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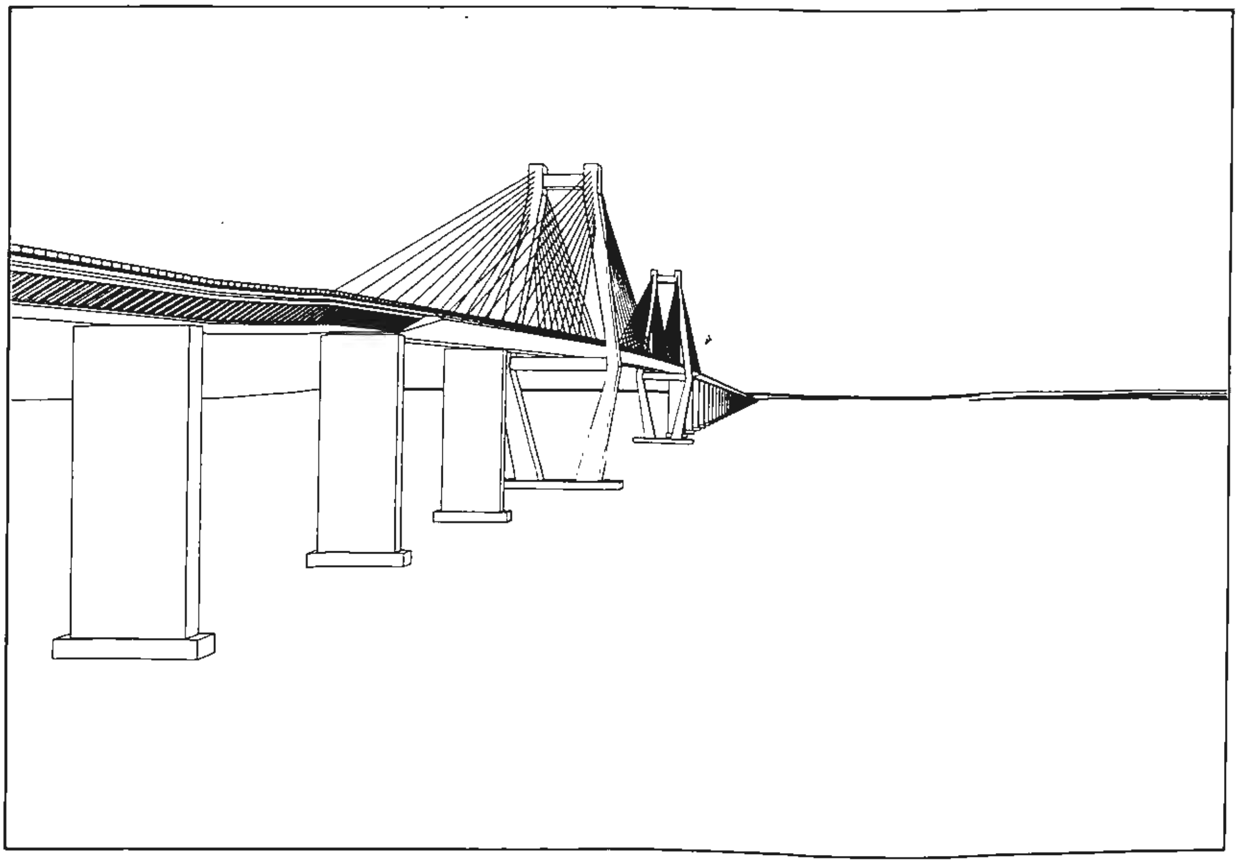

A PERMANENT TRAFFIC LINK ACROSS THE ÖRESUND CHANNEL

A study of the hydro–environmental effects in the Baltic Sea

SMHI / National Swedish Environmental Protection Board

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Summary

This report provides a summary of the calculated effects which a permanent bridge and tunnel connection between Malmö and Copenhagen could have on the exchange of water between the Baltic Sea and the North Sea. The calculations cover possible changes in the relatively uncommon yet vitally important inflows of saline deep sea water to the Baltic. The common exchanges of water with a lower salt content are not dealt with here, but have been included in the general overview in other ways.

The work has included:

a Intensive measurements of flow and salinity in the Öresund Channel with recording instruments. (SMHI)

b Computer simulation of a typical salt water through flow in the Öresund Channel with and without the presence of the proposed bridge/tunnel.

c Computer simulation of the oceanographic and biological conditions in the Baltic. The calculations cover a period of 100 years. Results for two such periods with or without a bridge/tunnel have been calculated. (SNV)

d Biological evaluation of the estimated effects of a bridge/tunnel (basic proposal) across the Öresund Channel. (SNV)

e Computer simulation of alternative bridge/tunnel designs which do not affect the salinity or oxygen balance of the Baltic. (SMHI)

A combined hydrodynamic and biochemical model has been used to study the effects of changed salt water inflow. The content of the model and the results have been discussed in an ecological reference group with representatives from the Board of Fisheries and the Askö Laboratory at the University of Stockholm.

The reduction of mean salinity which the model simulations predict in extreme cases would involve further danger for many marine species which already live at the limits of their distribution area. (fig. 13). The flora and fauna of the Baltic comprise marine species which can tolerate low salinity, and freshwater species which can tolerate salt water, plus a few species which live specifically in brackish water. The number of species would be drastically changed even with a small change in salinity.

The model simulations have not taken into consideration the changed water transports which planned bridges/tunnels in the Danish Belt Sea would cause. A final judgement on the ecological consequences of a bridge/tunnel across the Öresund Channel should also therefore include an estimation of the combined effects of all planned bridges and tunnels. In conclusion it must be stated that the design of the bridge/tunnel for the Öresund Channel in the basic proposal raises fears of considerable changes in the Baltic eco-system, mainly of a negative kind. Only so-called zero solution, which does not involve changes in the water exchange, would be acceptable.

Zero solution

A tunnel/bridge connection which does not negatively affect the ecological balance in the Baltic Sea can be designed. The criteria for such a solution (zero solution) are that the amounts and distributions of salt and oxygen in the Baltic Sea shall remain unchanged. This means that the quantities and distribution of water and salt through flows shall be unchanged by permanent traffic links.

A zero solution can be achieved through compensatory dredging above the tunnel and under the bridge to replace the loss of through flow area. The recess must be made so long that the slopes can be around 1:10 so that the velocities at the bottom will be high enough to allow for the same amounts as the bottom velocities outside the recess. In such a case, one need not fear serious sedimentation in the recess.

