon and resolution of the model;

5) identification of impact hypotheses that relate development activities to VECs;

6) preliminary screening of impact hypotheses for validity, relevance, and credibility;

7) evaluation of impact hypotheses; and

8) definition of research and monitoring programs necessary to test valid impact hypotheses.

Models and Workshops

Tasks 1 to 6 (described above) were facilitated by using the techniques and methods of Adaptive Environmental Assessment and Management (AEAM) (Holling 1978). This approach involves development of a simulation model of the relationships between development activities and the biophysical environment. The modelling process forces workshop participants to think in interdisciplinary, quantitative, dynamic terms about the interactions between the development and the environment. The simulation model is a set of linkages describing the interrelationships between the various components representing the biophysical processes of the Beaufort Sea and the proposed development activities. The elements of an impact hypothesis are defined by tracing through a series of linkages from a given set of development activities to an attribute or component of the environment for which there is public or scientific concern.

The modelling process was conducted in workshops and technical meetings. These workshops and technical meetings included experts from industry, government, universities and the consulting community (Appendix II), and were conducted by experienced facilitators/modellers. Table I-1 shows how the modelling, workshops, technical meetings and reporting relate to each of the eight fundamental tasks in the project.

TABLE I-1

TASKS AND ACTIVITIES IN MONITORING PLAN DESIGN

TASK	MODELLING	MEETINGS	REPORTING/DOCUMENTATI
Identification of VECs	Model building task	- scoping - workshop 1	- report documenting the VEC's prepared for presentation at workshop 1
Identification of Development Activities	Model building task	- scoping - workshop 1 - ongoing	- reports on each ne development scenari are prepared as scenario is revised
Identification of Spatial Extent and Resolution	Model building task	- scoping - workshop 1 - technical meetings	- workshop 1 report model description
Identification of Temporal Horizon and Resolution	Model building task	- scoping - workshop 1 - technical meetings	- workshop 1 report model description
Identification of Impact Hypotheses	Model structure is composed of linked impact hypotheses	- workshops - technical meetings	- preliminary flow-charts and statements of impact hypotheses were prepared prior to workshop 2, based o the model building programming and analysis and discussions in technical meetings
Screening of Impact Hypotheses	Quantification of the links eliminates unrealistic or ill-specified hypotheses	- technical meetings	
Evaluation of Impact Hypotheses		- workshop 2	- final report
Definition of Research/ Monitoring		- workshop 2	- final report

Identification of VECs

A list of potential VECs, based on the perceived environmental concerns and issues related to Beaufort hydrocarbon development was prepared before the first workshop. Four sources of information were reviewed during preparation of this list:

1) Volume 4 (Biological and Physical Effects), Environmental Impact Statement for Hydrocarbon Development in the Beaufort Sea - Mackenzie Delta Region, 1982. Prepared by Dome Petroleum Limited, Esso Resources Canada Limited, and Gulf Canada Resources Inc.;

2) The Biological Effects of Hydrocarbon Exploration and Production Related Activities, Disturbances and Wastes on Marine Flora and Fauna of the Beaufort Sea Region. Beaufort Sea - Mackenzie Delta EIS Support Document Prepared by ESL Environmental Sciences Limited, 1982, for Dome Petroleum Limited, 450 pp.;

3) The Interim and Second (Final) Compendium of Written Submissions to the Beaufort Sea Assessment Panel on the Dome, Gulf and Esso Environmental Impact Statement, February, 1983.;

4) Individual submissions of the Technical Experts retained by the Beaufort Sea Environmental Assessment Panel (Greisman 1983, Mackay 1983, Parsons 1983).

The preliminary list of VECs was reviewed at the first workshop, and as a result of discussions at this time and during subsequent technical meetings, was revised to the list shown in Table I-2. The identification of VECs is a critical process because it (1) defines the quantities for which the simulation model must provide predictions through time, and (2) most importantly, limits the discussion of impact hypotheses and monitoring programs to those resources and supporting biophysical processes that are of greatest concern with respect to development in the region.

TABLE I-2

FINAL LIST OF VALUED ECOSYSTEM COMPONENTS ADDRESSED AT THE SECOND WORKSHOP

- population, harvest, and available habitat for:
  - white whale
  - bowhead whale
  - ringed seal
  - bearded seal
  - polar bear
  - common eider
  - king eider
  - diving ducks (oldsquaw, scoters, scaups
  - thick-billed murre
  - brant
  - lake whitefish
  - broad whitefish
  - least cisco
  - Arctic cisco
  - Arctic char
- air quality

Identification of Development Activities

The development activity (action) is at the beginning of the causal chain defining an impact hypothesis related to a given VEC. In identifying the nature, extent and duration of development activities in the region, the project team worked closely with the proponents of hydrocarbon development to determine the range of activities contemplated. The activities were divided into four major groups:

1) exploration activities and drilling associated with discovery and delineation of oil resevoirs;

2) construction of islands and oil production facilities, and the drilling of production wells;

3) subsea pipelines and onshore gathering systems; and

4) transportation of produced hydrocarbons within the Beaufort Region by tankers.

The simulation model is designed to accept any number of different development scenarios and can be modified as required when the scenario changes. Scenarios for five different levels of development are currently included in the model, based on information provided by Dome Petroleum Limited and supplemented with specific estimates contained in the 1982 Beaufort Sea Planning Model (Dome Petroleum et al. 1982).

Identification of Spatial Extent and Resolution of the Model

The current geographic scope of the project and, therefore, the spatial extent of the model was determined as follows. The Alaska-Yukon border was selected as a practical western limit to the study area. A line directly west from the northwestern tip of Banks Island was expected to encompass most possible positions of the polar pack ice edge and, therefore, delineate the northern limit of the study area. Amundsen Gulf, considered important in terms of the ice dynamics of the region as well as marine bird and mammal habitat, was selected as the eastern boundary. Since the focus of BEMP is marine, the landward extent of the study area was limited to 2 km inland within the Mackenzie Delta region, and the level of maximum storm surges elsewhere along the coast.

Within these spatial boundaries, the study area was further subdivided into 11 spatial units on the basis of ice conditions and the influence of the Mackenzie River turbidity plume (Figure I-1).

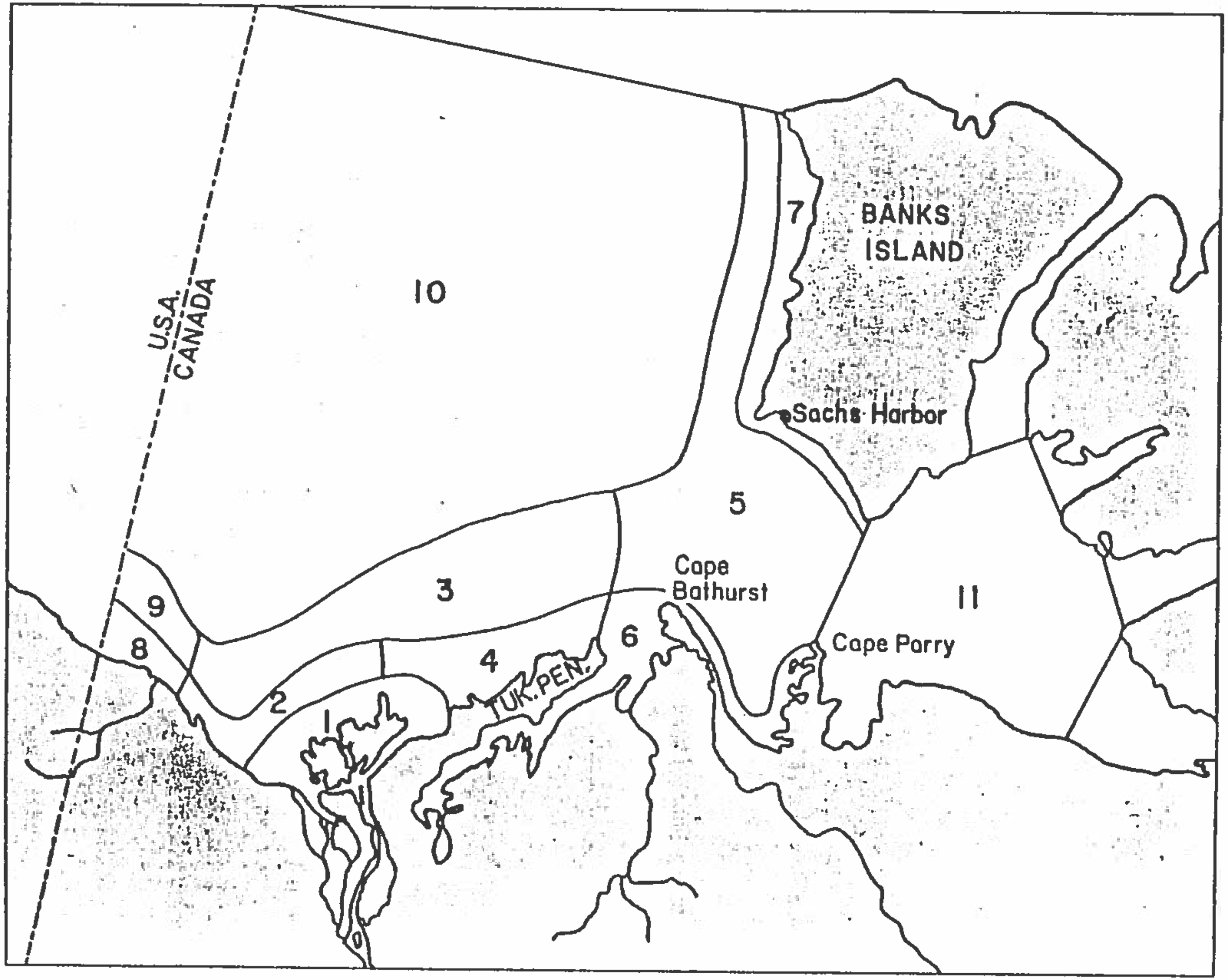

Figure I-1: Spatial units of the Beaufort Sea Region

Four ice zones were considered during the spatial bounding. The landfast ice zone was assumed to extend to approximately the 20 m isobath. The transition (shear) zone was basically defined as being located between the 20 and 100 m isobaths, although passing over much greater depths in the east (off Amundsen Gulf-Banks Island) and in the west (off Mackenzie Bay and the Yukon coastline). The polar pack was considered located seaward of the transition zone, while Amundsen Gulf was defined as a separate ice zone because of the expected importance of the recurring polynya in this region.

The location and spatial extent of the Mackenzie River plume was also taken into consideration during the definition of spatial subzones. Two different conditions were recognized:

1) a situation where sustained westerly winds cause the plume to be confined within the area bounded by the 20 m isobath; and

2) a situation where sustained easterly winds cause the plume to move offshore into the transition zone.

In addition, a zone shoreward of the 5 m isobath and adjacent to the Mackenzie River Delta was separately defined as an area of sustained and major plume influence. Within each of the 11 spatial units, water depths above and below the pycnocline were considered separately.

Identification of Temporal Horizon and Resolution

The development of a dynamic simulation model required specification of the maximum time over which the effects of development would be examined (temporal horizon) and the time step (resolution) within that horizon. A time horizon of 30 years and a time step of 1 year were selected during the first workshop, although these specifications were further refined as the project proceeded. For example, to satisfy all disciplinary requirements, a weekly time step was eventually established for the period from April through October and a single 21-week time step was established for the winter.

Identification of Impact Hypotheses

The simulation model is composed of hundreds of linkages that connect the development activities to the VECs. An impact hypothesis can be defined by tracing through a set of linkages from development activities to a given VEC. Some hypotheses are straightforward and involve only one or two linkages, while others must encompass complex food web interactions. In either case, each linkage must be specifically defined for use in the simulation model. These linkages were initially defined during the first workshop and later refined at the technical meetings.

Screening of Impact Hypotheses

Since the simulation model contains so many potential linkages and relationships, it was necessary to select a set of impact hypotheses from the large number of potential hypotheses for evaluation at the second workshop. The initial screening was conducted by the modellers. Preliminary flowcharts and impact hypothesis statements were developed on the basis of each individual's experiences in constructing the model and subsequent testing of the sensitivity of the VECs to critical assumptions used in development of the model. Unrealistic and ill-specified hypotheses were then corrected or deleted. In the technical meetings, this sub-set of potential impact hypotheses was further evaluated and eventually reduced to twenty-one hypotheses considered most important at that time. Another hypothesis was added to this list at the beginning of the workshop. Three of these hypotheses involving resource use could not be fully assessed by the present workshop participants, and are shown with their associated linkages in Appendix III.

A conceptual diagram of the hypotheses represented in the simulation model and the interrelationships among the linkages and VECs associated with these hypotheses is provided in the pocket on the back cover of this report.

The 19 hypotheses evaluated during the second workshop encompass a considerably larger number of perceived concerns associated with Beaufort hydrocarbon development by virtue of the multiple linkages involved in most of the hypotheses. One of the strengths of the Valued Ecosystem Component (VEC) approach is that it facilitates consideration of the cumulative indirect impacts of a number of environment-development interactions that may ultimately cause a change in a VEC. The range of environmental concerns that have been expressed in relation to Beaufort hydrocarbon production were reviewed during development of the simulation model, and most of these concerns are included as a linkage in one or more of the hypotheses presented in the following sections. Nevertheless, some of the potential concerns identified in the Beaufort Sea/Mackenzie Delta EIS, its support documents, and in the submissions of intervenors during the public review of the development proposal are not discussed in this report.

If an issue previously raised in conjunction with Beaufort development is not specifically addressed in this report, this is either because: (1) the concern was focused on environmental features or resources that are not within the geographic scope of this study; (2) the concern involves a component of the environment that is embodied within the structure of the simulation model, but would not be reflected in a change in a VEC; or (3) the workshop participants believed that on the basis of available scientific evidence, the issue was perceived rather than real. Examples of each of these categories of issues are provided below.

Examples of concerns that were not addressed because they lie outside the geographic scope of BEMP are: the potential attraction of polar bears and Arctic fox to solid waste disposal sites; disturbance of many species of birds that nest, stage and moult in coastal habitats adjacent to the Beaufort Sea but are not generally found in marine areas; and many strictly terrestrial issues that were raised in connection with the Yukon coast shorebase proposal.

Step 3) Conclusion:

This step required that the working group arrive at one of four possible conclusions. On the basis of discussions in step two (Documentation of Existing Knowledge), group participants concluded that a given impact hypothesis:

a) was extremely unlikely and not worth testing;
b) was possible, but too difficult to detect;
c) required more information before a monitoring plan could be designed (e.g., research); or
d) should be tested with a detailed monitoring plan.

Step 4) Monitoring and Research:

If the conclusion at step three was either (c) or (d), a discussion focussing on the linkages of the hypothesis was initiated. The discussion addressed the following questions in order to design a monitoring plan which would test the impact hypothesis:

a) What do we monitor ?
b) What do we want to know ?
c) What do we actually measure to accomplish (i) and (ii) ?
d) What information do we get from these measurements ?
e) How does this achieve what we want to know ?

Step 5) Documentation:

To adequately document the discussion and evaluation of each impact hypothesis, the "recorder" assigned to each working group delegated specific responsibilities to other group members, including the preparation of draft report sections. The recorder was responsible for ensuring that documentation of the discussion of a given hypothesis was completed and submitted at the end of the day.

In most instances, participants of each working group were given an opportunity to review the synthesized versions of the hypothesis documentation during the course of the workshop.

Preliminary Design of the Research and Monitoring Plans

In most cases, the preliminary design of research and monitoring programs emerged out of the discussions which occurred during the evaluation of the impact hypotheses. Edited versions of the reports produced for each of the hypotheses evaluated during the second BEMP workshop are presented in the following sections of this report.

Limitations in Scope

Limits in the scope of a project of this type are essential for efficiency. However, scope restrictions can be interpreted as shortcomings of a program unless specifically stated. This section identifies some of the subjects that were intentionally excluded from the present phase of the Beaufort Environmental Monitoring Project. Some of these subjects were considered outside the intended scope of the study, while others were worthy of consideration but could not be examined within the framework of the project due to time constraints or discipline expertise that was committed in advance to the workshops. In addition, specific assumptions regarding the Beaufort Sea hydrocarbon development scenario are also stated in this section.

1) This project was intentionally limited to consideration of the effects of hydrocarbon development activities on the environment, rather than the effects of the environment on industrial activities. It is recognized that various monitoring programs are ongoing and may be required in the future to examine the integrity of offshore facilities in relation to the ice environment and other aspects of industry operations in this region.

2) The hydrocarbon development scenario assumed throughout this project was the range and intensity of activities described in the Beaufort Sea/Mackenzie Delta EIS (Dome Petroleum et al. 1982). In particular, it was assumed that: (1) production facilities would not be located in waters less than 5 m deep; (2) if oil-base muds are used for exploratory or production drilling, oil-contaminated cuttings would not be discharged to the marine environment; (3) major dredging operations required for offshore island construction would not be conducted in inshore areas; (4) solid-fill causeways would not be required along the Yukon coast and Tuktoyaktuk Peninsula; and (5) all wastes associated with the development would be treated and discharged in accordance with the "best practicable technology" (Thomas et al. 1983).