Fasta förbindelser över Öresund - effekter på vattenmiljön i Östersjön

Sammanfattning

Denna rapport sammanfattar resultaten av beräkningar av vilken inverkan en fast bro och tunnelförbindelse Malmö - Köpenhamn kan få för vattenutbytet mellan Östersjön och Västerhavet. Beräkningarna gäller eventuella förändringar av de relativt sällsynta men ändå ytterst viktiga inflödena av salt djupvatten till Östersjön. Den vanliga, mindre salthaltiga vattenutväxlingen har inte behandlats här utan tas med i helhetsbedömningen på annat sätt.

Arbetet har omfattat:

a Intensivmätningar av ström och salthalt i Östersjön med registrerande instrument. (SMHI)

b Simulering i dator av ett typiskt saltvatteninbrott genom Öresund med och utan fast förbindelse enligt grundförslaget till en fast förbindelse. (SMHI)

c Simulering i dator av oceanografisk/biologiska förhållanden i Östersjön. Beräkningarna omfattar 100 år. Resultat för två sådana perioder med och utan fast förbindelse enligt grundförslaget har tagits fram. (SNV)

d Biologisk utvärdering av beräknad påverkan av fast förbindelse (grundförslaget) över Öresund. (SNV)

e Simulering i dator av flera alternativa utformningar av bro/tunnel som inte påverkar Östersjöns salthalt eller syreförhållanden. (SMHI)

En kopplad hydrodynamisk - biogeokemisk modell har utnyttjats för att studera effekterna av ändrade saltvattensinflöden. Modellens utformning och resultaten har diskuterats i en ekologisk referensgrupp med representanter från Fiskeristyrelsen och Askölaboratoriet, Stockholms Universitet.

Den sänkning av medelsalthalten i Östersjön som modellsimuleringarna som sett extremfall förutsäger, skulle innebära en ytterligare stress för många marina arter som redan nu lever på gränsen för sina utbredningsområden. Östersjöns fauna och flora är sammansatt av dels marina arter som tål en låg salthalt, dels saltvattenstoleranta sötvattenarter, samt ett fåtal arter som är specifika för brackvattensmiljön. Artantalet förändras drastiskt även vid en liten förändring av salthalten.

Modellsimuleringarna har inte tagit hänsyn till de förändrade vattentransporter som planerade fasta förbindelser genom de danska bältsunden kan innebära. En slutlig bedömning av de ekologiska konsekvenserna av en fast förbindelse över Öresund bör därför även innefatta en uppskattning av den sammanlagda effekten av samtliga fasta förbindelser som planeras. Sammanfattningsvis kan sägas att den i grundförslaget planerade utformningen av den fasta förbindelsen i Öresund inger farhågor om betydande förändringar, huvudsakligen av negativ art, i Östersjöns ekologiska system. Endast en s k nollösning, som innebär att vattenutbytet inte förändras, är acceptabel.

en tunnel/broförbindelse som inte rubbar den ekologiska balansen i Östersjön kan konstrueras. Kriterierna för en sådan lösning (nollösning) är att mängderna och fördelningen av salt och syre i Östersjön skall vara oförändrade. Detta innebär att storleken och fördelningen av vatten- och saltgenomströmningen skall vara opåverkad av fasta trafikförbindelser.

En nollösning kan åstadkommas genom att man kompensationsmuddrar över tunneln och under bron för att ersätta förlorad genomströmningsarea. Gropen måste göras så lång att sluttningarna kan göras omkring 1:10 för att hastigheterna vid botten skall bli så höga att de får ungefär samma belopp som bottenhastigheterna utanför gropen. Om så blir fallet behöver man inte befara allvarlig sedimentation i gropen.

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Introduction

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The Öresund Channel

Hydrographical conditions in the Öresund Channel have been described in various contexts, such as earlier reports on the effects which a tunnel between Helsingborg and Helsingor would have on the water conditions in the channel. We shall therefore only give a short description to provide a background to the information which follows. Furthermore, we shall give a general description of the oceanography of the Baltic to provide a basis for discussions as to the possible effects of a bridge/tunnel between Malmö and Copenhagen.

River water enters the Baltic at a rate of approximately 450 kms per year. River water mixes with the sea water and causes an outflow of brackish Baltic Sea water of around 900 kms per year. Of this some 20-30% passes out via the Öresund Channel, flows being greatest in April and May and smallest in November.

Apart from precipitation and the inflow of fresh water from drainage areas, the Baltic receives an influx of salt water from the North Sea. The major influxes of water from the North Sea are momentary, intensive and of short duration. Salinity usually varies between 15-25 units. The inflow varies considerably from month to month and year to year. Inflow also varies considerably between different 20 year periods. Annual average flow for the period between 1900 and 1919 was 10% lower than for the following two decades.

The volume and intensity of the inflow from the North Sea depend on the prevailing weather conditions, on salinity and on the difference in water levels between the Baltic and the Kattegatt. Salt water inflow occurs in two ways: a frequent, slow moving deep sea flow produced by the horizontal salinity gradient between the Baltic and the North Sea - and a momentary and more intensive inflow caused by persitent westerly winds. The latter occurs chiefly in Autumn and Winter. The interval between major inflows of this type can be up to several years. However, these salt water influxes are of great importance to the ecological balance in the Baltic.

Earlier it was considered that salt water supply mainly came from the Great Belt. However, more recent studies show that the Öresund Channel with its more direct and shorter transportation route is of equal importance for salt water inflow. It is reasonable to assume in this context that the Öresund Channel provides up to 50% of the transport of extremely salt water to the Baltic.

Formation of the Bridge/Tunnel (Basic Proposal)

The direction of the bridge/tunnel is shown in fig. 1. (ref Forbindelse Köbenhavn-Malmö, Vägverket och Vejdirektoratet, notat juni 1985 samt Öresundsförbindelser Rapport av 1984 års danska och svenska Öresundsdelegationer Ds K 1985:7 juni 1985).

A road and railway follows a 1800 m damm and ramp from the Danish coast out into the Drogden channel to a 1600 m tunnel beneath the navigation channel. This is followed by a 1200 m ramp to a 5000 m low bridge and a 7500 m high bridge over the Flint and Trindel channels.

The bridge piers for the high bridge reduce the available cross section area by 8%. The corresponding figure for the low bridge is 9%. No space-demanding collision protection has been planned. It is considered that the sturdy piers (12 m in width) near the navigation channels will withstand collision. The damm and ramps at the tunnel have been blocked off for through flow in the calculations.

Field Measurements

In order to study the flow and layer pattern of the Öresund Channel, instruments were placed at three stations between Helsingborg and Helsingor. The surface flow (5 metres) and the bottom flow (20 metres) are recorded by the instruments, which also measure the salinity and temperature at these levels. At one station in the middle of the channel, near Lous Flak, the water temperature is continually measured at 11 levels from the sea bed to the surface.