3) Catastrophic oil spills and blowouts, while an important area of potential concern related to any hydrocarbon development, were not considered in this project because their infrequent and unpredictable occurrence makes these events an inappropriate target for routine monitoring. It was assumed that a scientific response to determine the short- and long-term effects of a major oil spill may be initiated in the event of this type of environmental emergency, but was outside the scope of this project.

4) The definition of the study area used throughout this project included that portion of the coastal zone to the level of maximum storm surges in areas outside the Mackenzie Delta, and to a point 2 km onshore within the Delta itself. However, the impacts of shoreline developments on the coastal zone *per se* were not considered during this project. It is recognized that such potential concerns may have to be addressed in future programs of this type.

5) As indicated earlier, a list of potential Valued Ecosystem Components was prepared prior to the first workshop. This list and other possible VECs were discussed amongst workshop participants, and a number of recommendations regarding VECs were not accepted by the group as a whole for various reasons. Among these were the following:

   a) *Thick-billed murre*: The colony at Cape Parry was originally identified as a VEC, but was not included in the modelling process or in the hypotheses considered in the second workshop, because potential concerns related to the impacts of hydrocarbon development on this colony were viewed as a very site-specific issue. Undoubtedly, protective measures should be instituted whenever development activities impinge on the Cape Parry area.

   b) *Snow goose*: The snow goose was selected as a VEC early in the project, but was excluded from further consideration prior to the second workshop because use of the marine environment by this species is extremely limited.

   c) *Red-throated loon*: The red-throated loon was recommended for inclusion as a VEC during a technical meeting held after the first workshop. However, since the full group of workshop participants did not have the opportunity to evaluate arguments for and against inclusion of this species, it was not added to the list of VECs.

d) <u>Coastal zone, Bathurst polynya, landfast ice</u>: The latter two environmental components were included on the list of potential VECs prepared in advance of the first workshop, while the inclusion of the coastal zone as a VEC was suggested by several of the participants during the first workshop. These environmental components were not included in the final list of VECs for the project because the full group of workshop participants did not have the opportunity to evaluate arguments for and against their inclusion.

6) The hypotheses considered in this report involve one or more linkages between development activities and a VEC. Where the hypothesis and its associated linkages were not only considered valid but also an area of potential concern related to Beaufort development, monitoring and/or research has generally been recommended. It is important to emphasize that this monitoring and/or research should include detailed measurements of the industrial activity, and not just focus on the VEC or the linkages between development and the VEC.

7) Three hypotheses involving native and non-native harvests of resources were considered during the second workshop. The focus of these hypotheses was the effect of changing harvest methods and patterns on VEC populations. However, the direction and magnitude of these changes could not be adequately addressed by the discipline specialists that attended the workshop. A logical framework for consideration of changing harvest was discussed during the workshop, but because judgements regarding the dynamics of the processes involved were not possible, only flowcharts for these hypotheses have been included in this report (Appendix III).

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Deep Water Exchange in Rupert-Holberg Inlets

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1. INTRODUCTION

1.1 Objective

In this report we present and discuss some of the unique observations of deep water exchange made in Rupert-Holberg Inlet. In addition, the first set of long term observations from Quatsino Sound and Holberg Inlet will be interpreted in terms of simple models of exchange processes. The goal is to improve our understanding of the oceanography of Rupert-Holberg Inlet and other inlets with similar characteristics.

This study is particularly relevant to the practice of submarine tailings disposal. Utah Mines, a copper-molybdenum mine located on the north shore of Rupert Inlet, has been discharging mine tailings and waste rock into Rupert Inlet since 1971. The resulting turbidity field and the widespread dispersion of mine wastes are closely related to the physical oceanography of these inlets. An understanding of the oceanography of the receiving waters is essential to the proper assessment of environmental consequences of submarine tailings and rock disposal.

1.2 Brief Review of Deep Water Exchange

In many fjords and silled basins the circulation of the deep waters (water below sill depth) is restricted by the sill. The low dissolved oxygen content or anoxic conditions of the deep waters highlight the lack of exchange with surface waters or waters of comparable depth outside the sill. Conservative properties such as salinity and temperature tend to change slowly in the deep waters of many fjords. However, there are times when the deep waters experience comparatively rapid change in their properties. In these instances the density of the deep water increases, and frequently the dissolved oxygen content also increases. (Convective overturn resulting from gravitational instability of the surface waters is not considered in this report.)

The deep water is exchanged or renewed by more dense water which spills or intrudes over the sill. The intruding denser water spreads out along the basin bottom, filling the deeper portions and elevating the original deep water. The volume of water replaced can be determined from the observed elevation of the original waters and Gade (1970) has described a convenient method for making such estimates. Intruding waters of intermediate density will displace only the less dense deep waters. Thus, the deep waters of silled basins provide a temporary record of the high density extremes of the outside waters at sill depth. The record is temporary because the homogenizing effect of the vertical turbulent diffusion of heat and salt slowly reduce the density of the deep waters. Vertical turbulent diffusion is a controlling factor in the exchange process as it reduces the density threshold thus making deep water exchange more probable. The frequency, duration and form of deep water exchange are determined by several factors, namely the density characteristics of outside waters, the geometry of the basin and sill, local meteorology, run-off, tides and, as previously mentioned, vertical turbulent diffusion. The following brief review of deep water exchange in a number of local fjords shows the diversity of this process.

Saanich Inlet, located at the southern end of Vancouver Island, has a maximum basin depth of 236 m and a sill depth of 70 m through which it communicates with Haro Strait. Anderson and Devol (1973) have concluded that the intermittently anoxic deep waters of this inlet are replaced annually in varying amounts. Deep water exchange occurs in late summer or early fall coincident with the presence of denser water in Haro Strait. The flushing waters are introduced in the form of short bursts (boluses) during the flood tide. The overall duration of a particular exchange in which there was 37% renewal was calculated to be about 12 days.

Nitinat Lake, a fjord located on the west coast of Vancouver Island, experiences sporadic renewals, as the shallow 4 m sill effectively isolates the fjord's permanently anoxic water from the Pacific Ocean (Ozretich, 1975). Ozretich concludes that deep water exchange occurs in response to reduced volumes of Fraser River water and to below average rainfall. The exchange takes place only during the flooding tide and is enhanced by high tides and wind stress.

During a two year study of Bute Inlet, a deep silled (350 m) fjord on the mainland coast of British Columbia, Lafond and Pickard (1975) observed five deep water exchanges. The deep waters of this fjord are renewed by the denser deep waters of the Strait of Georgia. The duration of inflows during the exchange varies between one and two months.

Howe Sound, a mainland fjord just north of Vancouver, has an inner basin with a 60 m sill. The upper deep waters of the inner basin undergo replacement frequently while the bottom waters are only renewed every three or four years (Bell, 1973). The occurrences of deep water exchange are related to large surface water outflow caused by either strong down channel winds or periods of high run-off.

In the Port Susan estuary, a silled basin within Puget Sound, Cannon (1975) reports current measurements of deep water exchange made on the 100 m sill. The current meter data obtained in August and September reveals four separate inflows of duration 4 to 7 days. Observed changes in dissolved oxygen and density are consistent with deep water exchange.

1.3 Physical Description of Rupert-Holberg Inlet

Rupert and Holberg Inlets are located near the northern end of Vancouver Island and they communicate with the Pacific Ocean via Quatsino Sound (see Figure 1). The geometrical properties of these two inlets are summarized in Table 1. Together, the two inlets form one basin — Rupert-Holberg Basin — 44 km in length. Quatsino Narrows, a long, shallow, slender channel, connects the basin to Quatsino Sound. The depth of Quatsino Narrows decreases from 38 m at its southern extremity to a minimum of 18 m at its northern end, where it opens into the basin (see Figures 2 and 3).

1.4 Precipitation and Run-off

The precipitation pattern typical of the west coast of Vancouver Island is one of high precipitation during late fall and winter months and minimum rainfall in the summer months (Pickard, 1963). The run-off pattern is similar with its peak in winter and late fall, and its minimum in summer. The Marble River is the only major river discharging into the Rupert-Holberg Basin. Its mouth is just east of Quatsino Narrows, on the south shore of Rupert Inlet (see Figure 1). This differs from the situation in most fjords and estuaries where the river is located at the head; consequently the classical model of estuarine circulation will probably not be applicable. About 50% of the approximate drainage area surrounding Rupert and Holberg Inlets is drained by the Marble River (Drinkwater, 1973). Average and peak total freshwater inflows approximated by Drinkwater are listed in Table 1.

1.5 Tides

The tides along the west coast of Vancouver Island are mixed, mainly semi-diurnal. At Coal Harbour, in Holberg Inlet, the average tidal range is 2.8 m; 4.2 m is the maximum range (Canadian Hydrographic Service, 1974). The corresponding tidal prisms are included in Table 1. The average and maximum tidal exchanges constitute approximately 3% and 5% of the total Ruper-Holberg Basin volume. Tidal currents as large as 3 m/sec have been observed (Canadian Hydrographic Service, 1972) at the north end of Quatsino Narrows on both the ebb and flood tides. Strong currents, back eddies and other signs of turbulent stirring are evident throughout Quatsino Narrows. On the flood tide the area between Hankin Point and Quatsino Narrows is visibly turbulent with numerous patches of turbidity, boils of upwelling, eddies and strong currents. The vertical uniformity of the water column as well as the large annual variation in properties have been ascribed to tidal mixing in Quatsino Narrows and the active region in front of the Narrows (Drinkwater and Osborn, 1975).

2. 1974 OBSERVATIONS OF DEEP WATER EXCHANGE

During the period from 20 April to 7 May, a string of three Aanderaa current meters, equipped with conductivity and temperature sensors, was moored between Hankin Point and the northern end of Quatsino Narrows (see Figure 2). The current meters were positioned at depths of 5, 70 and 155 metres, as shown in Figure 3. Current velocity, temperature and conductivity were sampled at 5 minute intervals.

The vertical current structure throughout the period is readily seen from Figures 4 and 5 to be one of strong bottom currents during most of the time that the tide is flooding. Mean flood speeds of 40-45 cm/sec near the bottom (155 m) are appreciably higher than mean flood speeds at the surface (5 m, 20 cm/sec) and at mid-depth (70 m, 10∿15 cm/sec). Peak current speeds of 154 cm/sec at 155 metres are considerably larger than the maximum flood speeds of 117 cm/sec and 80 cm/sec observed at 5 and 70 metres respectively. The prevailing direction for the flood currents, at all depths, is north, as shown in Figure 4. It is evident from Figure 5 that the bottom currents persist for approximately one hour after the predicted time of high water slack. The turn of the tide is based on the time of slack surface water in Quatsino Narrows even though drogue observations showed the deeper water to be still flooding at this stage of the tidal cycle (Canadian Hydrographic Service, 1972). Figure 4 shows that during the flood tide the bulk of the tidal exchange occurs near the bottom whereas during the ebb tide the exchange occurs near the surface. Ebb tide currents are smaller than the flood currents at 5 m and at 70 and 155 m they are non-existent. This is because of the shallow sill which restricts the outgoing flow to only the near surface waters, and also because the geometry of the junction of Quatsino Narrows with Rupert-Holberg Inlet is such that only on the flood tide is a jet produced. On the ebb tide, surface water flows towards the Narrows reaching large speeds only in the immediate vicinity of the entrance. Thus the tidal currents,

TABLE 1*

	Rupert Inlet	Holberg Inlet
Length	10 km	34 km
Mean Width	1.8 km	1.3 km
Mean Mid-Inlet Depth	110 m	80 m
Maximum Depth	165 m	170 m
Volume	$2.0 \times 10^9 m^3$	$3.4 \times 10^9 m^3$
Freshwater Inflow to Rupert-Holberg Basin	average	$12 \times 10^6 m^3$/day
	maximum	$40 \times 10^6 m^3$/day
Tidal Prism	average	$170 \times 10^6 m^3$/tidal cycle
	maximum	$260 \times 10^6 m^3$/tidal cycle

* from Pickard (1963) and Drinkwater (1973).

below sill depth, in front of the Narrows are rectified by the geometry of this junction.

The salinity and temperature data from these same instruments are presented in terms of averages over ebb and flood periods in Figure 6 and a portion of the actual salinity and current speed from 5 and 155 metres is presented in Figure 7. The salinity data in Figure 7 are representative of the entire time series. Figure 7 reveals that higher than average salinities are coincident with the high bottom currents. Since density is primarily determined by salinity (in this situation salinity is approximately 6 times more important than temperature) it is then evident that the water of the bottom current is more dense than the ambient water. The strong flow near the bottom appears to be a density current. A rough calculation reveals that a density difference of 0.25 Sigma-t, σ_T, units between the inflowing and ambient waters, is sufficient to cause the inflowing water to sink to the bottom by the time it reaches the current meter mooring. Using a reduced gravity ($g' = g\frac{\Delta\rho}{\rho}$) of 0.25 cm/sec^2, the time taken for the jet to sink from the surface to the bottom, a depth, D, of 155 metres is

$$(\frac{2\ D}{g'})^{\frac{1}{2}} = \left(\frac{2 \times 155 \times 10^2}{0.25}\right)^{\frac{1}{2}} = 352 \text{ seconds.}$$

The time taken for the jet to travel from the end of Quatsino Narrows to the current meter mooring is longer, approximately 450 sec if an average speed of 200 cm/sec is assumed.

A closer inspection of the vertical current structure reveals a phase lag with respect to depth during the flood tide. The flood current appears first at the surface then at mid-depth and finally at 155 metres. The time difference between the current at 155 m deep and the surface current is approximately two hours. This time difference in the flood currents may be explained in terms of density variations of the inflowing water over the flood period. The water in Quatsino Narrows at the turn to flood is Rupert-Holberg Inlet surface water that was drawn out on the preceding ebb tide. It is less saline than both the deeper water of Rupert and Holberg Inlets and the Quatsino Sound water which enters later in the flood. From the turn of the tide it takes approximately 1-1/2 hours for this water to pass through Quatsino Narrows. Later in the flood the more saline waters of Quatsino Sound are injected into Rupert-Holberg Inlet. The salinities observed during the flood tide support this hypothesis. Initially, at 5 metres, high currents are correlated with higher salinities, however, these higher salinities are still about 0.5°/₀₀ lower than salinities at 70 metres. Since the inflowing water is less dense than the deeper water the currents are confined to the upper portion of the water column. Later as the surface currents diminish, the bottom currents increase and so does the salinity associated with these currents.

The instruments were in the water for 17 days and during this period there was a net temperature increase of 0.3-0.4°C at 70 and 155 m, and ∿ 0.5°C at 5 metres. More significantly, the salinity increased by ∿ 1°/₀₀ at 5 m, 0.4°/₀₀ at 70 m and ∿ 0.3°/₀₀ at 155 m. (At 155 metres there are periods when the salinity decreases, but these may be due to fouling of the conductivity sensor by mine tailings.) The density of the water column has increased because of the salinity increase. Since salt, unlike heat, can only be exchanged through Quatsino Narrows, a net salt flux into Rupert-Holberg Inlet has occurred from Quatsino Sound during this period. The salt input has occurred during the flood tide in the form of a density current flowing from Quatsino Narrows down the side of Rupert and Holberg Inlets to the basin bottom. The density of the top 20 m (sill depth) of Quatsino Sound water injected into Rupert-Holberg Inlet on the flood tide is generally greater than that of the resident water.

The density current is certainly a turbulent flow as the Reynolds numbers associated with speeds of 100 cm/sec or more are high. The turbulent nature of the flow is evident from the significant amounts of high frequency variance in all of the measured vaiables. On the basis of the observed vertical current and density structure, and the long term increase in salinity, we conclude that a rectified deep water tidal exchange process was occurring from the 20th April to 7 May, 1974.

3. LONG TERM DATA

3.1 Background Temperature and Salinity Data

The seasonal temperature and salinity variations in Quatsino Sound and Rupert-Holberg Inlet have been monitored primarily by Utah Mines. Mine data representative of Quatsino Sound Station D and Rupert-Holberg Inlet Station H are displayed in Figures 8 and 9 respectively. In addition, daily sea surface (1 m) temperature and salinity data were taken near the mouth of Quatsino Sound at Kains Island Lighthouse from 1935 to 1970 (Hollister and Sandnes, 1972). The 36 year grand mean of monthly temperatures and salinities and standard deviation are plotted in Figure 10. In spite of the sparseness of the mine data, a similar seasonal trend is evident in the data from all three stations. The salinity increases during the late spring and summer to a maximum (∿ 32°/₀₀) in August-September and the declines quickly to a minimum (28 ∿ 29°/₀₀) in winter or early spring. The temperature is at a maximum (11°C) in August-September and at a minimum (6°C) in March-April.

In Holberg Inlet the 167 m salinities are higher (0.2 to 1°/₀₀) than those at 30 m but otherwise similar in detail. The surface salinities in Quatsino Sound (Station D) are also very similar to the salinities of Rupert-Holberg Inlet but the resemblance diminishes in the deeper salinities in Quatsino Sound. The profiles of temperature, salinity and density in Rupert-Holberg Inlet are similar throughout the inlet and can be characterized as having very little stratification except for a thin surface layer. These contrast sharply with the very stratified Quatsino Sound profiles (see Figure 11).