Just south of Nordre Röse in the Drogden channel, flow, salinity and temperature are measured at 1 level in two stations between Kastrup and Saltholm.

In the Flint channel data is collected from the existing automatic measurement and registration device at Oskarsgrund, where data measurements are continually collected and sent via the telephone network to SMHI.

Flow and layer measurements in this area, on the Swedish side, are backed up by an instrument in the Trindel channel.

The research was carried out in the Öresund Channel during the period from 18 November 1986 - 10 January 1987, with a few minor exceptions. Owing to the extremely fast freeze-over, measurements at certain stations carried on into February, and in one case to the end of that month.

During the period from 25 November to 7 December 1986 there was a southerly flow in the channel with the exception of a few short interruptions. Water from Skagerrak-Kattegatt flowed through, and during five days in December a salinity of 25 units (0/00) at a depth of 6 metres was noted in the Drogden channel. We thus registered a salt water influx which can be used as a comparison for the calculations. The inflowing salt water raised the salinity west of Bornholm in the Arkona Basin from 13-14 units to 20-21 units on 14 December.
The temperature in the Öresund Channel fell rapidly after the New Year, and on 10 January a below zero temperature was recorded. A change in flow from north to south on 22 January provided high flow speeds for a few days and an inflow of salt water of 22-23 units. Salinity remained at a level of 18-19 units during the period up to the removal of the instruments in the beginning of February. This was another period of southerly flow.

The Model

Flow conditions in the Öresund Channel have been studied with the aid of a numerical model, PHOENICS. The channel has been divided into a large number of calculation volumes (see fig. 2).

The Navier Stokes equations have been solved for two phases; brackish water and salt water, which means that the channel has been considered as a two-layer system, where one layer can, for example, disappear at one end of the channel. For a description of the model, please refer to Funkqvist L., Gidhagen L., and Svensson, U. The mathematical modelling of baroclinic waves and fronts in the ocean. Appl. math. modelling, 1987, vol 11.

The model has been used to simulate a salt water influx through the Öresund Channel which is of the same nature as that registered by SMHI in the beginning of December 1986. The onset situation resembles that of an outflow where brackish water down to a depth of 12 m forms a layer over the salt water in the entire Öresund Channel. The inflow of water through the channel is generated by a water level rise of 30 cms in the Kattegatt incorporated in the model. The model simulation covers 6 days with constant high water in the Kattegatt without the bridge/tunnel and the same 6 days with the bridge/tunnel.

The model has also been used to simulate ten or so alternative bridge/tunnel designs. Tunnels of various length have been simulated, plus varying depths for the tunnel opening and under the bridge (zero solutions).

Results

A reduction in the cross-section surface of the bridge/tunnel cross-section reduces the inflow of salt water in two ways. The flow is obviously reduced by friction which means that salt water transports during a lengthy inflow are reduced. The increased friction also means that the brackish water which is to move back through the Drogden and Flint channels is slowed down, thus delaying the salt water penetration. A situation in which 100% of the salt water inflow is prevented by the bridge/tunnel is not impossible. If, say, under natural conditions, the inflow acts pulsatingly in two-day periods and if the salt water without a tunnel/bridge comes in past Drogden at the end of the second day, the salt flow can cease entirely if the tunnel/bridge delays the salt water transport so that no salt water passes Drogden before the flow returns to its northerly direction. Situations such as these are not common, but can serve as an example. The results from the model show that short (2 day) inflows are more affected than long ones.

Fig. 3 shows a picture of the lower salt layer after 2 days' inflow without a bridge/tunnel. The salt water has just reached Drogden, whereas the brackish water remains in the areas with weaker flows, e.g. Lundåkrabukten and around Saltholm. Fig. 4 shows the flow in the saline bottom water after 6 days' inflow. The extended part of the salt water in the figure has passed the threshold into the Baltic and cannot flow out again when the flow changes.

The reduced cross section area which the basic proposal for the bridge/tunnel involves would result in a reduction of salt water influx through the Öresund Channel. If it is considered that inflows through the Öresund Channel with southerly flows vary in time and have periods of 4-6 days, the reduction of inflowing salt water will be on average 17%. For much longer, very infrequent inflow periods the reduction will be less.

On its way from the Öresund Channel down to the Arkona Basin west of Bornholm, the penetrating salt water is mixed with the Baltic water which has a salinity of 8 units. The result from the example studied shows that the water coming in through the Öresund Channel, salinity 25 units, has been mixed to a lower salinity when it enters the Arkona Basin. When a small amount of salt water flows through the gap in a thin layer over the sea bed, the mixing becomes more noticeable and the inflowing water is more diluted by the fresh water. The bridge/tunnel reduction of the flow through the channel means that this dilution via fresh water would be somewhat greater on the way down to the deep basins of the Baltic.

The following table shows the amounts of salt water and the salinities which, according to the calculations, reach down into the deep basin west of Bornholm (Arkona Basin) during the studied salt influx.

Table

Amount of water into the Arkona Basin during the studied salt water influx through the Öresund Channel

	Öresund without bridge/tunnel		Öresund with bridge/tunnel		
	Water km^3/d	Salinity units	Water km^3/d	Salinity units	Volume change %
Day 1	0	--	0	--	--
Day 2	0.770	12.4	0.658	11.9	- 15
Day 3	2.008	16.9	1.857	16.4	- 8
Day 4	3.252	19.1	2.855	18.6	- 12
Day 5	4.543	20.5	3.924	19.9	- 14
Day 6	5.408	21.1	4.608	20.6	- 14

The Baltic Sea

The Baltic Sea is characterised by a unique ecological system which is extremely sensitive to change. This is because of the its low salinity, its limited water exchange and strong vertical layer formation, and also because of pollution. Increased amounts of nutrient salts have led to an increased biological production and sedimentation of organic material and an increased consumption of oxygen which has led to oxygen starvation in its deep basins. Even in coastal regions there is an increased amount of oxygen-free sea bed areas, and an increasing mass production of poisonous algae. The Baltic eco-system consists of a few, mainly marine species, which because of the low salinity live close to the limits of their distribution. The low salinity and the layer formations, with a permanent halocline at a depth of 65 m are maintained by a balance between the inflow of salt water through the Danish channels and the Öresund Channnel into the deep waters and a supply of fresh water and mixing in the surface waters.

The inflowing, salt and oxygen-rich water is mixed with the outflowing surface water from the Baltic and flows in under the halocline at various depths depending on its salinity. Only on rare occasions is the salinity so high that the water in the Baltic's deep basins is exchanged for more salty and oxygen enriched water. The last major salt water influx occured in 1977, and the Baltic's central deep basins are without oxygen from a depth of around 100 metres. Oxygen concentrations do not only affect the survival of marine fauna, but also the critical processes which control the conversion of nutrient salts in the eco-system. Changed salinity does not only affect the distribution of various plants, but also the transportation of oxygen and nutrient salts in the system.