The increasing salinity in Rupert and Holberg Inlets during the late spring and summer months is accomplished by deep water exchange. Salinity increases from Quatsino Sound are communicated to Rupert-Holberg Inlet by deep water exchange, as was observed in the 1974 data and described in Section 2 of this report. The increasing density of the surface Quatsino waters is in part a response to the reduction in precipitation and run-off during these months. Upwelled water from west of Quatsino Sound is believed to be the source for the maximum density waters observed in August and September (Pickard, 1963). There is also a suggestion from the mine data that deep water exchange occurs for short periods during the fall and winter months. The variability in precipitation and run-off during the fall and winter months is probably responsible for these brief periods of deep water exchange. An examination of the Kains Island data reveals that the variability (indicated by the vertical bars in Figure 10) of the salinity is highest in the fall and winter months, i.e., the standard deviation is twice that in the summer months.

Except for the short periods of deep water exchange when the salinity increases, the salinity decreases during the fall and winter months. The exchange process acting at these times is able to extract salt from the entire water column of Rupert-Holberg Inlet. The salt extraction process is controlled by the reduced densities of the surface waters, which are in turn a response to the high precipitation and run-off that occurs at this time of year. This salt extraction process may also occur briefly during the spring and summer months as the mine data suggests.

Unlike deep water exchange, the salt extraction process requires that potential energy be supplied to the entire water column so that the denser, more saline water may be mixed upward. The uniformity of the water column and the large seasonal property changes of the deep waters in Rupert-Holberg Inlet are evidence for the presence of such a mixing process. The region of active mixing is the area between Hankin Point and the northern end of Quatsino Narrows, an area that is visibly active during each flood tide. Calculations of the available tidal mixing energy (Drinkwater and Osborn, 1975) appear to indicate that there is sufficient energy to mix a 10 m surface layer from Quatsino Sound into the water column of Rupert-Holberg Inlet. Furthermore, tidal mixing is certainly enhanced by the 'T'-shaped geometry of the junction of Quatsino Narrows and Rupert-Holberg Inlet, as portions of the tidal jet will be deflected vertically. During deep water exchange the density current is deflected upward by Hankin Point. Upwelling of the deep waters has been observed and it can be identified in the photograph (Figure 12) by the marked turbidity of the water just off Hankin Point.

3.2 Models of Exchange Processes

Two points have emerged from the examination of the background temperature and salinity data; first, the importance of the density of the inflowing surface water from Quatsino Sound, as indicated by its similarity to the waters of Rupert-Holberg Inlet, and second, the role of tidal mixing as evidenced by vertical homogeneity of the water column and the property changes at depth in Rupert-Holberg Inlet. These two points must be included in any realistic model of the exchange processes.

The 1974 data provides a base for a simple model of deep water exchange. The incoming jet of denser Quatsino Sound surface water flows down the side of Rupert-Holberg basin to the bottom, entraining resident water into the flow as it proceeds. A portion of this bottom flow is deflected upwards by Hankin Point and further mixing with the surrounding waters occurs. The remaining portion of the flow is diverted laterally along the basin bottom, displacing the less dense waters upwards. Horizontal density gradients created by the input of denser water at depth transport salt towards the head of Rupert and Holberg Inlets away from the active region. As a result, the temperature and salinity fluctuations of the deep waters resemble those of the incoming water. At higher levels in the water column the temperature and salinity fluctuations are not as closely related to the incoming water. On the outgoing tide the less dense surface waters are drawn out through the Narrows. Thus, as the salt input process continues, the overall density of the water column increases.

Tidal mixing is an essential feature of the salt extraction model. Buoyancy forces act to confine the incoming jet of less dense water to the surface while the entrainment of resident waters into the flow acts to increase the vertical extent of the jet. The vertical penetration of the jet is, in part, governed by the relative density contrast and the speed of the inflowing jet. The 'T' shaped geometry of the junction may also affect the vertical penetration of the jet.

Two extreme configurations of the salt extraction process can be visualized; first, a neutrally buoyant inflow and second, a very fresh inflow. In the first extreme case the tidal jet spreads over the entire water column since there is no density stratification to limit the vertical penetration. In the second case large buoyancy forces confine the tidal mixing to the upper portions of the water column leading to the mechanism subsequently referred to as surface water exchange. Because of the more intense mixing near the surface, fluctuations in temperature and salinity occur first near the surface. The deep waters of the basin remain static and unaffected by the tidal jet. Regardless of the depth of penetration represented by these two extreme cases, during the flood tide salt is transported upwards, thus allowing its removal during the ebb tide. Horizontal density gradients created by the mixing of the tidal jet cause a lateral readjustment of the mass field. For the salt extraction process this implies a net horizontal flux of salt towards the active area in front of Quatsino Narrows.

3.3.1 1975 Long Term Data

In order to investigate the relationships between the surface waters of Quatsino Sound and the waters of Rupert-Holberg Inlet, a long term monitoring program for temperature and salinity was initiated in mid-March 1975. The program consisted of two moorings, each with two Aanderaa current meters with temperature and conductivity sensors. The Quatsino Sound mooring was located off the seaward side of Drake Island with current meters at 10 and 30 metres, hereafter referred to as Q10 and Q30. The Holberg Inlet mooring was located southeast of Coal Harbour, with current meters at 32 and 164 metres, hereafter called H32 and H164. The locations of these two moorings are shown in Figure 2, denoted Q and H respectively.

Except for data from Q30, the first set of temperature and salinity data from March 14 to May 13 is presented in Figure 13 as ebb tide averages and flood tide averages. No salinity data was obtained from the deep instrument on the Holberg mooring because of a sensor failure.

The increasing long-term temperature trend is similar at all four depths. Superimposed on the trend are temperature variations of length 3 to 10 days and varying amplitude. In particular, one of these temperature variations - a temperature dip of 5 to 10 day duration - can be traced at all 4 depths. The chronology of the temperature dip is: March 17 at Q30, March 20 at Q10, March 22 at H32 and March 25 at H164. The averaged temperature time series at Q10 has the largest variance, especially in the latter half of the time series. In contrast, the temperature at H164 is very smooth.

All three time series of salinity show a net increase in salinity of approximately $1^\circ/_{\circ\circ}$. The long term trend is similar on all three time series, however, they are different in detail. The Q30 salinity is markedly different from the other two series in that it exhibits a strong 14 day periodicity of amplitude as large as $0.5^\circ/_{\circ\circ}$. The H32 m time series is smooth, exhibiting little difference between ebb and flood averages, a sharp contrast to the Q10 time series which exhibits a large difference ($<0.5^\circ/_{\circ\circ}$) between ebb and flood averages. These large differences are to be expected in the very stratified surface waters.

3.3.2 Interpretation of 1975 Long Term Data

During the first 6 or 7 days, ending on March 20, deep water exchange appears to be occurring as the salinity at H32 rises slightly. Unfortunately, there are insufficient temperature data available at H164 during this initial period to support this argument. Between March 21 and March 25 the salinity at H32 has dropped about $0.1^\circ/_{\circ\circ}$, indicating that the salt extraction process is occurring. This hypothesis is further supported by the chronology of the temperature dip mentioned earlier. The temperature dip observed at Q10 appears a few days later at H32, while the temperature at H164 remains relatively static. This is consistent with surface water exchange, i.e., the salt extraction mechanism. An upper bound for the vertical eddy diffusivity, K_z, associated with the salt extraction process can be estimated from this data by using an appropriate length scale, L and time scale, T. For at least two days surface water exchange was observed to be occurring while the deep waters were static. Using a time scale of 2 days and the vertical separation between H32 and H164 as a length scale,

$$K_z \lesssim \frac{L^2}{T} \sim \frac{(132x10^2)^2}{2x24x3600} \sim 10^3 \text{ cm}^2/\text{sec.}$$

The time scale used may be inappropriately short since the water property changes at H164 are a result of a switch in the exchange process not a result of the vertical eddy diffusivity. Thus, this calculation must be considered as only providing an upper bound. The temperature dip shows up at H164 only after the salinity begins to increase, around March 25. The rise in salinity begins first at Q10 and then at H32. Moreover, the salinity increase at Q10 is steeper (about $0.7^\circ/_{\circ\circ}$ between March 26 and April 10 vs. about $0.5^\circ/_{\circ\circ}$ at H32). After the salinity at Q10 reaches a value of about $31.1^\circ/_{\circ\circ}$ it remains fairly stable, the salinity at H32, however, increases steadily until April 25 and only gradually until the end of the record, by which time it has reached $31^\circ/_{\circ\circ}$. Salinity is a better indicator of exchange than heat since salt can only be exchanged through Quatsino Narrows, whereas heat can also be exchanged through the air-sea interface. Nevertheless, comparison of temperatures at Q10 and H164 reveals that those at H164 closely follow those at Q10, except for some scattered points around April 18, May 5 and 13. The departures at these times are almost certainly due to a thicker warm layer in Quatsino Sound. This similarity in temperature at H164 and Q10 and the increasing salinity at H32 are both consistent with our model of deep water exchange. The above discussion of the long term data in terms of the exchange processes is summarized in the following table.

	DATES			
STATIONS	UP TO MAR 20	MARCH 20-25	MAR 25-APR 25	APRIL 25 TO END
Q10 θ	Steady	Decreasing	Increasing	Increasing
S	Steady	Slight Decrease	Increasing	Steady (Slight Drop)
H164 θ	———	Steady	Increasing	Increasing
H32 θ	Steady	Decreasing	Increasing	Increasing
S	Increasing	Decreasing	Increasing	Slight Increase
Exchange Process	Deep Water Exchange	Salt Extraction Process	Deep Water Exchange	Deep Water Exchange

3.3.3 Parameterization of Exchange Processes

A more quantitative explanation of the long term data may be achieved if the rates of change of salinity and temperature are considered. In the absence of salinity data from H164, the rate of change of H32 salinity, $\frac{\Delta S}{\Delta T}H32$ is interpreted as determining the particular type of exchange process in effect, i.e., a positive slope for deep water exchange and a negative slope for the salt extraction process. The rate of change of H164 temperature (i.e., $\frac{\Delta\theta}{\Delta T}H164$) coupled with the temperature difference between Q10 and H164 (i.e., $\theta_{Q10}-\theta_{H164}$) may reveal whether or not deep water exchange is occurring. If deep water exchange is in progress then the rate of change of deep water temperature, $\frac{\Delta\theta}{\Delta T}H164$, should be non-zero providing there is an appreciable temperature difference between the resident deep waters and the intruding waters. When the deep waters are quiescent, we would expect $\frac{\Delta\theta}{\Delta T}H164 \sim 0$, and surface water exchange would be occurring. The following table summarizes the above discussion.

	$\frac{\Delta S}{\Delta T}H32$	$\theta_{Q10}-\theta_{H164}$	$\frac{\Delta \theta}{\Delta T}H164$
Deep		+	+
Water	+	0	0
Exchange		-	-
Surface		+	0
Water	-	0	0
Exchange		-	0

The validity of the above method of analysis depends upon several points. First, it is assumed that the temperature at Q10 is representative of the water entering Rupert-Holberg Inlet on the flood tide. This assumption is weak, in light of the observed stratification of the surface waters of Quatsino Sound. On the other hand the long term trends occurring in the Quatsino surface water are more likely to be faithfully represented by the time series at Q10. Second, it is possible that during the flood tide both types of exchange process occur in series as the 1974 data show. Thus, in periods when deep water exchange is dominant, fresher water may be mixed down to 30 m by surface water exchange which occurs for only a short period at the beginning of the flood tide. This may affect the salinities at, say H32 so as to mask the deep water exchange. Also, in a neutral situation in which the tidal jet is spread over the entire water column, properties of the entire water may be changing, thus providing ambiguous data. This latter situation may only occur as a transitional phase between the two exchange processes.

From daily averaged time series of temperature at H164 and Q10 and salinity at H32, daily rates of change of salinity at H32 and temperature at H164 were computed. The temperature difference between Q10 and H164 was also computed. These computed quantities are plotted in Figure 14 and in addition the type of exchange process believed to have been occurring is indicated. The data are dominated by the deep water exchange process especially from March 25 to April 26. There are several instances during this period when surface water exchange may be occurring. In these three instances $\frac{\Delta S}{\Delta T}H32$ is near zero and $\frac{\Delta \theta}{\Delta T}H164$ is correspondingly small. On April 4, $\frac{\Delta S}{\Delta T}H32$ is zero, yet $\frac{\Delta \theta}{\Delta T}H164$ is appreciable; this may be due either to both exchange processes acting in series or to the existence of a neutral condition. A similar situation occurs on May 10, in this case $\frac{\Delta S}{\Delta T}H32$ is definitely negative yet $\frac{\Delta\theta}{\Delta T}$H164 is appreciable. The temperature difference between Q10 and H164 is not always consistent with $\frac{\Delta\theta}{\Delta T}$H164 but the trends in $\theta_{Q10}-\theta_{H164}$ usually are. For example, during April 20-25, a time of deep water exchange, $\frac{\Delta\theta}{\Delta T}$H164 is negative even though $\theta_{Q10}-\theta_{H164}$ is positive. However, it is apparent that $\theta_{Q10}-\theta_{H164}$ is decreasing rapidly during this period. The Quatsino surface water have cooled considerably during this period but the temperature at Q10 is not representative of the inflowing waters.

This first attempt at parameterizing the exchange processes has achieved some measure of success. Better results may be achieved if salinity data from H164 are available and if a better description of the inflowing waters is obtained. Ultimate success depends upon improved modelling of the exchange mechanism.

3.4 Further Details of Deep Water Exchange

A closer examination of the 1974 data reveals several subtle details not considered in our model. The effect of the fortnightly amplitude variation of the tides can be seen in the mean flood currents at 155 metres (see Figure 4). The magnitudes of the mean flood currents are appreciably reduced between April 27 and May 2, a period of neap tides. The mean flood currents at 5m and 70 m do not exhibit this tidal modulation. The salinity and temperature data from all three depths shows no appreciable tidal modulation.

Cross-spectral analysis of salinity and speed at 155 m reveals that at frequencies higher than 8 cycles/day the time lag between salinity and speed is less than 10 minutes although coherence squared is less than 0.4. This suggests that the more saline parcels of water are usually passing at higher speeds.

An important detail not discussed earlier is the apparently anomalous low salinity at 155 m during the initial stages of deep water exchange. The salinity initially drops below ebb tide levels and then increases to a maximum in the latter portion of the flood tide, whereas the bottom currents initially rise rapidly to maximum and then generally decrease in the latter portion of the flood tide. This decrease in salinity during the early flood tide appears to be inconsistent with concepts of a salinity induced density current. The explanation may lie in the effect of mine tailings suspended within the sinking jet. If tailings settle out on the Quatsino Narrows side of the Rupert-Holberg basin during the ebb tide, they may be resuspended by the more vigorous action of the inflowing jet, thus changing the density of the jet sufficiently to cause it to sink to the bottom of the basin, even though it is initially less saline than the surrounding fluid. As the tide progresses the salinity of the jet rises above that of the surrounding water, although suspended tailings would continue to influence the jet's density.

A second possibility, which is consistent with the above hypothesis, is that the operation of the sensors is affected by suspended tailings. Calculations based on the proportion of suspended particles necessary to produce the observed conductivity change, show that the density effect of the suspension above would correspond to the effect of almost doubling the salinity. The concentration of suspended particles necessary to maintain a marginally denser initial flow are only 0.2-0.3 gm/litre which would produce no noticeable effect on the conductivity of the water. Thus whether or not we allow for effects of tailings on the sensor operation, it seems likely that they play an important role in determining the density of the jet and may influence its location in the water column during the early part of the flood tide.

There are two major implications of this last argument; first, the density can no longer be adequately described by only temperature and salinity as the amount of suspended solids significantly affects the water density. Second, the presence of mine tailings adds an interactive aspect to the deep water exchange process. The resuspension of mine tailings by the flood currents increases the density of the water thereby promoting a density flow.

The observed lower salinities at 70 m during the flood tide may be due to the downward mixing of fresher water by the currents in the upper half of the water column.

4. SUMMARY AND CONCLUDING REMARKS

Models of the deep water exchange and the salt extraction process in Rupert-Holberg Inlet have been developed from existing temperature, salinity and current velocity data. The area where the exchange processes act is at the junction of Rupert-Holberg Inlet with Quatsino Narrows, the general area between Hankin Pt. and the north end of Quatsino Narrows. Tidal mixing and the density of the incoming tidal jet are the two main features considered.

In the model of deep water exchange the tidal jet is negatively buoyant; consequently it flows down the side of Rupert-Holberg Inlet to the bottom as a density current. A portion of this flow is deflected vertically by the far shore at Hankin Pt. Driven by the horizontal density gradients the denser waters flow along the basin floor displacing the less dense waters upward in the water column. As the input of denser water of depth continues the density of the water column increases. Temperature, salinity and current velocity measurements made in the spring of 1974 provide good evidence of deep water exchange.

In the salt extraction process the incoming tidal jet is buoyant; consequently its activity is concentrated in the upper portions of the water column. Strong vertical mixing, deriving its energy from the tidal exchange then works to decrease the resulting salinity stratification, thus the salinity of the surface waters is increased at the expense of the deeper waters. The salt that is mixed upwards is then drawn out of Rupert-Holberg Inlet on the ebb tide. As the salt extraction process continues the salinity of the water column decreases. The flux of salt towards the active area is driven by horizontal density gradients created by tidal mixing in front of the Narrows.