Ecological Model for the Baltic Sea

A combined hydrodynamic and biochemical model has been used to study the effects of changed salt water inflow. The model has been developed in a joint project between the Askö Laboratory at the University of Stockholm and the Oceanographic Institute at the University of Gothenburg. It describes the physical transports and the biological processes which control the oxygen conditions and the production and breakdown of nitrogen pollution. Nitrogen is the nutrient salt (ammonium, nitrate) which largely controls biological production in the Baltic itself. The model has a high vertical resolution and describes the distribution of salt, temperatures, oxygen, organic nitrogen (in water and sediment), nitrate and ammonium in 1 metre layers from the surface to the bottom (0 - 250 metres). The model is one dimensional and describes mean values within each layer, and therefore cannot resolve the differences between coast and sea and various parts of the Baltic proper.

The model is described in more detail in Stigebrandt, A. & Wulff, F. (1987): A model for the dynamics of nutrients and oxygen in the Baltic proper (Journal of Marine Research, in perparation). The statistical effects of weather (wind, sunshine, temperature) are randomly introduced daily from breakdowns of monthly average values. The inflow of salt water (flow volume, salinity) are randomly introduced every 5 days according to an observed distribution function. By simulating development over a very long period, 100 years, it is possible to study the effects of both long-term changes and random combinations of inflow and weather conditions.

How is the "initial state" of the heavy bottom current in the Arkona Basin affected by a bridge/tunnel across the Öresund Channel?

In the model for the Baltic Sea (Stigebrandt and Wulff, 1987) the heavy bottom current gets its initial value (flow and salinity) in the Arkona basin. The heavy water in Arkona comes both from the Öresund Channel and the Belt sea. SMHI has calculated that the bridge/tunnel will reduce the inflow through the Öresund Channel by approx. 17% for water with a high salinity (> 20 units). On its way down to the Arkona Basin the heavy water is mixed with the surrounding Baltic sea water, reducing the salinity by approx. 5 units. With the bridge/tunnel, the salinity will be reduced by a further ½ unit, since there will be a smaller flow.

The Belt Sea also contributes to the heavy bottom flow in the Baltic. Calculations were based on daily salinity measurements from 1971 - 1973 from Drogden and Gedser Rev, plus calculated water level and density driven flows. Fig 5 shows that barely 40% of all water with a salinity of more than 20 units comes via the Öresund Channel, the diagonal area in fig. 4. The shaded areas show the contribution from the lower layers in the Belt Sea, while the unshaded areas show the contribution from the upper layers of the Belt Sea. For lower salinities the contribution from the Öresund Channel is considerably lower (fig. 5).

In the model it is assumed that the flow volumes through the Öresund Channel are reduced by 20% for salinities of over 20 units. Since the Öresund Channel (without a bridge) provides less than half of the high salinity inflows, the flow volumes for high salinities will be reduced by a maximum of 10% of the present flow. Water with a salinity of 20 units in the Belt and the Öresund Channel will have its salinity in Arkona reduced down to around 15 units because of mixing. All flow volumes with a salinity of over 15 units in Arkona will be reduced to 90%. Flow volumes with a salinity between 15- 20 (10 - 15 in Arkona is reduced to 95%, corresponding to a 25% contribution from the Öresund Channel in this salinity interval). This is probably an exaggeration: see the interval 15 - 20 units in fig. 5.

SMHI has estimated that the salinity of the water stored in the Arkona Basin which comes from the Öresund Channel will be reduced by ½ unit for Arkona saliniies in excess of approx. 15 units. This means a total reduction of 1/4 unit, since approx. half of the water comes from the Belt. For salinities in the interval of 10 - 15 units (in Arkona) the salinity is reduced in the model by 1/8 unit.

Results

Two model simulations have been carried out: one standard case where the model is governed by weather, water exchange and a nutrient salt load corresponding to present conditions, and one where the inflow function has been altered to correspond to the most extreme situation which could arise from a bridge/tunnel over the Öresund Channel (described above), yet with all other conditions corresponding to the standard case.

The reduced inflow through the Öresund Channel results in a reduction of deep water salinity within a few years (fig. 6 A). The two graphs are displaced in a parallel manner and show the same fluctuations depending on the salt water inflow to the deep water. The vertical water exchange eventually results (after approx. 10 years) in a reduction of the surface water salinity (fig. 6 B). A long term fluctuation dependant on the deep water salinity is clearly visible. The seasonal variation at the surface depends on fluctuations in fresh water supply and in the vertical exchange. The vertical salinity variation, based on mean monthly values for January over a period of 100 years (fig. 7 A) shows a reduction of salinity by 0.3 units above the halocline and by 0.6 units in the deep water (fig. 7 B). The vertical temperature distribution (fig. 8 A) shows a somewhat lower temperature (0.1 C) in the deep water (fig. 8 B).

The maximum depth of the halocline throughout the year has been lowered by approx. 0.5 - 1 metre during the 100 years, compared with the reference case (fig. 9). The vertical distribution of nitrate, based on mean monthly values for January (fig. 10 A) shows increased amounts around the halocline, max. approx. 0.6 mmol m^{-3} (fig. 10 B). However, the surface concentration has increased by less than 0.05 mmol m^{-3}. The oxygen concentration (fig. 11 A, B) shows a slight increase, max. approx. 0.15 ml at a depth of 75 metres.

Primary production of organic materials (fig. 12 A) and sedimentation through the halocline (fig 12 B) does show differences during the same year in both cases, but the mean values for the 100 years are identical.

Lack of oxygen and low salinity can influence the distribution of sensitive marine species, e.g. cod. The table below shows the number of months over the 100 year period when the salinity is higher than 10 units and the oygen content above 2, respectively 3 ml l^{-1}, based on observations from every 25th metre.

Salinity 0/00	Oxygen ml/1	Öresund without bridge/ tunnel	Öresund with bridge/ tunnel
> 10	2	1 622	1 155
> 10	3	395	357

Ecological conclusions for the Baltic Sea

The content of the model and the results have been discussed in an ecological reference group with representatives from the Board of Fisheries an the Askö Laboratory at the University of Stockholm. The model contains a description based upon present knowledge of the complex hydrodynamic and bio-geochemical processes which govern the salinity, oxygen and nitrogen balance in the Baltic Sea. The model can therefore be used for an approximative analysis of the large scale changes which an altered water exchange can involve. In its present form the model cannot reproduce regional differences and the possible effects on productivity which a changed group of species or conversion of phosphor can produce. Changes in salt and water balance can therefore be viewed with greater reliability than biological changes.