In both these models the vertical extent of the tidal jet is determined by the density difference between the resident waters and the inflowing jet and also by the speed of the tidal jet from which the mixing mechanism derives its energy. In addition the 'T' shaped geometry of the junction increases the vertical penetration of the jet.

Deep water exchange is dominant during the spring and summer months when low precipitation and run-off and the presence of upwelled water in Quatsino Sound are responsible for the increased density of the inflowing water. The salt extraction process occurs in the fall and winter months when the density of the inflowing waters is reduced by high precipitation and run-off.

The first set of long term data has been successfully interpreted in terms of these exchange models, and an attempt at a more quantitative interpretation has also had some measure of success. Better results can be achieved with more representative and reliable long term data. Refinements have been made to the ongoing long term monitoring program and future analysis of these data will provide a better basis for modelling the exchange processes.

The widespread dispersion of mine tailings in Rupert-Holberg Inlet (Goyette, 1975) has added another dimension to the oceanography of this inlet. The active region in front of the Narrows is a turbidity source during times of deep water exchange when strong currents scour the bottom. The resuspension of mine tailings may modify the flow by increasing the density of the water. This raises the possibility of a feedback loop that could serve to extend the time of scouring action beyond the periods during which deep water exchange might be expected solely on the basis of temperature and salinity conditions.

This study has raised several interesting questions about the flushing of Rupert and Holberg Inlets. We still do not understand the significance of the T-junction geometry in front of the Narrows. Is this an essential feature determining the vertical extent of stirring and mixing during the salt extraction phase as suggested by Drinkwater (1973), or can such a process occur solely as a result of intense turbulence near the inflowing jet? It would be useful to understand the effect on efficiency of the salt extraction mechanism of small changes in salinity of the inflowing water; does a more saline jet, which penetrates deeper, remove salt more effectively than a fresher inflow? What effect will density stratification, within the jet itself, have on the exchange? There is also a real need to verify our hypothesis for turbidity effects on the density of the jet. It is not inconceivable that the structure of the exchange process could be altered by man, either unintentionally through the resuspension of mine tailings, or perhaps intentionally by changing surface salinities through the control of river discharge.

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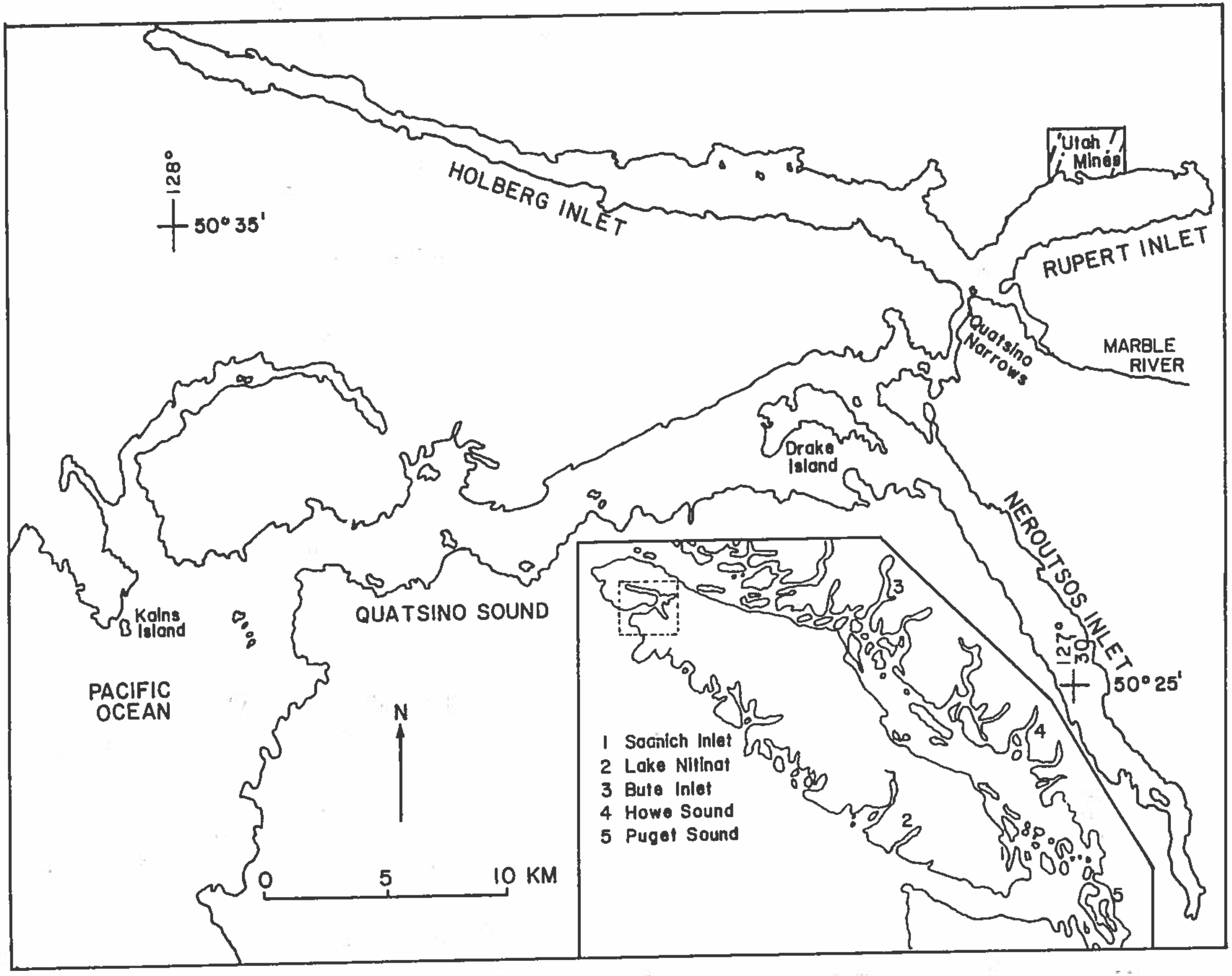

Figure 1. Map of Quatsino Sound, Rupert-Holberg Inlet and Neroutsos Inlet.

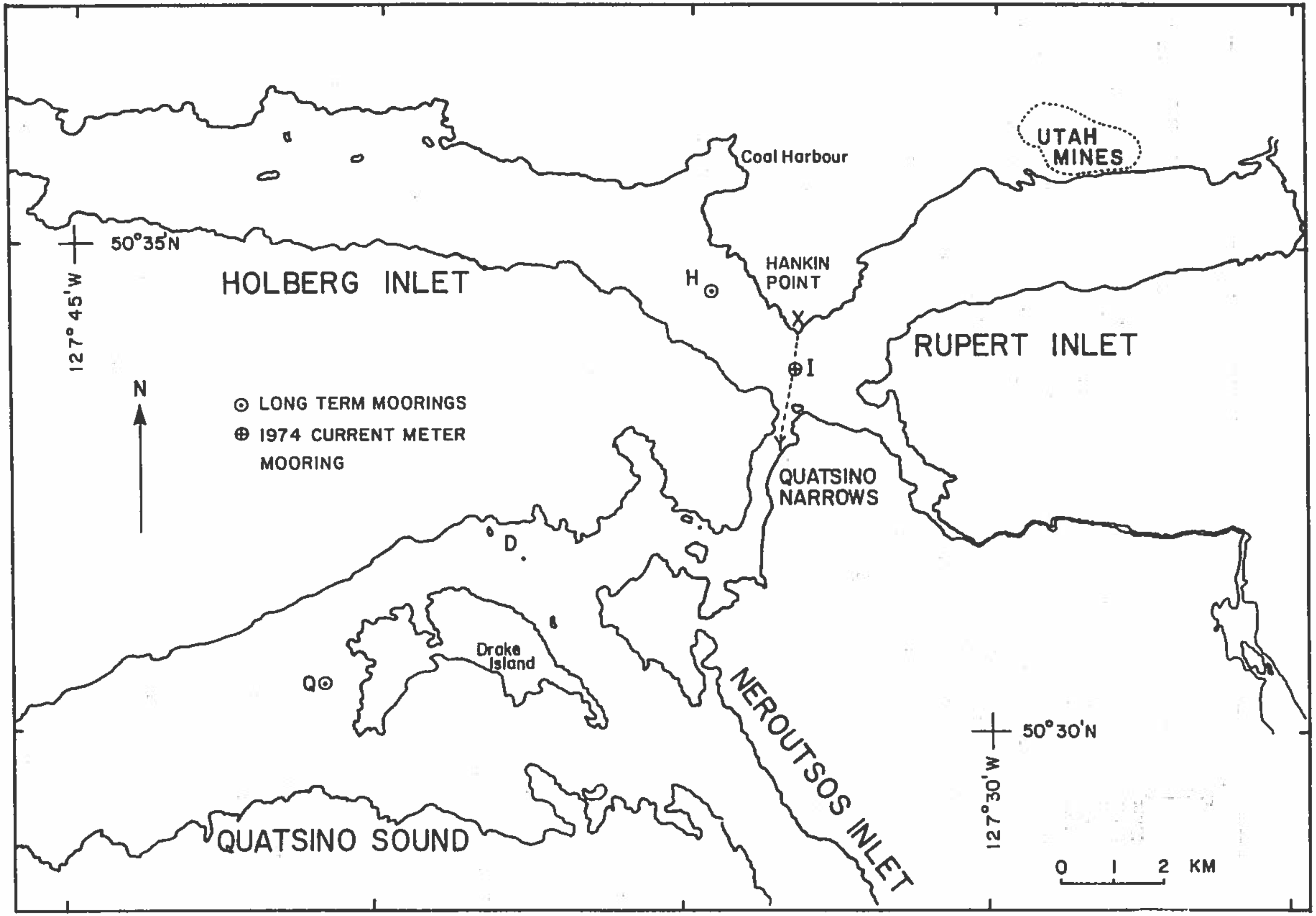

Figure 2. Map of inner Quatsino Sound and Rupert-Holberg Inlet showing locations of current meter and temperature, salinity stations.

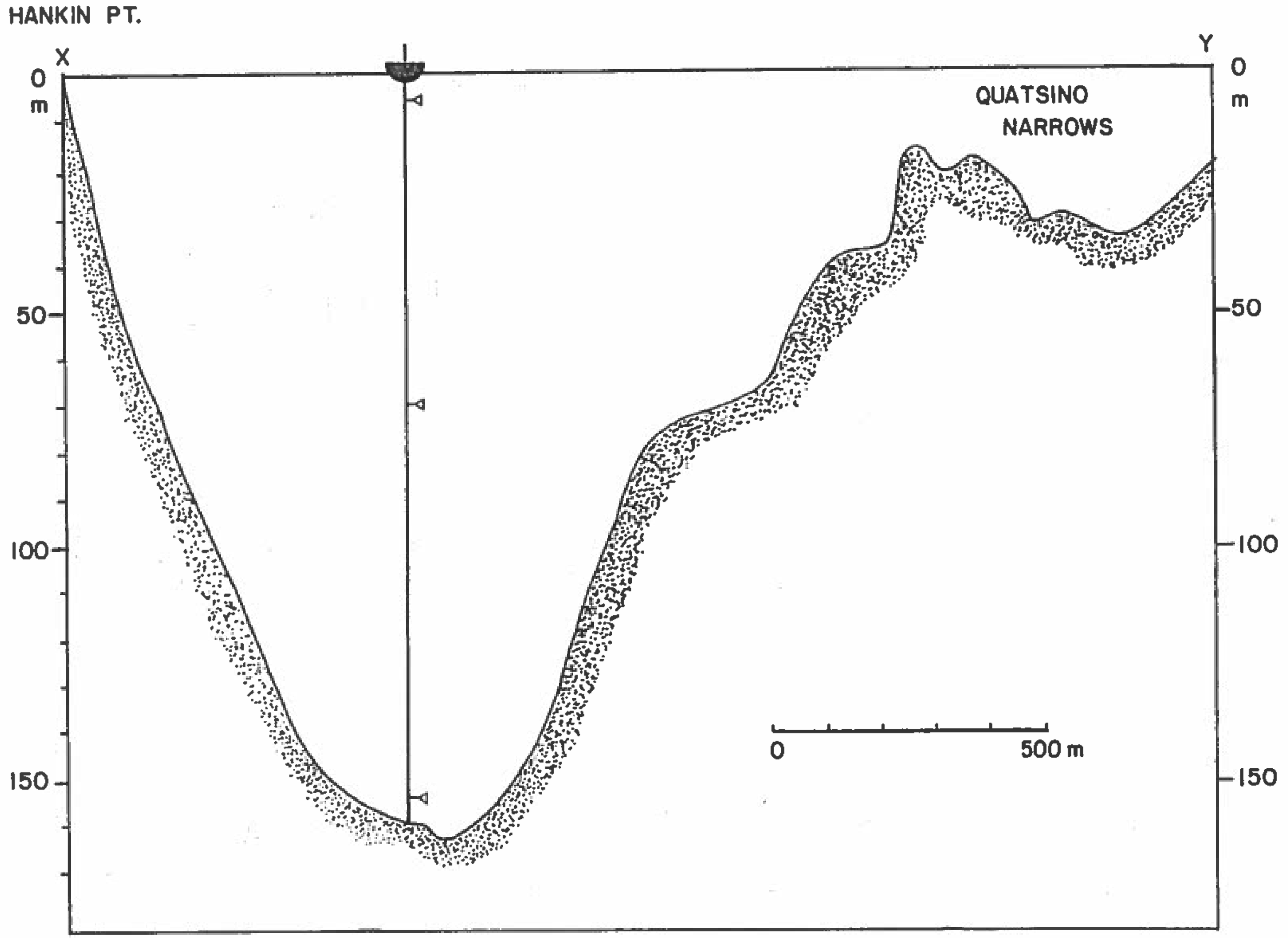

Figure 3. Sectional diagram, from Hankin Pt. to Quatsino Narrows, showing 1974 current meter mooring

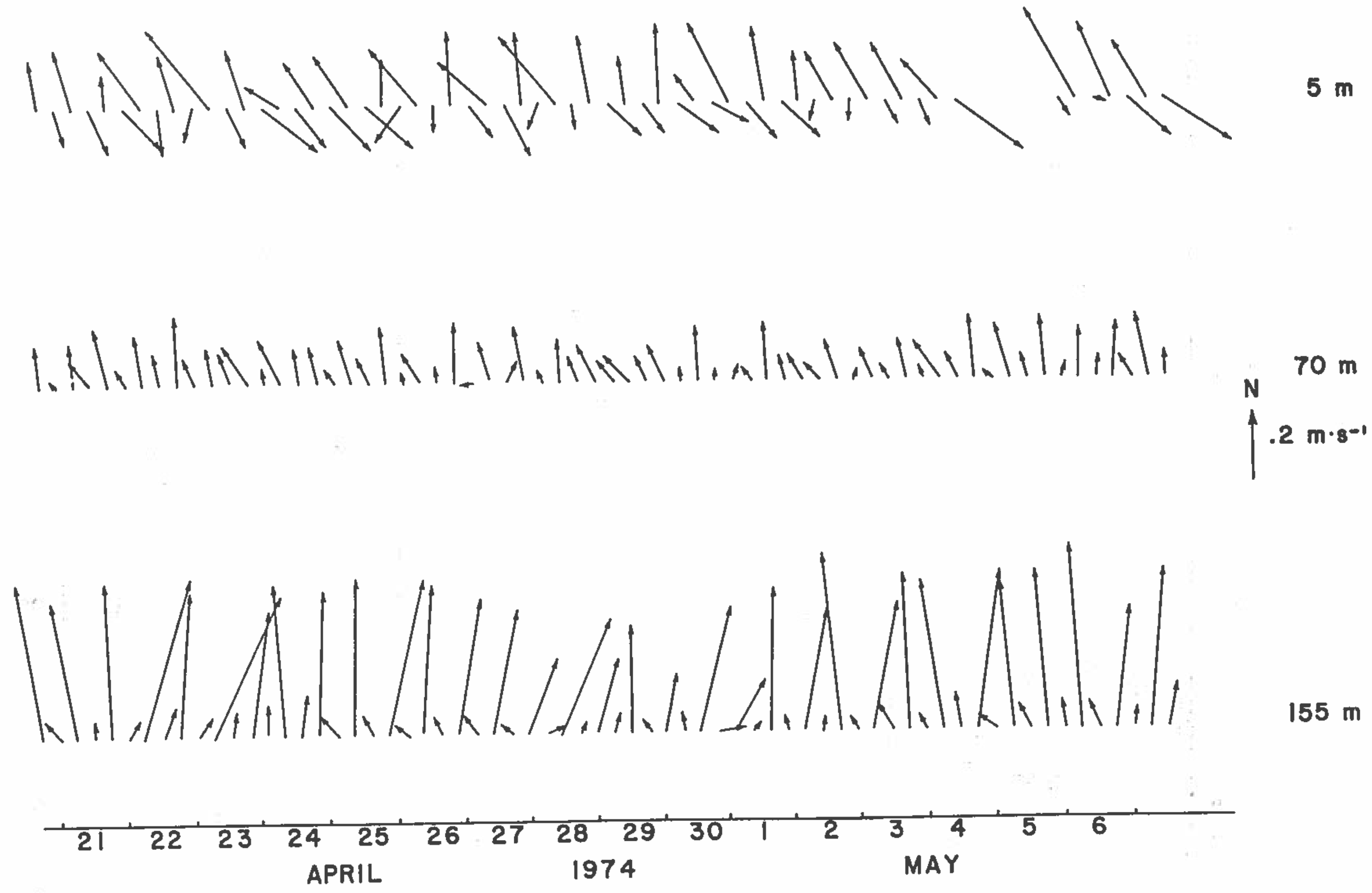

Figure 4. Mean ebb tide and mean flood tide current vectors of the 1974 current meter data.

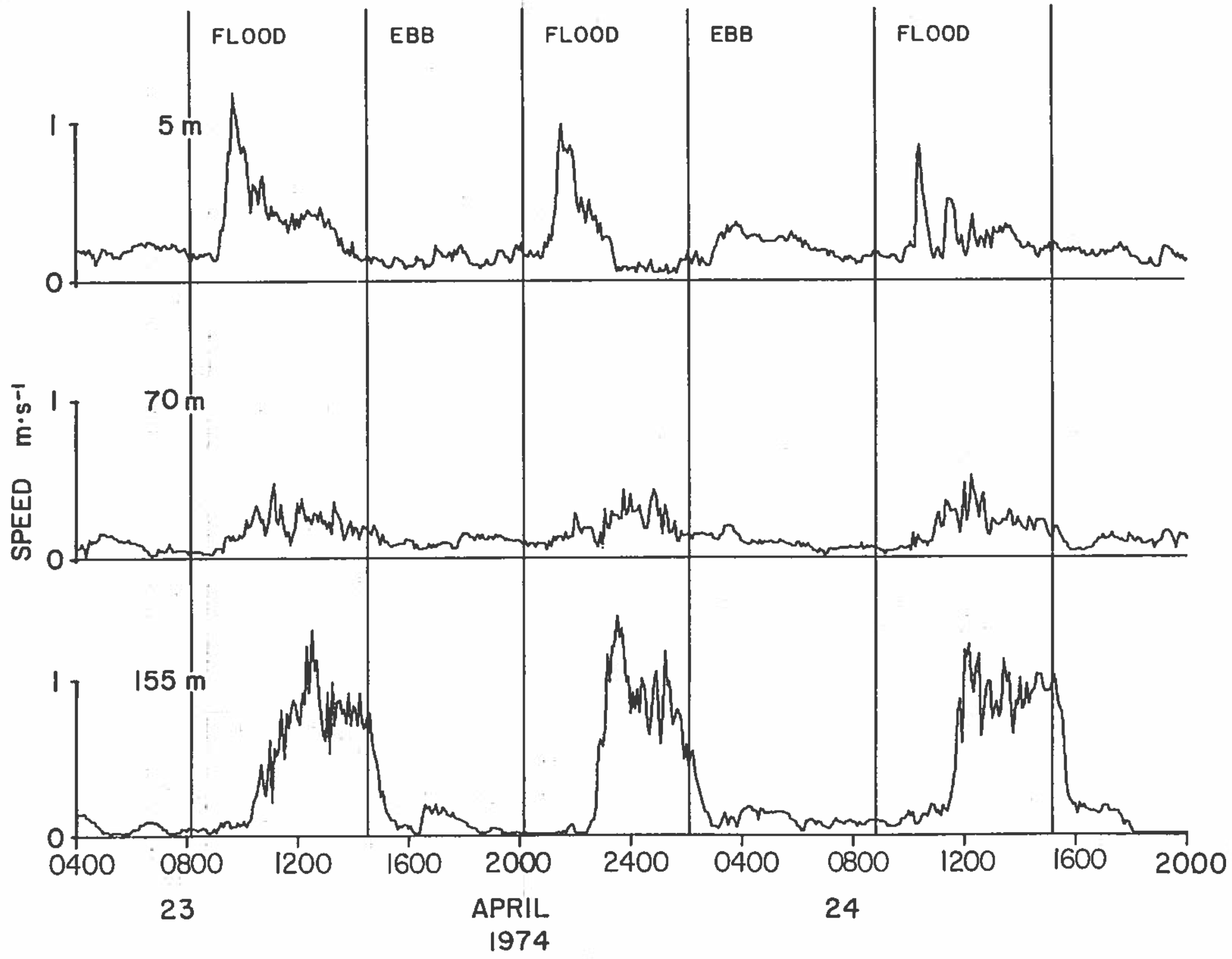

Figure 5. A portion of the actual time series of current speed from 5, 70 and 155 metres.

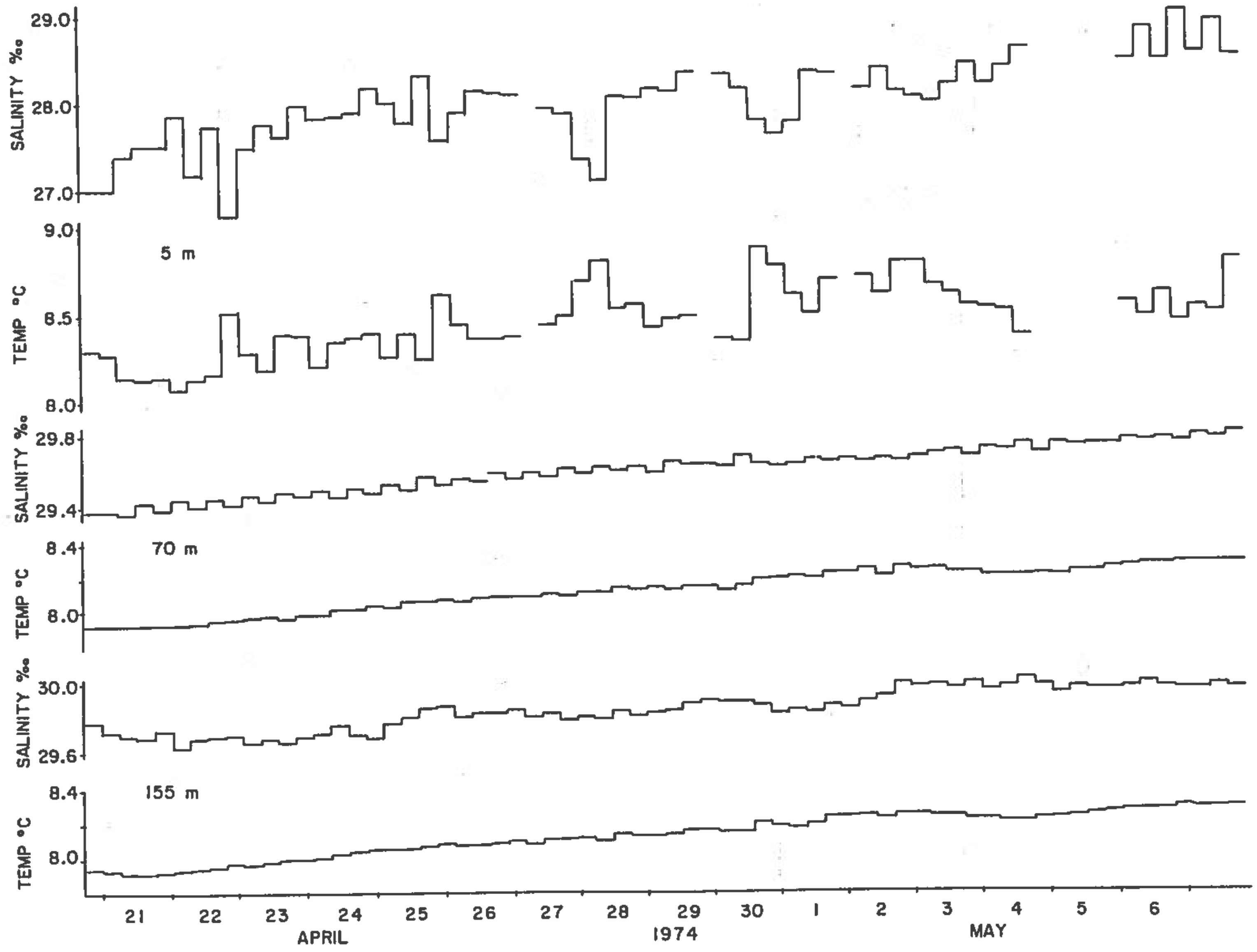

Figure 6. Mean ebb tide and mean flood tide salinities and temperatures from 1974 data.

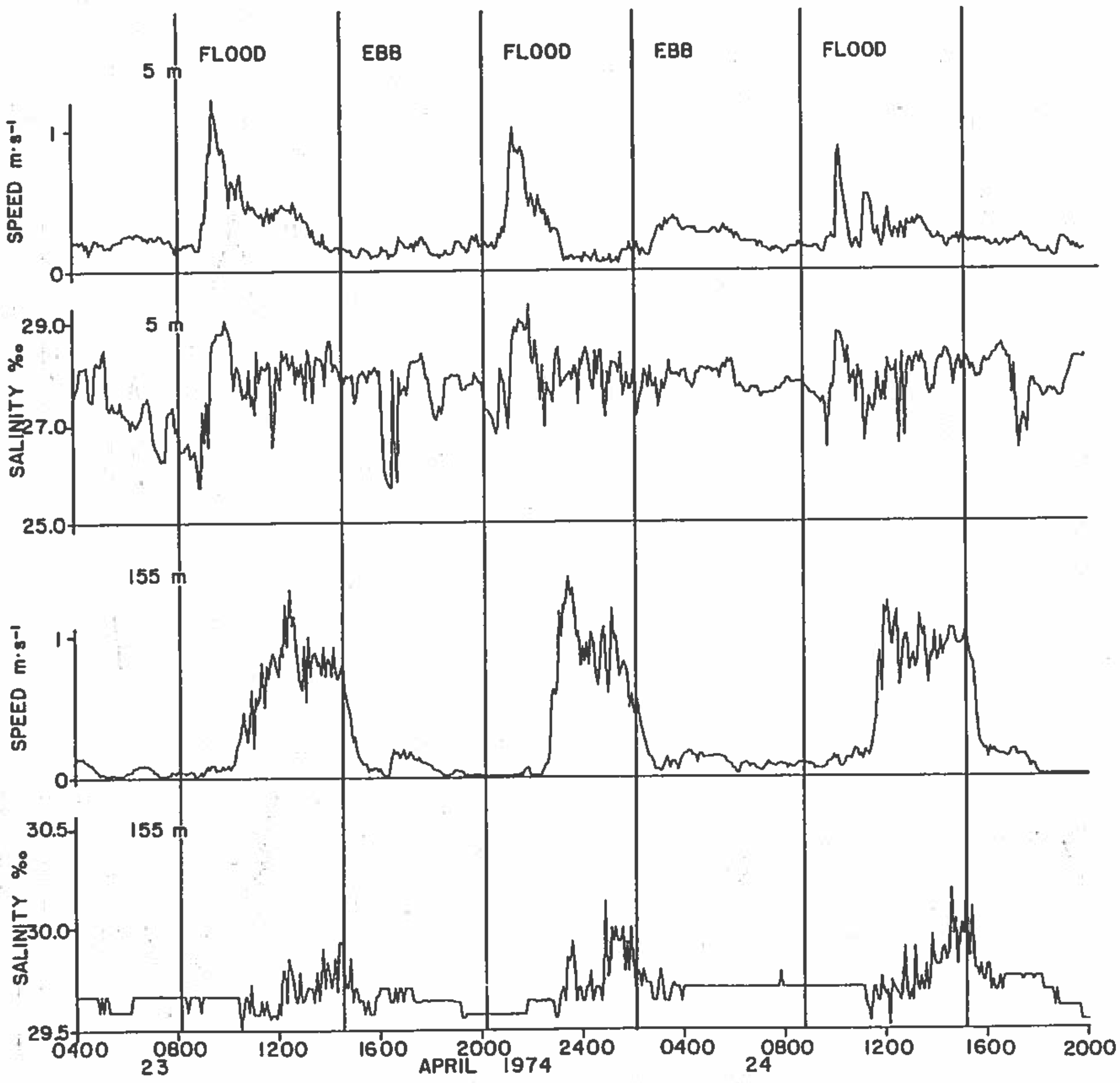

Figure 7. A portion of the current speed and salinity time series of the 1974 data from 5 and 155 metres.

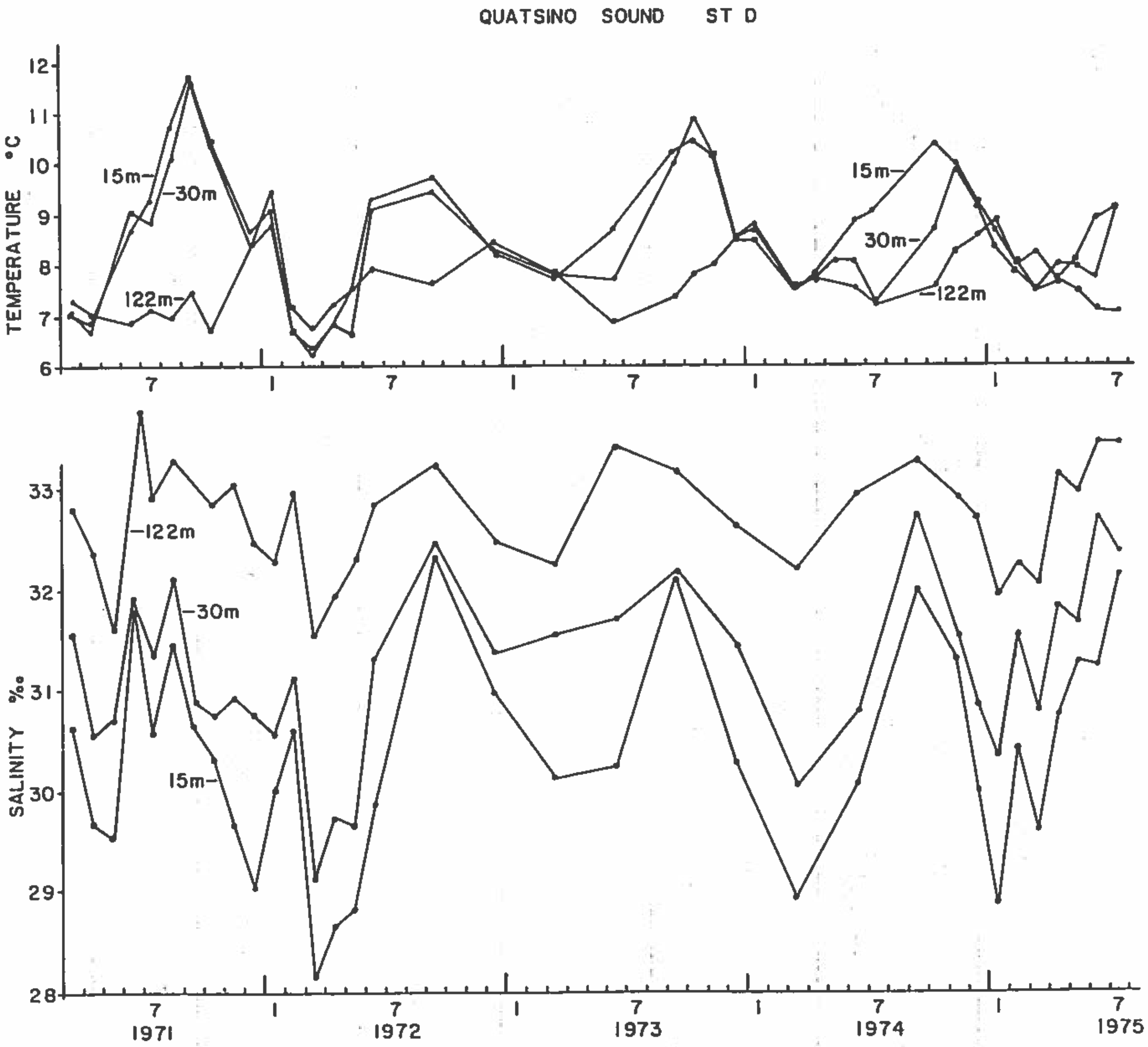

Figure 8. Representative background temperature and salinity data from Quatsino Sound. For location of Station D see Figure 2.