The reduction of mean salinity which the model simulations predict in extreme cases would involve further danger for many marine species which already live at the limits of their distribution area (fig. 13). The flora and fauna of the Baltic comprise marine species which can tolerate low salinity, and freshwater species which can tolerate salt water, plus a few species which live specifically in brackish water. The number of species would be drastically changed even with a small change in salinity. This relationship is schematically represented in fig. 14 which also shows the total number of species which require a minimum salinity of approx. 6 - 8 0/00, which corresponds to the surface salinity in the largest part of the Baltic proper, south of the Åland Sea.

The surface salinity and the northerly distribution limits for certain important marine species are shown in fig 13. Salinity is quickly reduced in the narrow entrances to the Baltic Sea, from around 20 0/00 in the Kattegatt to 8 0/00 in the Arkona Basin in the southern Baltic. This means that characteristic marine species such as starfish and crabs cannot establish themselves in the Baltic Sea. Other species which tolerate lower salinities can penetrate farther north. Differences in salinity inside the Baltic are very small. This means that a reduction of surface salinity by only 5% (0.3 0/00) leads to a move southwards of the highest surface salinity by up to 100 - 200 kms. In the salinity gradient from the southern Baltic to the Bay of Bothnia there is a gradual reduction of the number of species, the size and the biomass (the total number of organisms expressed in weight or volume units) inside the various ecological communities. The increase in number of species at low salinities (as per fig. 14) only occurs in shallow areas where the importance of insect larvae increases. The natural long-term salinity variation in the Baltic is of the same order of magnitude that the Öresund bridge/tunnel would involve, but both the mean and extreme values are systematically lower. Knowledge of the changes in structure of the eco-system along the salinity gradient and those changes which have taken place in connection with natural variations can be used when judging the consequences of a systematic reduction of salinity. However, this judgement must take into consideration the fact that variations do not only depend on salinity but also on differences in climate and productivity. The northern basin (the Bay of Bothnia) is a system low in nutrients with a vegetation period of 4-5 months, where there is limited access to phosphor for biological production, but the southern Baltic is a system rich in nutrients, limited in nitrogen, with a vegetation period which is twice as long.

The distribution of commercially important species such as plaice, dab and turbot would be moved farther south in the Baltic proper. The lower salinity would favour certain species such as the bleak which is now limited to the northern part of the Bay of Bothnia, whereas salmon and trout fishing would not be affected. Fishing in the Baltic is completely dominated by three marine species: cod, Baltic herring and sprats. Baltic herrings can spawn in almost all parts of the Baltic, from approx. 3 0/00 salinity in the northern part of the Bay of Bothnia. Sprats spawn from the Åland Sea and southwards, since the eggs require more than 5 0/00 to survive. Cod are occasionally found in the Bay of Bothnia, but can only spawn successfully in salinities of over 10 0/00. This can only take place in the deep waters of the Arkona, Bornholm and Gotland Basins of the southern Baltic.

The model simulations do not predict any decisive differences in the Baltic's productivity, nor its oxygen or nitrogen status. The effects of the Öresund Channel bridge/tunnel on the vertical exchange and inflow of nutrient salts and oxygen are small. On the other hand, a reduction of salinity involves a further limitation of water volume in the Baltic which shows the combination of high salinity and good oxygen supply necessary for cod reproduction. This volume is already greatly limited by the low oxygen content of the deep salt water. The model simulations show that possibilities for cod reproduction are reduced. The cod is, together with man, the most important predator (consumer) of the Baltic herring and sprat. A changed supply of cod therefore affects the fishing of all three species. The Swedish fishing industry is largely based upon the fishing of cod.

In the nutritive network of the Baltic there are many other marine species which are food organisms, e.g. small mussels, shellfish and fish. A reduced salinity involves a movement of species groups and altered competitive relationships. A reduced number of species, individual size and total biomasses can mean that access to foodstuff for commercially important species is changed.

Bladder wrack forms characteristic belts of brown algae on shallow, hard beds in the entire Baltic Sea proper, but only occurs as dwarf examples at greater depths in its most northerly distribution limit in the Sea of Bothnia. The bladder wrack belt provides protection and food for many organisms, and is the part of the Baltic richest in species. The most northerly limit for the continuous bladder wrack belt would be moved southwards some 100 kms or so if the salinity were reduced in the way which the model simulation indicates. This could, for example, mean that the continuous bladder wrack belt in the Stockholm Archipelago would be reduced, thus also reducing the rich animal life dependant on this environment. The deeper-lying belt of red algae with its rich fish-life is even more sensitive to a reduction in salinity. This would mean a reduction in coastal fishing and also a reduction in the value of the coastal zones as recreational areas.

Marine mussels (blue mussels and Baltic mussels) are not present in the Bay of Bothnia, where microscopic sea bed fauna, of little value as foodstuff, are dominant. Most mussels are water filterers, effectively converting organic material to potential fish food and nutrient salts. Sea birds such as eider and long-tailed duck are entirely dependant of the abundant blue mussel banks
in the Baltic proper. As is the case with most other marine species, mussels are more scarce in the areas of the Baltic with fresher water compared to a marine environment, but are extensive on all suitable sea beds, since their main predators in the Kattegatt and Skagerrak are not present in the Baltic. To move them further south would thus mean a reduction in the production capacity of the Baltic.

Qualitative changes in plankton communities cannot be ruled out. The distribution of jelly-fish would decrease, but the probability that poisonous blue-green algae would bloom in the southern Baltic is increased by the lower salinity.

The model simulations have not taken into consideration the changed water transports which planned bridges/tunnels in the Danish Belt Sea would cause. A final judgement on the ecological consequences of a bridge/tunnel across the Öresund Channel should also therefore include an estimation of the combined effects of all planned bridges and tunnels. In conclusion it must be stated that the design of the bridge/tunnel for the Öresund Channel in the basic proposal raises fears of considerable changes in the Baltic eco-system, mainly of a negative kind. Only so-called zero solution, which does not involve changes in the water exchange, would be acceptable.

Zero solution

A tunnel/bridge connection which does not negatively affect the ecological balance in the Baltic Sea can be designed. The criteria for such a solution (zero solution) are that the amounts and distributions of salt and oxygen in the Baltic Sea shall remain unchanged. This means that the quantities and distribution of water and salt through flows shall be unchanged by permanent traffic links.

A zero solution can be achieved through compensatory dredging above the tunnel and under the bridge to replace the loss of through flow area. If the bridge piers are sturdy and fitted with protection against collision, and if long damms are created in the vicinity of the tunnel, the necessary compensation dredging will be extensive. Less compensation dredging would be needed if the tunnel were laid under the sea bed and the ramp to the bridge placed in shallow water on the lee flow side of Saltholm. SMHI has studied a large number of such alternative zero solutions in the numerical model. An example of this is shown in figs. 15 A and B, which shows water level when a bridge/tunnel is introduced into the model. The transports southwards through the Öresund Channel are the same as in the natural case. This has been achieved in the model by an area of increased depth over the tunnel and under the bridge. In the appendix there are examples of other zero solutions.

Dredging to provide unchanged through flow

The efficiency of an increased depth above the tunnel or under the bridge is linked to the possibility for the water to flow umimpaired through this extra cross-section area. If the excavation is made too steep, the water will flow past and over it. Sand and seaweed will amass in the recess and it will not fullfil its function. SMHI has therefore produced a model study to test various forms for compensation dredging in order to clarify, for example, how steep such a recess should be for it to serve its purpose. If the water penetrates the recess, it performs its function as an extra through flow area and the need for maintenance dredging subsides. A discussion of the calculation results is given in appendix 2.

If the slopes down to the recess are too steep, e.g. 1:2, an eddy in will form in the recess, and there will be a relatively weak flow near the bottom. If the slopes are less steep, e.g. 1:12, there will be no eddy and the water will be able to penetrate the recess. The recess must be made so long that the slopes can be around 1:10 so that the velocities at the bottom will be high enough to allow for the same amounts as the bottom velocities outside the recess. In such a case, one need not fear serious sedimentation in the recess.

PERMANENT TRAFFIC LINK ACROSS THE ÖRESUND CHANNEL - ALTERNATIVE ZERO SOLUTIONS

To study various formations of a bridge/tunnel across the Öresund Channel SMHI has devised a numerical model for the Drogden-Flint channel.

Alternative 1, the first study, is identical with Liconsult's drawing no. 112, i.e. a tunnel in Drogden 1600 m long, where the water depth above the tunnel has been dredged to 15 m. The ramp to the bridge is around 2 kms long. The bridge piers under the bridge are compensated by dredging on the Swedish side, deepening 5000*200 m^2 by 1/2 m.

Alt. 1 is compared to the flow conditions which exist under "natural" conditions, without the permanent traffic link. The transport of water is without the bridge tunnel in the example 45.6*10^3 m^3 /s.

If we only place the bridge in the model and increase the depth by 1/2 m the calculated water transport will be 45.9*10^3 m^3 /s. This constitutes a zero solution. This bridge alternative is used in all the following examples. The amount to be dredged is 0.5*10^6 m^3 .

If we also put in a tunnel with ramps, the flow patterns and water level will correspond to figs. 15. According to calculations, water through flow will be 45.7*10^3 m^3 /s. Thus Alternative 1 is a zero solution. The amount to be dredged above the tunnel will be 9.9*10^6 m^3. The total dredged as per Alternative 1 will be 10.4*10^6 m^3 .

Alternative 2 involves lengthening the tunnel to 2100 m so that the ramp to the bridge is situated in relatively shallow water, leaving the deeper parts of the Drogden channel free for through flow. On the Danish side, the fill-in will extend 100 m farther into the channel. The ramp length is the same (around 2 kms). The proposed dredging allows for a depth of 13 m over the tunnel. In the example, the through flow in the channel will be 46.1*10^3 m^3 /s. Thus Alternative 2 is a zero solution. The total dredged as per Alternative 2 will be 7.4*10^6 m^3 .

Alternative 3 involves the tunnel starting at the same place as in Alternative 2, but in a slightly more northerly direction. In this way the tunnel would go almost at right angles across the Drogden channel in a section where the channel is deeper than in the original position. If the tunnel is constucted so that there is a water depth of 12 m above it, there is no need for extensive dredging since the natural depth in part of the cross section is already 12 m. The tunnel will be 2000 m long, with the ramp placed in shallow water. In the example, the through flow will be $45.7*10^3$ m^3 /s. Thus Alternative 3 is a zero solution. The total dredged as per Alternative 3 is $3.1*10^6$ m^3 .

The calculated amounts to be dredged have been worked out from the depth given in the sea charts, bearing in mind that the figures given in the charts often refer to single shallow areas. The estimated amounts can therfore be considered as realistic.

MODEL SIMULATION OF SEDIMENTATION IN DEEPENED DROGDEN CHANNEL

Background

A permanent traffic link across the Öresund Channel reduces the cross section of the channel through the construction of road banks, ramps for the tunnel, bridge piers, etc. Through deepening certain areas in the channel its barotropic transport capacity (i.e. transport capacity irrespective of salinity) would be maintained. One of the so-called zero solution alternatives involves dredging an area of the Drogden channel, above the planned tunnel. It is theoretically possible to calculate the amount which must be dredged by assuming the need to maintain the same cross section surface across the main flow direction. So as to avoid the risk of the excavation immediately becoming filled with sediment and of erosion of its edges, the edges of the recess should be formed in a special way. The risk for sedimentation is greatest at the upstream edge, but since the flow alternates between two main directions, the recess edges should be formed symetrically. This study is an attempt to describe how different inclinations of the upstream edge of the recess (plus varying recess lengths) affect flow and the sedimentation processes.

Model scenario

The Drogden channel is modelled by a 10 metre-deep and 1.5 km long channel, in which a length of 350 metres would be dredged to a depth of 15 metres.
Four inclinations are analysed: 1:2, 1:4, 1:8 and 1:12.
Increasing the depth by 5 metres is assumed to take place at 10, 20, 40 and 60 metres in a horizontal direction.

A channel flow profile is established upstream of the recess, with the highest speed at the surface and a slow reduction down to a depth near the bottom. Close to the bottom, the speed quickly falls towards zero. A gentle transition to deeper water reduces the speed in proportion to the increase in the cross section area, but the profile is maintained. If the inclination is great, an eddy can form in the lee of the upstream edge (see fig. 2/1). Heavy turbulence develops at the edge, spreading downstream. In the final section of the recess the flow returns to channel flow form, provided that the recess is sufficiently long.

Note that the simulation of velocities is based on the provision that the width of the channel is kept constant, in order to facilitate interpretation of the data. If the width is reduced at the same time as the depth is increased, speed reduction is avoided; but turbulence generation naturally remains.

The bottom is assumed to consist of hard and smooth material, such as limestone and glacial deposits. The choice of suspended material to be transported in over the recess is not obvious. Since flow speeds in the area are so high it is reasonable to assume that relatively large particles arein suspension, e.g. fine sand with a diameter of 0.1 mm. Sinking speed for these particles is approx. 1 cm/s (Bagnold, 1966).