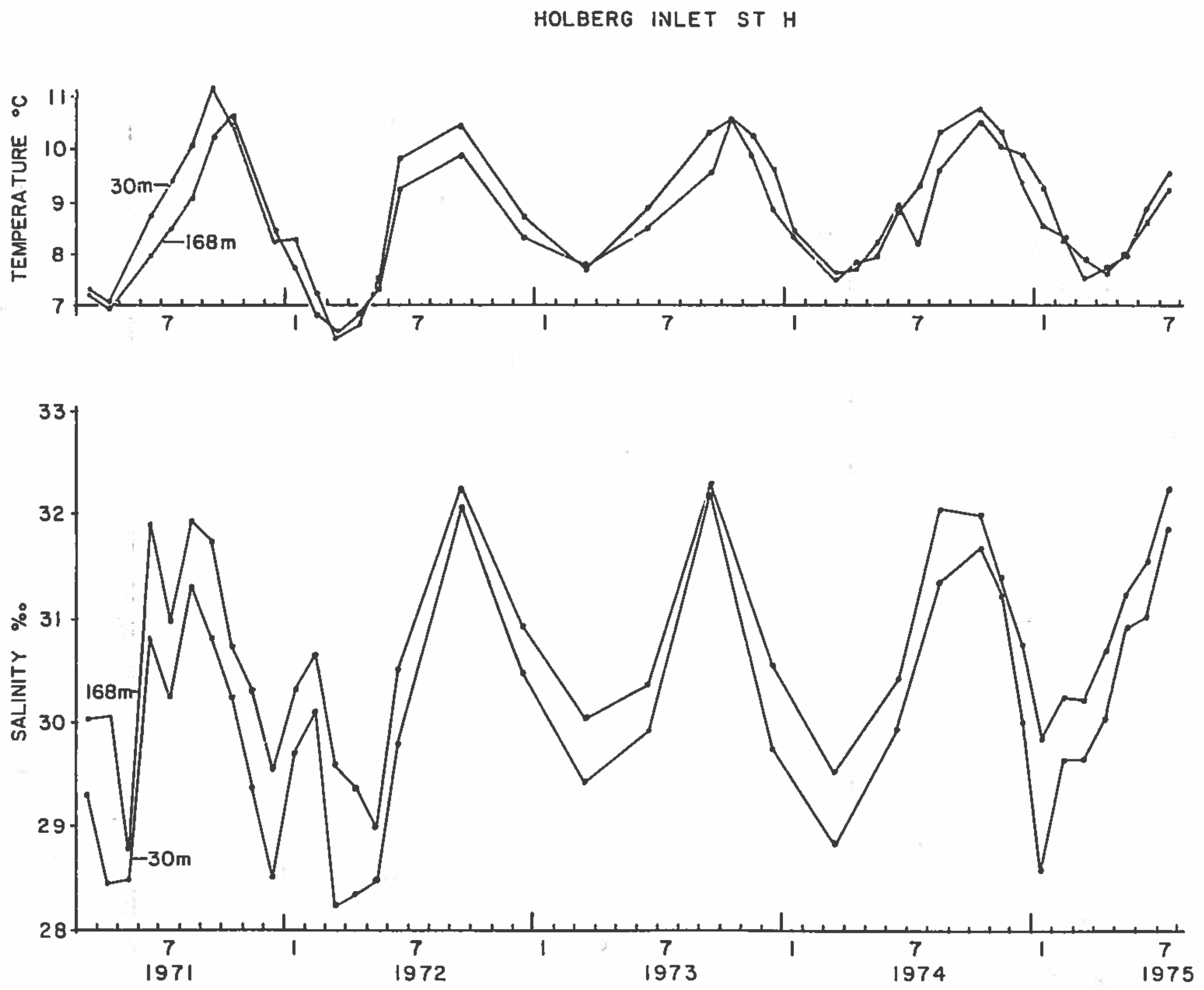

Figure 9. Representative background temperature and salinity data from Rupert-Holberg Inlet. For location of Station H see Figure 2.

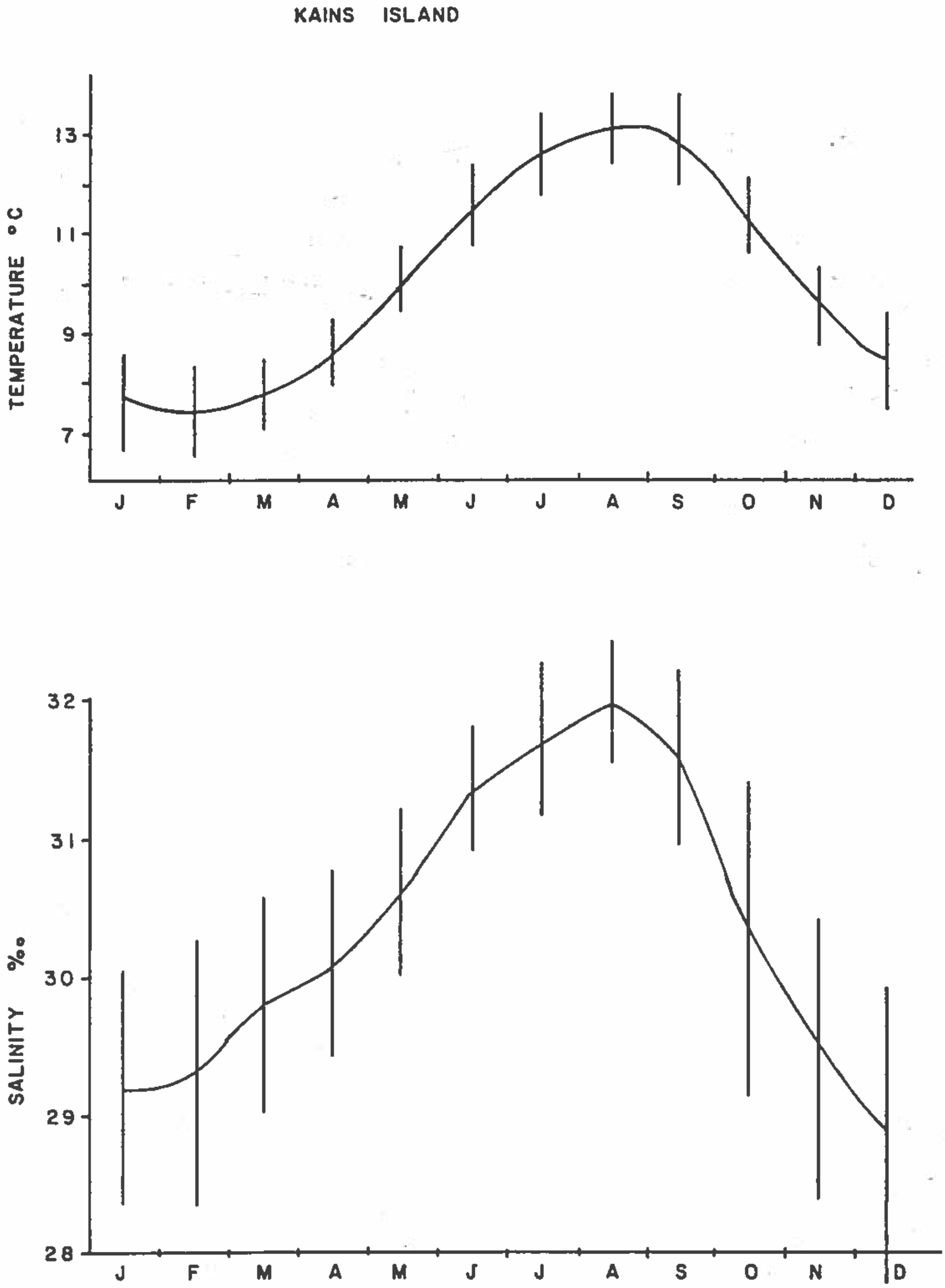

Figure 10. Thirty-six year grand mean of daily sea surface temperature and salinity from Kains Island Lighthouse. Vertical bars represent standard deviation. For location of Kains Island see Figure 1.

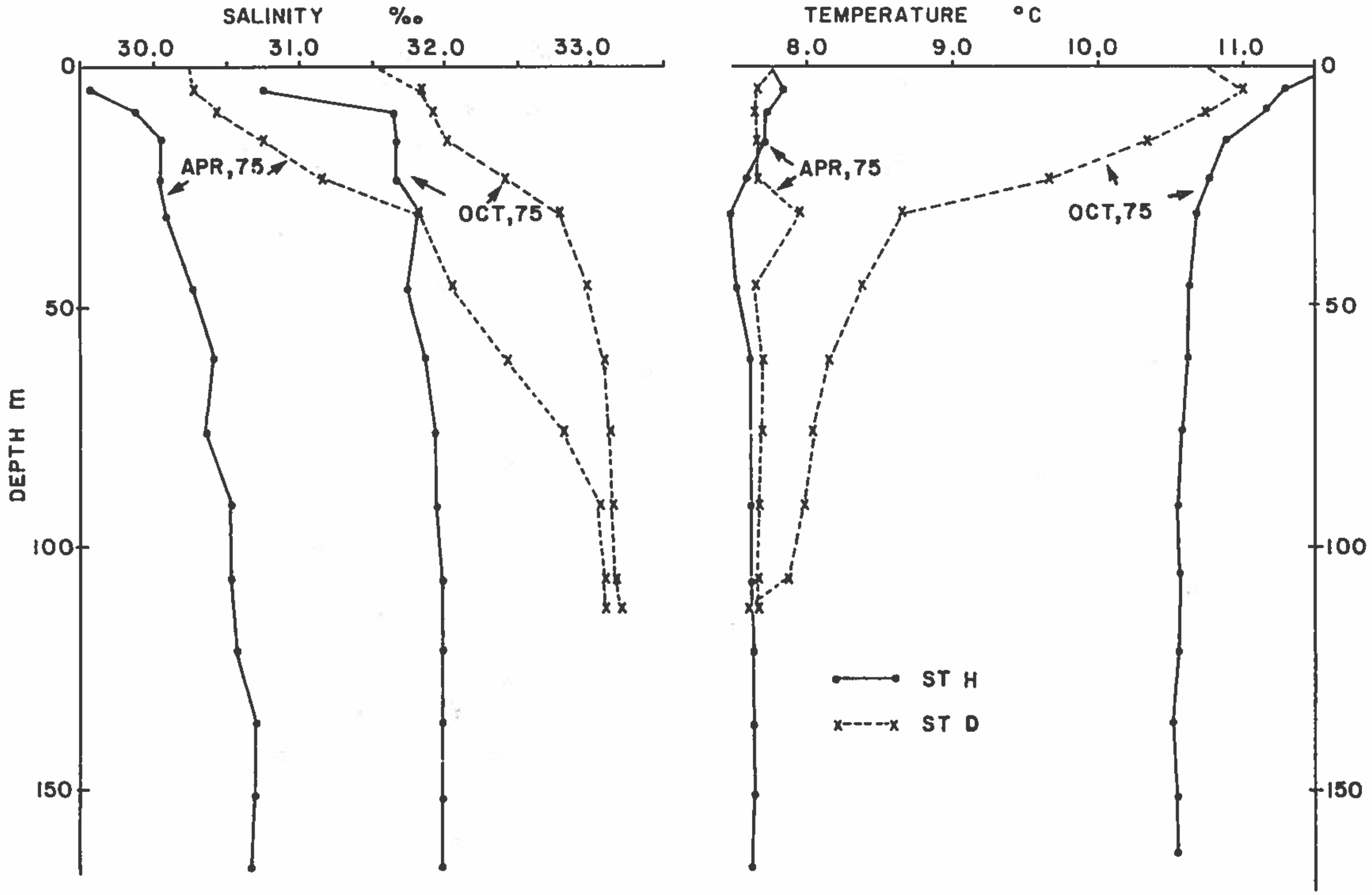

Figure 11. Representative temperature and salinity profiles from Quatsino Sound (St. D) and Rupert-Holberg Inlet (ST. H).

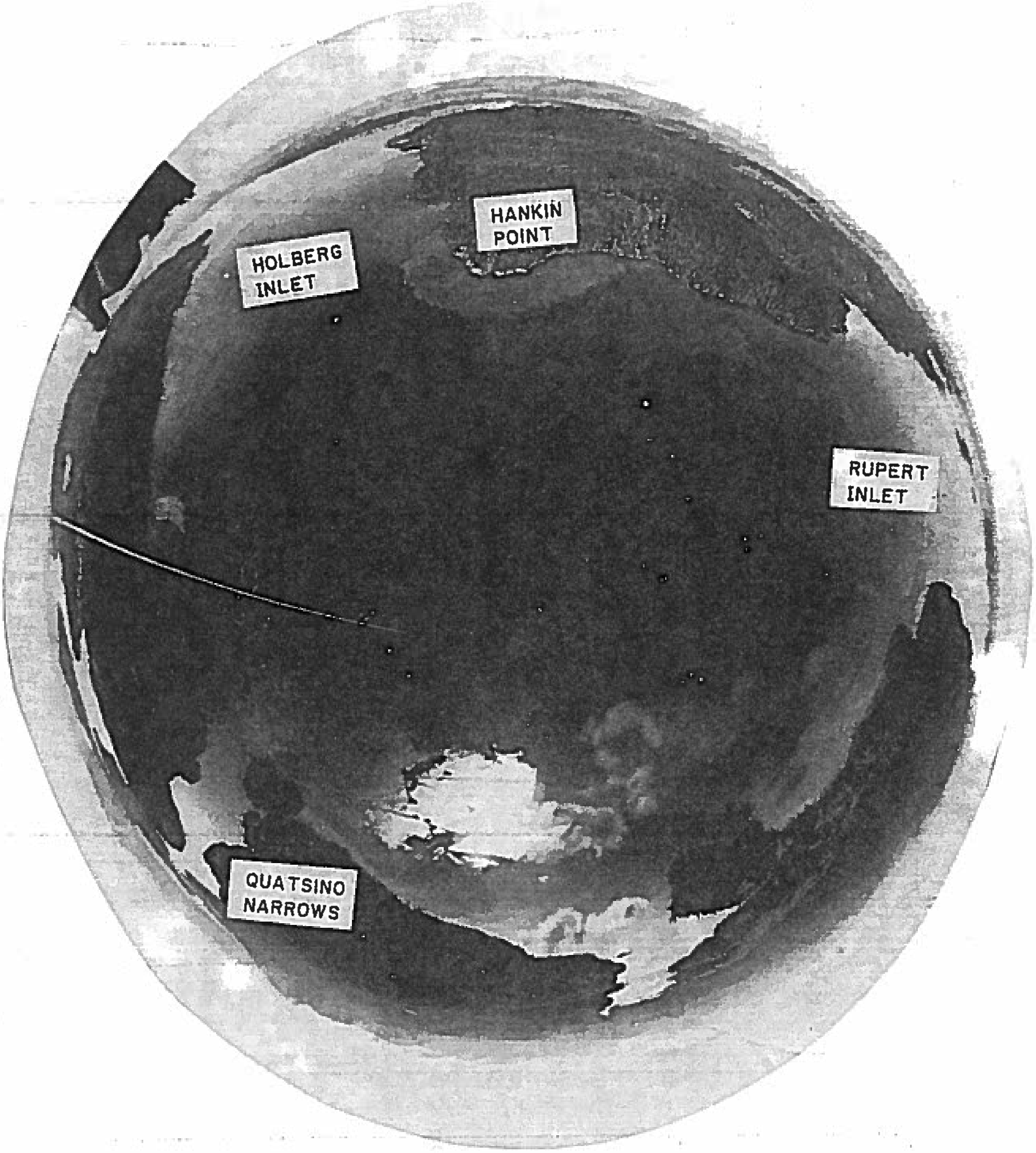

Figure 12. Balloon photograph of active region in front of Quatsino Narrows. Upwelling of turbid water is evident off Hankin Pt.

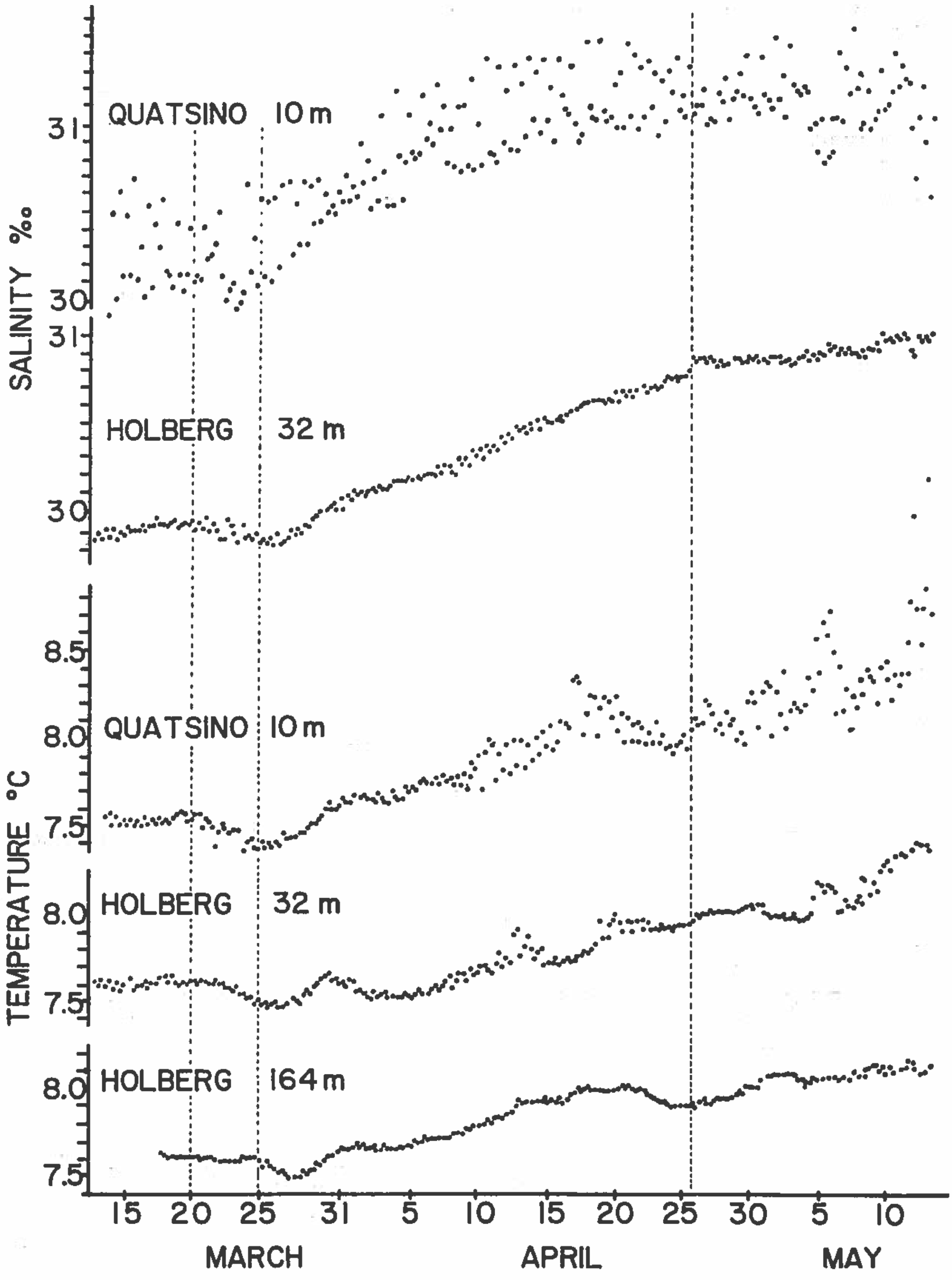

Figure 13. Mean ebb tide and mean flood tide salinities and temperatures from the first set of long term data, 1975.

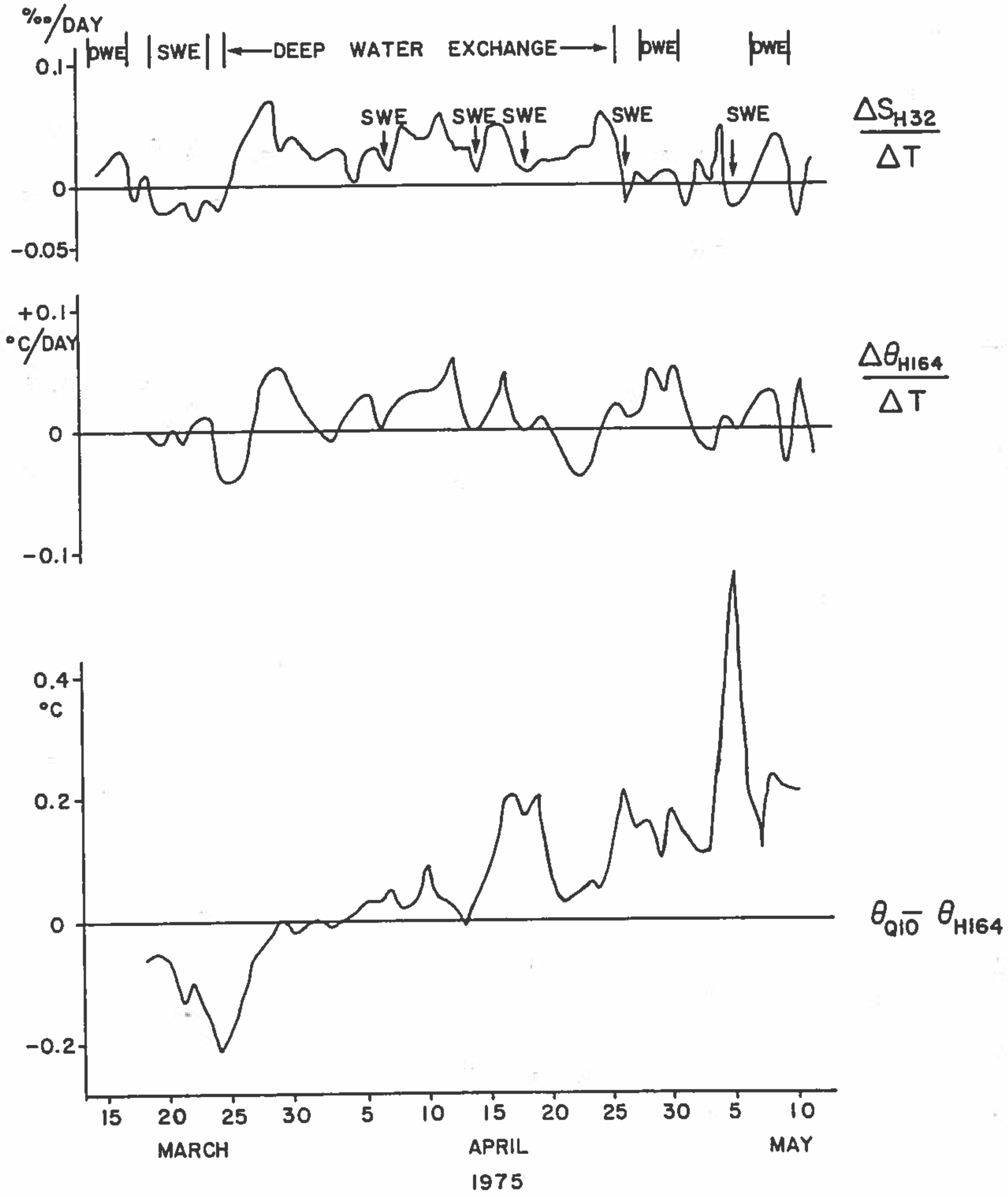

Figure 14. Daily rate of change of salinity at H32 and temperature at H164, and temperature difference between Q10 and H164. (DWE = Deep Water Exchange, SWE = Surface Water Exchange).

PREDICTING LONG-TERM CHANGES IN MARINE BENTHIC COMMUNITIES

by

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Vol. 13: 87–94, 1983 | MARINE ECOLOGY – PROGRESS SERIES
Mar. Ecol. Prog. Ser. | Published July 28

REVIEW

Predicting long-term changes in marine benthic communities

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ABSTRACT: Analysis of long-term hydrographic data for the North Atlantic Ocean shows evidence of cycles with periods of 3 to 4, 6 to 7, 10 to 11, 18 to 20 and 100 yr. There are known physical explanations for such cycles. Plankton data indicate that at least 3 to 4, 6 to 7 and 10 to 11 yr cycles occur. Benthic data suggest 6 to 7 and 10 to 11 yr cycles are present, and evidence exists for a secular cycle. Not all species show or can be expected to show cyclic behaviour. Constancy of numbers through decades occurs at depths of over 100 m in some species and even with species at shallow depths. Whilst, using spectral analysis, cycles can be found in benthic data, cycles longer than those studied will undoubtedly interact giving rise to departures from predictions. Since there is evidence that periods of up to over 4000 yr are to be expected there is little hope of accurate prediction of future trends in numbers. Instead, a monitoring strategy covering the same species over large areas is suggested. Departures from a common pattern may indicate local effects of pollutants.

INTRODUCTION

In examining effects of pollutants on marine benthic communities one has to be aware of natural long-term fluctuations which might wrongly be attributed to effects of the pollutant (e.g. Bowman, 1978). Yet many monitoring programmes are only done over relatively short time periods (4 to 5 yr is long in this context). In this review we analyse some time series for marine benthic populations and examine the consequences of long-term cycles found for the prediction of long-term changes in such populations.

SCALES OF LONG-TERM VARIATIONS IN THE SEA

In analysing for regular variations in data sets it is not sufficient, for example, to cover a period of 10 yr and find a simple harmonic wave over this period and then assume that a 10-yr cycle is the rule. The next 10 yr data set may well not fit due to interference by even longer-term variations. Thus it is necessary to analyse really long-term data sets covering many decades to obtain some reasonable insight into periods of cycles. Light- and weather-ship observations extend back to the mid 1800s and thus records of salinity and temperature variations in the oceans can be used to assess the sorts of scales of variability we can expect in marine data. Analysis methods have greatly improved recently with the advent of computers and spectral analysis programmes which can scan for wave periods in data sets (e.g. BMD programmes, Dixon, 1974, which we use in this paper). One well known cycle which need not be considered when analysing for long-term trends is the annual seasonal cycle. In typical data sets it does not matter whether mean annual numbers, summer maxima or winter minima are used – the long-term trend is still apparent, particularly if running averages are used. Thus we confine our analyses to year-to-year variations and do not take seasonal data into account.

In an analysis of long-term temperature anomalies (variations from a long-term mean) on data for the North Atlantic Ocean using spectral analysis on moving averages, Maximov et al. (1972) found a multi-

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0171-8630/83/0013/0087/$ 02.00

component cyclic character in temperature variations. The variations had periods of 6 to 7, 10 to 12 and 18 to 20 yr, and these accounted for 50 % of general long-term trends.

Maximov (1952) explains the 6 to 7 yr cycle as the result of the free fluctuations (nutation) of the rotation pole of the earth. The free nutations of the pole have a period of 14 mo giving a maximal deformation force at these times. The period of the earth's rotation about the polar axis is 12 mo, thus a maximal force will be generated at a certain point on the earth when the forces coincide, which is once every 7 yr. This force is called the Pole Tide. After removing the 10 to 12 and 18 to 20-yr components, plots of the rotation pole radius-vector on the Greenwich Meridian against water temperature anomalies for 60 yr show remarkable agreement (r = 0.82) with a shift of 1 to 2 yr (Maximov et al., 1972). The scale of change due to this cycle was of the order ± 0.6 C°.

Similar 6 to 7 yr cycles occur in the Northern North Pacific Ocean, in mean sea level (Favorite and Ingraham, 1976); these were related to changed wind patterns, presumably with the same physical origin as Maximov's postulate.

The 10 to 12-yr cycle is one of the best known of all, the solar or sun-spot cycle. The 11-yr cycle has been traced back to 647 BC (Schove, 1965) and can be accurately predicted (Ottestad, 1979). The effect on the ocean is probably due to the fact that an increase in solar activity is accompanied by an increase in air pressure over high latitudes, whilst meridional pressure gradients decrease. This gives a breakdown in zonal atmospheric circulation and an intensification of meridional processes. Ultimately this leads to a strengthening of the N. Atlantic, Norwegian and E. Greenland currents and sea water temperature increases in the north and decreases in the south. The scale of change is around ± 0.2 C° (Maximov et al., 1972).

In addition to the 11-yr cycle there is a longer-term change in solar activity of 93 to 94 yr which also affects water temperature (Maximov, 1961; Waldemeier, 1961; Smirnov, 1967). From the beginning of this century to 1940, solar acitivity increased on this cycle giving an increased water temperature resulting from an intensification in the North Atlantic current flow and a less clear 11-yr trend over this period. Thus the whole North Atlantic Ocean was warm in the 1920–1930 period and colder in the '60s and '70s, especially in northern areas where a 1 C° change occurred.

The 18 to 20 yr-cycle is thought to be due to the long-term lunar tide (Pettersson, H., 1913; Pettersson, O., 1930; Maximov, 1959), with a period of 18.6 yr. The variations in the tidal force can be calculated accurately and can cause changes of ± 0.4 C° in mean temperatures (Maximov et al., 1972).

Thus we can expect that these cycles together will produce changes in the oceans. Maximov et al. (1972) have used 3 cycles (6 to 7, 11 and 18.6 yr) to predict long-term temperatures in the Faroe-Shetland Channel (Fig. 1). Predicted data agree well with observed data (r = 0.73). It is clear that there are no obvious cycles but that regular changes occur. However, underlying the data are clear cyclical variations.

In an analysis of salinity data from the European Shelf areas of the North Atlantic, Dickson (1971) found correlations between high salinity anomalies from the long-term mean and establishment of an anomalous athmospheric circulation pattern, the Namias pattern (Namias, 1965). This pattern leads to advective changes in the eastern Atlantic giving an influx of salt to shelf areas. This atmospheric change also influences the deep currents and the inflow of water into the Baltic. Whilst the pattern has a roughly 6 to 7-yr cycle, it is clear that other longer-period effects are confounding the patterns, and these may well be the 11, 19 and secular cycles discussed previously.

A further cyclical trend in North Atlantic data is a 3 to 4-yr cycle (Maximov and Smirnov, 1965). Colebrook and Taylor (1982) found a 3 to 4 and a 10 to 12-yr cycle in salinity-temperature data but the data were out of phase with each other in the 3 to 4 yr cycle. They related this cycle to changes in heat flux and evaporation under the influence of changes in the frequency of westerly weather.

Spectral analyses of salinity and temperature data taken from the Skagerrak at Torungen und Faerder

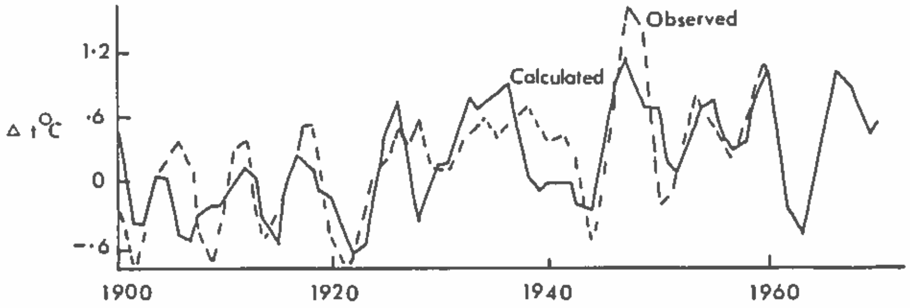

Fig. 1. Predicted and observed temperature anomalies over the Faeroe-Shetland ridge based on long-term cycles. (After Maximov et al., 1972)

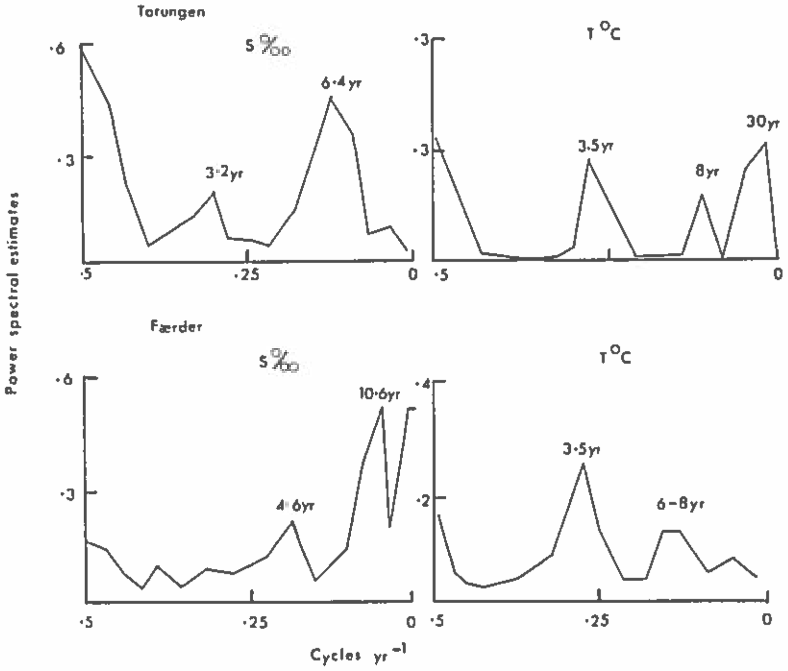

Fig. 2. Spectral analysis of temperature and salinity data from 2 stations in the Skagerrak (1960–1976). (Data provided by the Norwegian Oceanographic Data Centre)

from 1960 to 1976 show (Fig. 2) clear 3 to 4 and 6 to 8-yr cycles. The data do not cover a long enough period to show longer cycles with any degree of certainty.

Concluding from these data sets there are known cycles in hydrographic conditions (salinity and temperature) over 3 to 4, 6 to 7, 10 to 12 and 18 to 20-yr and 100 yr with direct physical causes. The first 3 cycles could, however, be simple harmonies of the 18 to 20-yr cycle, but this has not been tested. The cycles found must, however, influence the biology of the area affected.

CONSEQUENCE OF HYDROGRAPHIC CYCLES ON BENTHOS

One of the best long-term data sets in the marine environment is that of the Continuous Plankton Recorder (CPR). Colebrook and Taylor (1982) have analysed data on phyto- and zooplankton taxa from 1948–1980 and find evidence of cycles at 2 to 2.5, 3 to 3.6, 5 to 6.6, and 10 to 20 yr. The 2 to 2.5-yr cycle was explained as being due to interaction between the seasonal cycle and a longer cycle giving a beat-frequency at this wavelength. A simulation confirmed the interaction as the most likely cause of this cycle. Thus the clearly demonstrated hydrographic cycles also induce responses in phyto- and zooplankton. However, the latter, due to persistence of overwintering stocks, amplify the longer term wavelengths (Colebrook, 1981).

It is to be expected that known variations in hydrographic patterns (3 to 4, 6 to 7, 10 to 12 and 18 to 20-yr cycles) will lead to direct effects on the dominant members of the phyto- and zooplankton. Population growth rates and production feeding rates etc. will all alter as a direct response to temperature and salinity changes. With benthic communities one can expect delayed responses due to the time-lags in organisms feeding directly on plankton, to settlement of organic matter from the plankton which lead to alterations in feeding rates of deposit feeders and ultimately to changes in reproductive rates of the benthos. Yet the coupling between plankton and benthos is poorly known and response times cannot be predicted. Species living at depths of 100 m or more in the Skagerrak are remarkably stable over long-time periods (Josefsson, 1981). Organic matter settling from surface layers is presumably degraded en route to such depths and thus there are no clear cycles to be expected in response to the hydrographic changes demonstrated. Boesch and Rosenberg (1981) have noted that there is a direct correlation between habitat constancy in physiocochemical conditions and fluctuations in benthic populations; intertidal and shallow subtidal populations show large fluctuations in numbers and have variable environmental conditions whereas the fauna from depths below 100 m show narrow fluctuations in a more constant environment. Thus such deep populations are not to be recommended in a pollution monitoring context because they respond so slowly to environmental change.

Yet even at shallow depths not all species in a community show large fluctuations. Buchanan (pers.

comm.), examining populations of the burrowing decapod *Calocaris macandrae* from a muddy bottom at 90 m depth off the British east, coast found over a 10-yr period a density of 13.7 m^{-2} with a coefficient of variation of only 5 %. *C. macandrae* is territorial and presumably if one individual dies it is replaced, thus maintaining a constant density.

Constant numbers over time may also occur in species with slow growth and recruitment rates. Svane and Lundälv (1982) report the ascidian *Pyura tessulata* from subtidal hard substrata in the Gullmarfjord, Sweden, which has had at 2 sites almost constant numbers showing a slight decline over a 10-yr period.

The converse of the constant populations are opportunist species which with slight changes in the environment can rapidly respond by increasing population densities. In sediments the polychaete *Capitella capitata* can increase from 10 to over 400 000 m^{-2} in the course of a 6-wk period following disturbance of its habitat (Grassle and Grassle, 1974). In this species, colonisation of newly available habitat is rapid; the life-cycle is short and fecundity high, leading to the potential for rapid increases in population size. We know of no data linking fluctuations in numbers of individuals of species of opportunist to hydrographic cycles, but this could be possible.

In the Baltic Sea, there is a limited benthic fauna due to the low salinity; and in the Bothnian Sea, the amphipod *Pontoporeia affinis* is numerically highly dominant. This species was sampled over a large area of the Bothnian Sea at 19 stations with 5 to 10 grabs per station from 1961 to 1974 (Andersin et al., 1978).

Fig. 3 (and Fig. 4a) shows that a 7-yr sine curve fits the mean numbers almost perfectly. Whilst not over the same period, data for *P. affinis* from Askö in the Baltic Sea (Fig. 4b) and the south tip of Sweden at Hanö Bay

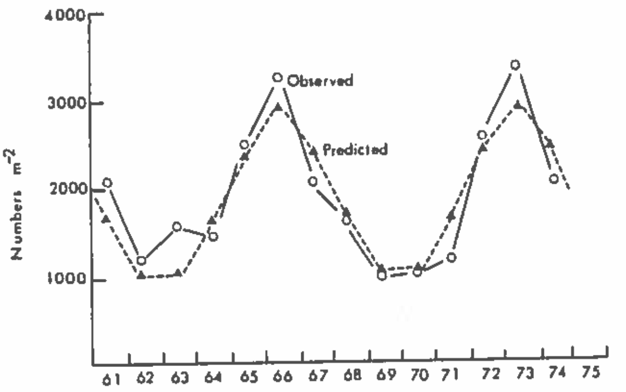

Fig. 3. *Pontoporeia affinis*. Variation in mean numbers in the Bothnian Sea, based on 19 stations and 5 to 10 grabs per station, and fitted sine curve with period of 7 yr. (Data from Andersin et al., 1978)

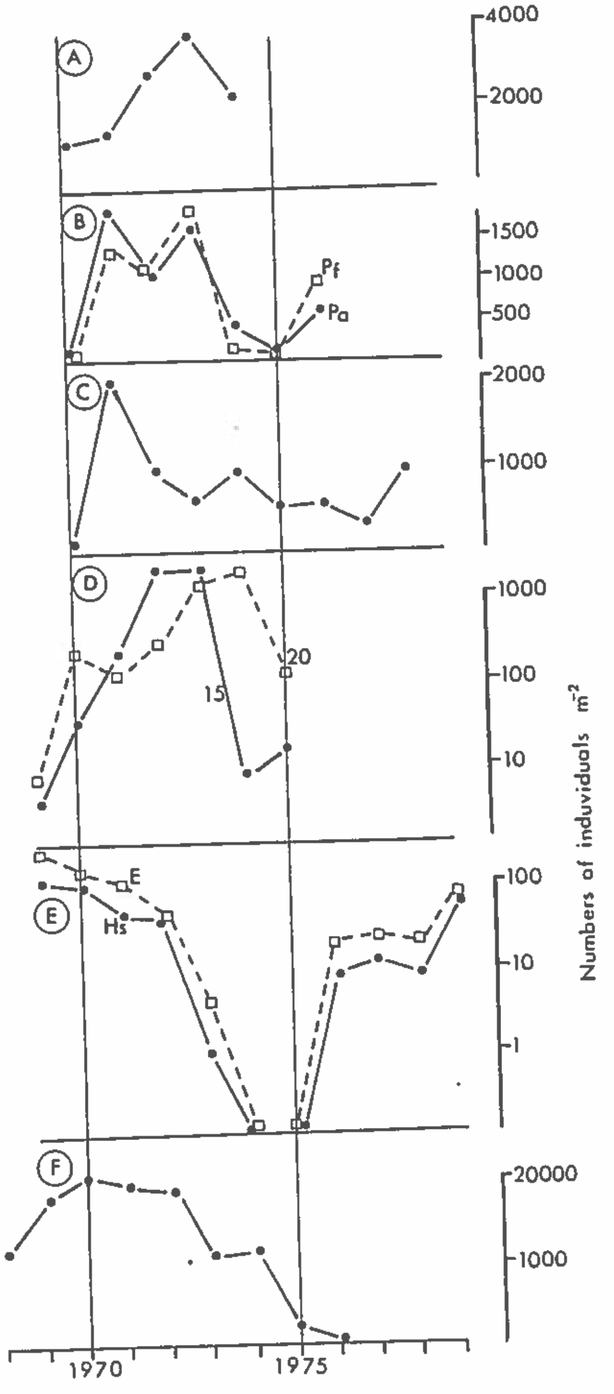

Fig. 4. Variations in numbers of benthic organisms. (a) *Pontoporeia affinis* in the Bothnian Sea. (Data from Andersin et al., 1978). (b) *P. femorata*, *P. affinis* at Askö, Sweden. (Data from Cederwall, unpubl.). (c) *P. affinis* in Hanö Bay, Sweden. (Data from L. E. Persson, unpubl.). (d) *Ciona intestinalis* in Gullmarfjord, Sweden, at 15 and 20 m depth. (Data from Lundälv, unpubl.). (e) *Harmothoe sarsi* and *Echiurus echiurus* in the German Bight. (Data from Rachor, 1980). (f) *Paronychocamptus nana* in an enclosed estuarine area, Belgium. (Data from Heip, 1980)

(Fig. 4c) show data with low values in 1970, high values in 1971–73 and a low in 1974–75 revealing approximate agreement with Bothnian Sea data with perhaps a slightly different period being earlier in Askö which is south of the Bothnian Sea.

Remarkably, other long-term data sets also show similar patterns: data on *Ciona intestinalis* at 2 stations in the Gullmarfjord (Fig. 4d): on *Harmothoe sarsi* and *Echiurus echiurus* (Fig. 4e) from the German Bight; and on the copepod *Paronychocamptus nana* from a lagoon on the Belgian coast (Fig. 4f). *Pontoporeia affinis* in the 3 areas and *C. intestinalis* show, in general, lows in 1969, 1970; highs in 1972–73; and a low again in 1974–76. This suggests a 6 to 7 yr cycle. The other pattern is highs in 1970 and lows in 1974–75, and highs again in 1979–80 with cycles more approaching 10 to 11 yr (perhaps *H. sarsi*, *E. echiurus* and *P. nana*). None of these data are of a long enough period to allow spectral analysis.

Off the N. E. coast of Britain, Buchanan et al. (1978) recorded a change in the composition of the benthos at 70 m depth in 1970 coincident with many of the changes above. Buchanan noted a sudden 1 C° rise over the long-term mean sea-water temperature in 1970. Thus the changes can probably be linked to the known cycles of salinity and temperature.

Walker (1956) has shown that the quantity and ratio of species of *Laminaria* around Scotland varied with an 11-yr cycle which he correlated with the sun-spot cycle. André (1970) has suggested that macroalgae in the Gulf of Gascony show a secular cycle with minima around the turn of the century and maxima around 1944–45 for *Fucus spiralis*, *F. ceranoides*, *Pelvetia canaliculata*. *F. vesiculosus*, *Ascophyllum nodosum* also show a change of range in tidal height, and *F. spiralis*, *F. vesiculosus*, *F. serratus*, *P. canaliculata*, and *Himanthalia elongata* changed their biogeographic range during the cycle. Further evidence of such cycles has been provided during the 17th Marine Biology Symposium at Brest, France (papers by Herman and Heip, Rees and Walker, and Eleftheriou and Basford, Océanologica Acta, in press). Table 1 summarizes the data.

Thus there is good evidence, albeit from a limited number of studies, that many benthic species do respond to long-term hydrographic cycles. It cannot be expected, however, that all species in a community will show such response. In a typical sediment community of 100 species only a few are opportunists, but their response is extremely short-term (weeks). There are probably 8 to 12 species of moderate abundance with numbers appropriate for statistical analysis, whereas the majority of the species (60 to 70 % usual) are rare with low abundance. Causes of rareness are many and probably can never be unequivocably explained, hence Gray and Pearson (1982) suggest objective methods for deciding on a suite of 8 to 12 responsive species which can be used in sedimentary monitoring programmes. Lewis (1976) has analysed extensively the criteria for isolation of species suitable for monitoring on rocky shores.

From these analyses one can suggest that there will be a number of species in most benthic communities which show responses to long-term hydrographic cycles. One cannot, however, expect that because a population has shown a regular cycle for one 7-yr period that it will continue to do so. Other long-term influences will be expected to influence the species.

In order to illustrate just the sorts of complexities to be expected, Ottestad (1979) has suggested that all time-dependent variables are affected by the energy emitted by the sun. He suggests that this energy stream can be described by a linear function of sine (at) and cosine (at), where a = 2 k/L; t = time; k = 1, 2, 3, etc. Based on analyses of many data sets, Ottestad maintains L is 4048 yr and all cycles are parts of this value. Thus, according to Ottestad, the sunspot species is made up of 11 components varying from 5.47 to 92 yr.

Table 1. Hydrographic cycles with examples of species showing similar cycles

Cycle (yrs)	Biological data	
3– 4	Zooplankton, N. Atlantic[1]:	*Canuella*, *Tachidius*, *Paronychocamptus*, Belgium[2]
6– 7	Zooplankton, N. Atlantic[1]:	*Pontoporeia*, Baltic[3]; *Ciona*, Skagerrak[4]; Bluecrab catch[5]; *Lanice*, *Abra*, *Scalibregma*, *Pectinaria*, Liverpool Bay[6]; *Amphiura*, Brittany[7]
10–12	Zooplankton, N. Atlantic[1]:	*Harmothoe*, *Echiurus*, N. Sea[8]; *Paronychocamptus*?, Belgium[9]; Blue crab catch[5]: Shrimp catch, Irish Sea[10]; *Laminaria*, Scotland[11]
18–20	Blue crab catch[5]	
100	Macroalgae, France[12]	

[1] Colebrook and Taylor (1982); [2] Herman and Heip (in press); [3] Andersin et al. (1978); [4] Lundälv (pers. comm.); [5] Hurt et al. (1979); [6] Rees and Walker (in press); [7] Aldana et al. (in press); [8] Rachor (1980); [9] Heip (1980); [10] Driver (1978); [11] Walker (1956); [12] André (1970)

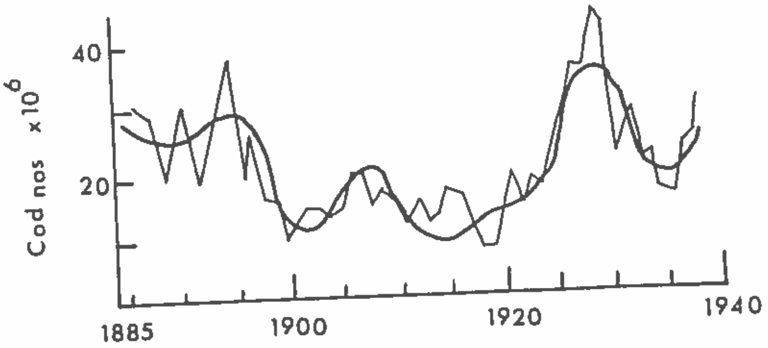

Fig. 5. Cod catch at the Lofoten fishery, Norway (jagged line) and pool curves of periodicities in widths of annual rings in pine trees in Vestfjord. (Data from Ottestad, 1942)

Ottestad (1942) has shown a most interesting comparison of the yield of cod in the Lofoten fishery and periodicities in the widths of annual rings in pine trees in the same region. Using the tree data, Ottestad fitted cycles of periods 57, 23, 17.5, and 11 yr each with different phases in any given year. The summed curves were fitted by least squares to the data on fish catches ($r = 0.84$); they are shown in Fig. 5. There is clear evidence, therefore, that climatic cycles affect trees and fish stocks in the same area. Similarly, Cushing (1972) has demonstrated that recruitment in the Arcto-Norwegian cod stock varies with changes in wind strength and direction between the Iceland low and the Azores high pressure areas.

Hurt et al. (1979) have shown by spectral analysis of blue crab landings for a 50-yr data set that cycles of 6.8, 8.6, 10.7 and 18 yr occur. The data are again in keeping with the periodicities of the known long-term hydrographic cycles. Based on these data, compound sine curves using all cycles were produced and predictions of the catch made. The data fitted the observations well and predictions of crab landings have been made up to 1990. Similarly Driver (1978) related catches of shrimp landings over a 10-yr period to the sunspot cycle and suggests the sun-spot number alone can be used to predict future catches. The danger is that longer-term cycles are not expected and the data may rapidly depart from prediction due to interference of such cycles. If Ottestad is correct and cycles in excess of 100 yr are to be expected then prediction of future trends in marine data becomes almost impossible.

A MONITORING STRATEGY

Yet we believe there are ways to overcome the difficulties. Our strategy is, having accurately established the annual cycle over a 3-yr period, to survey a wide area a few times per year only. Then if one site is out of phase with the cycles at the other sites further investigation is needed to establish whether or not this is a local pollution effect. Christie (in press) has shown the approach taken. The choice of community (and species) analysed is critical. We use an ascidian community on vertical subtidal hard substrata which shows similar faunal composition for the Swedish west and Norwegian south coasts in the Skagerrak. This community has been studied by Lundälv and Svane (1982) for over 10 yr in the Gullmarfjord and by us since 1978 (Christie, 1980), giving an extensive monitoring programme for the Skagerrak (Fig. 6). This is broadly similar to Lewis' (1976) rocky-shore monitoring scheme except that Lewis recommends study of factors affecting recruitment rather than population numbers.

Soft-sediment communities are more variable spatially over large areas than are the rock communities (Gray, 1981), and it is difficult to envisage a programme comparable to the above covering sediments. Here one possible strategy is to examine microgrowth bands in species of bivalves (Rhoads and Panella, 1970; Richardson et al., 1980) since on can retrospectively monitor changes in growth over short time intervals for periods of the length of life of the bivalves

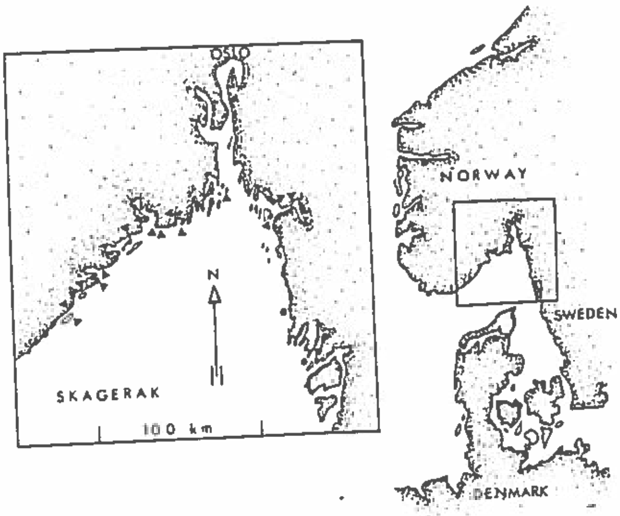

Fig. 6. Localities covered by sub-tidal hard-bottom monitoring programme in the Skagerrak. Arrows: Norwegian sites H. Christie UiOslo; dots: Swedish sites, T. Lundälv, Kristinebergs Marine Biological Station, Fiskebäckskil, Sweden

which is often in excess of 10-yr. It is, however, necessary to understand how the bands are established and the relationship to the annual gametogenetic cycle for interpretation of the bands. The bands are supposedly laid down in response to lunar cycles, but even species down at 30 m depth in the tideless Oslofjord have bands. Shallow depths were, earlier in this paper, suggested as being the areas where monitoring should be concentrated, and here microgrowth bands are found in many species. Here then is a sensitive technique that can be applied over spatial and temporal scales for retrospective monitoring.

In conclusion, predicting long-term changes in benthic communities is an unattainable goal due to the extremely long period cycles expected. Cycles may be apparent, but it cannot be expected that the cycle will be repeated since longer-term trends will interfere.

Acknowledgements. We thank the Norwegian Oceanographic Data Centre (NOD) for access to salinity and temperature data for the Skagerrak. We give special thanks to Thomas Lundälv, Ib Svane, Lars Erik Persson, and Hasse Cederwall for allowing us to use some of their unpublished data in Fig. 5. Åge Larsen ran the spectral analyses and we are grateful to him.

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This review was submitted to the editor; it was accepted for printing on April 20, 1983