The suspended material is simulated as a number of particles released and evenly distributed in a water column upstream of the recess. After a short stretch the particles are brought in line with the prevailing speed and turbulence conditions. High speeds and high turbulence cause the particles to whirl in the entire water column, whereas low flow speeds and slight turbulence cause them to be transported along the bottom. If the speed near the bottom is sufficiently low, the material forms a sediment. The calculations have been made based on four different surface flow speeds: 0.5, 0.8 1.1 and 1.4 m/s.

A flow direction change has been simulated by allowing a flow of 0.8 m/s in the opposite direction to act on the particles which have been deposited in the recess.

Model description

Simulation of the sedimentation process takes place in two stages: Firstly, the hydrodynamic quantities are calculated as velocity and turbulence parameters with the aid of PHOENICS. PHOENICS is used by SMHI for all types of flow problems. It is well suited to the present case (no stratification, constant forcing). For more details, see table 1.

Thereafter a number of particles are spread out with the aid of the calculated flow and influenced by the turbulence and sinking speed. The model has been developed by SMHI and is further described in Rahm-Svensson (1987). The particles in question are able to form a sediment if the friction speed falls below 1 cm/s (Dyer 1986). For more details, see table 1.

Results and Discussion

A section from two given flow fields is reproduced in fig. 1. An eddy is formed in the upstream edge of the recess if the inclination is as much as 1:2.

Fig. 2/2 shows trajectories of 5 particles. The upper figure shows how the particles are transported along the bottom at low velocity, becoming deposited in the recess. At a higher velocity (lower figure) more turbulence is generated and the particles have a chance of remaining in suspension. In this way, some particles avoid becoming deposited in the recess.

Fig. 2/3 shows a time sequence for a model simulation. The critical area where sedimentation is possible is concentrated here to the lower corner of the upstream edge.

Fig. 2/4 represents an attempt to summarise the risk for sedimentation at various velocities and inclinations. It is fairly certain that further runs at low velocity (0.5 m/s) with 1:4 and 1:8 inclinations would have resulted in 100% sedimentation. It is worth noting that velocities around 0.8 m/s with 1:4 and 1:8 inclinations show more tendency towards sedimentation than a 1:2 inclination. It is obvious that such heavy turbulence generated at the recess edge causes many particles to flow past the critical area. For the slightest inclination (1:12) sedimentation ceases to occur at 0.8 m/s.

Using those sedimentation divisions which resulted at 0.8 m/s as a starting point, attempts have been made to reverse the flow whilst maintaining its strength. Eddy and turbulence generation at the downstream end of the recess are less than at the upstream edge. The result shows that a 1:2 inclination reduced the number of sedimented particles from 23 to 18%, i.e. a flow reversal give rise to a very small degree of re-suspension. The effect is greater for a 1:4 inclination, where the majority are re-suspended (from 71 to 4%). For a 1:8 inclination, all sedimented material is re-suspended.

There is a temptation to arrive at a conclusion from fig. 2/4 that a steep inclination of 1:2 would involve relatively little risk for sedimentation problems. However, the risk is that erosion and the sedimentation which will in any case occur (see, for example, top left in fig. 2/4) would alter the inclination to something in the region of 1:4, in which case conditions would soon worsen. For angles of inclination as great as 1:2, a reverse flow does lead to re-suspension of already sedimented material.

According to SMHI's measurements from early winter 1986, velocities in the area are in the order of 0.5 - 1.0 m/s, with shorter periods when the velocity rises to 1.5 m/s. To prevent suspended material from forming sediment in the recess, the edges of the recess should be formed at an inclination of around 1:12.

This study should be seen as a pilot study. When the bridge/tunnel designs are complete, it will be possible to study sedimentation risks in a three dimensional perspective. A future study should also include time-based variations in flow.

References

Bagnold, R. A. (1966) "Mechanics of marine sedimentation" The Sea, ed. Hill, M N John Wiley and Sons, New Yourk

Dyer, K. R. (1986) "Coastal and estuarine sediment dynamics" John Wiley and Sons

Rahm, L. and Svensson U. (1987) "Dispersion of marked fluid elements from a bottom source within a turbulent channel flow" Submitted to J. of Coastal Eng.

TABEL 1

Hydrodynamic model

Computed variables:	* v, w	velocity components in Y and Z directions
	* k	kinetic energy
	* ε	energy dissipation (exchange coefficient for momentum is compared from k, ε)
Computational grid:	* channel with length = 1 540 m, depth = 10 - 15 m * 750 computational points, with a minimum resolution of 1 m in Y direction (at the resess) and 5 m in Z direction (at the bottom)	
Forcing:	* defined (constant in time) uppstream velocity profile with surface current in the interval 0.5 - 1.4 m/s	
Bottom boundary value:	* logaritmic wall layer	

Disepersion model

Partical movements:

- Markov chain:

$$w'_{n+1} = a_n w'_n + b_n \sigma_w + c_n$$

Where n = time step

w' = turbulent (vertical) velocity

σ_w = velocity variance

a_n, b_n, c_n = time- and space dependent amplitude functions

a_n governs the memory

b_n includes a stocastic vaiable

c_n includes a korrection term for non homogenius turbulence

Particle characteristic:

- diameter (d) = 0.1 mm
- sinking velocity = 1 cm s^{-1}
- particle Reynolds number:

$$\frac{u_* \cdot d}{\nu} < 2$$

Where u_* = friction velocity

ν = kinematic viscosity

- resuspension condition: $u_* > 1$ cm s^{-1}

Time step: 1 second

Number of particles: 100

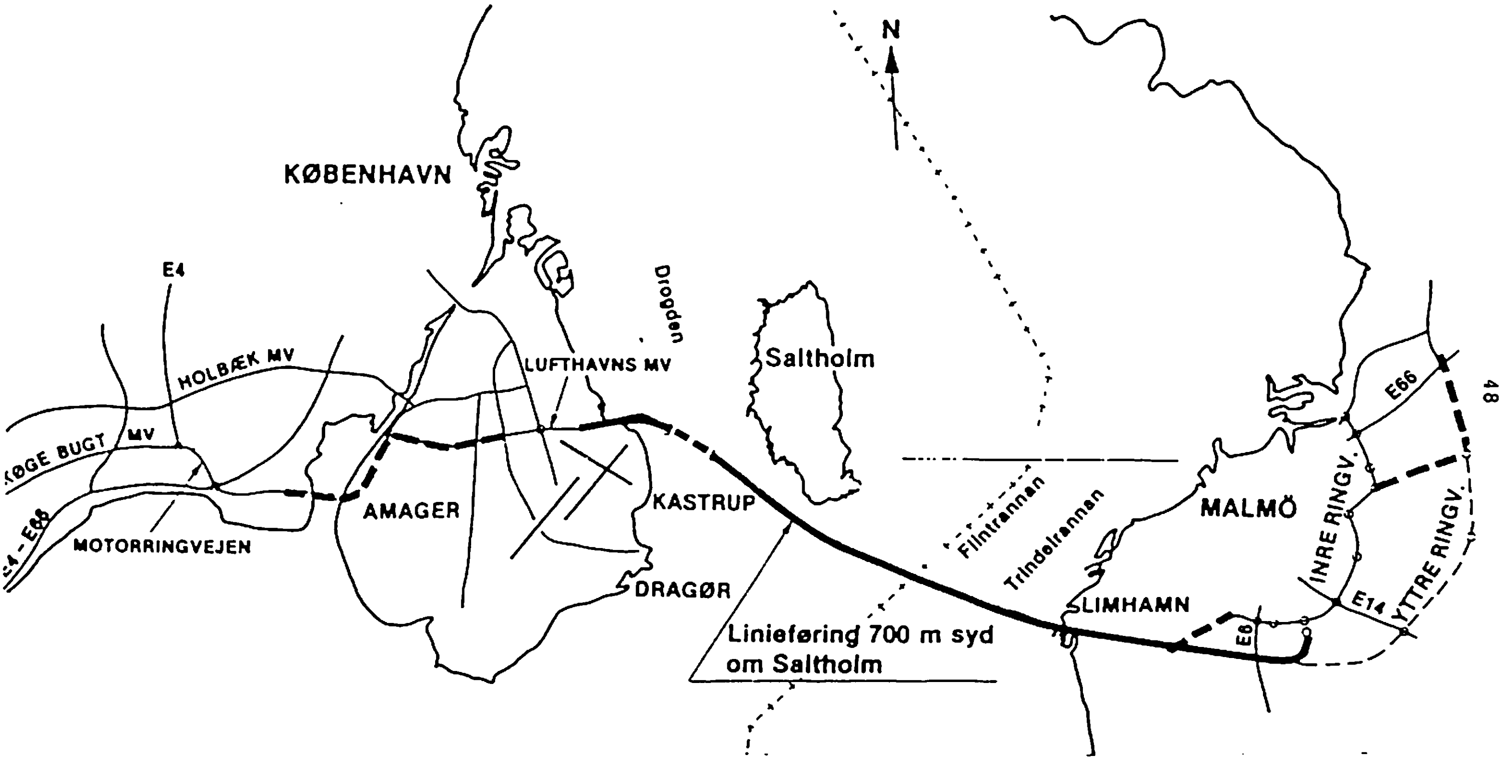


Figure 1. Bridge / tunnel position

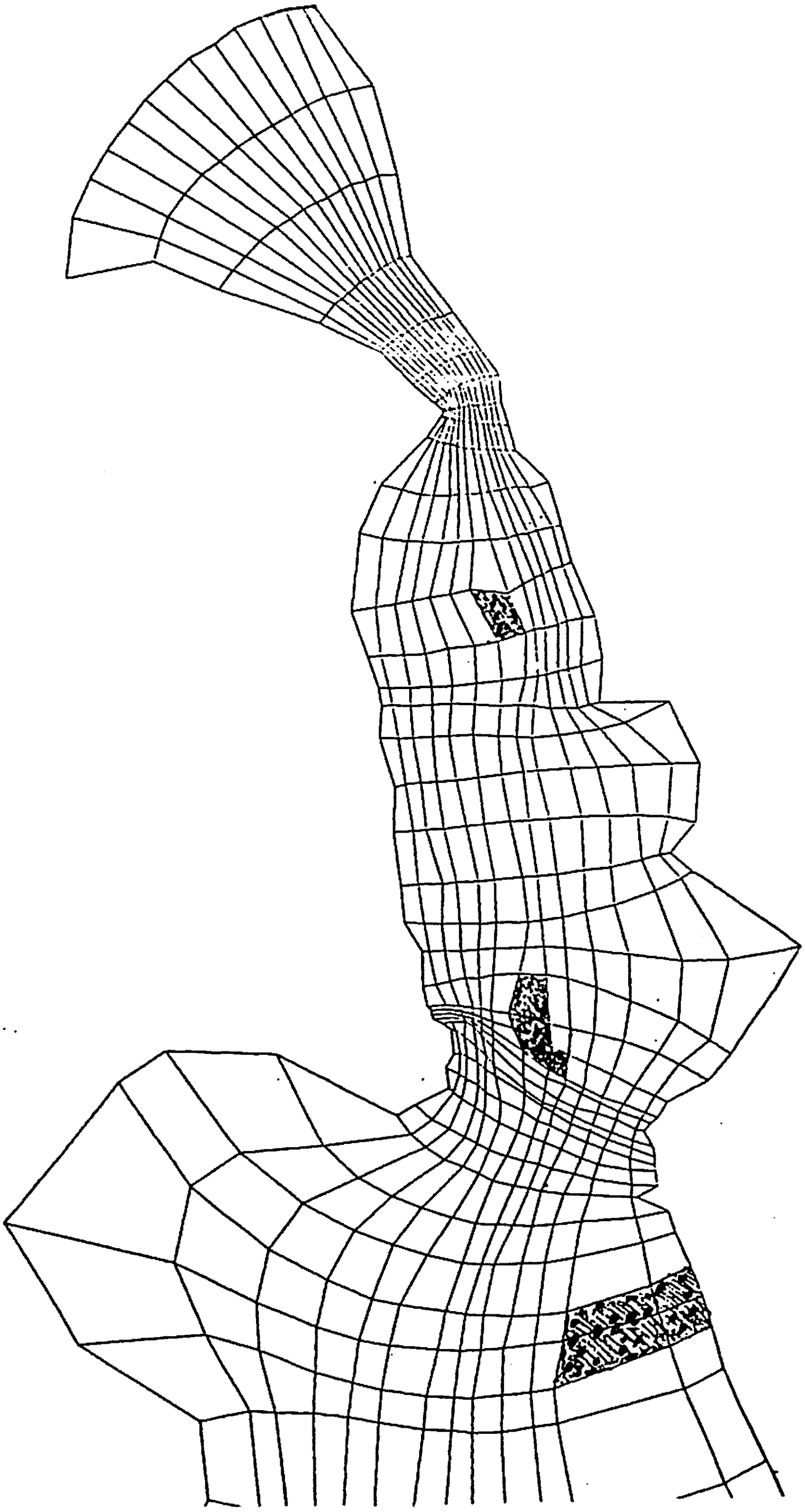


Figure 2. Division in calculation volume for studies of flow conditions in the Öresund Channel

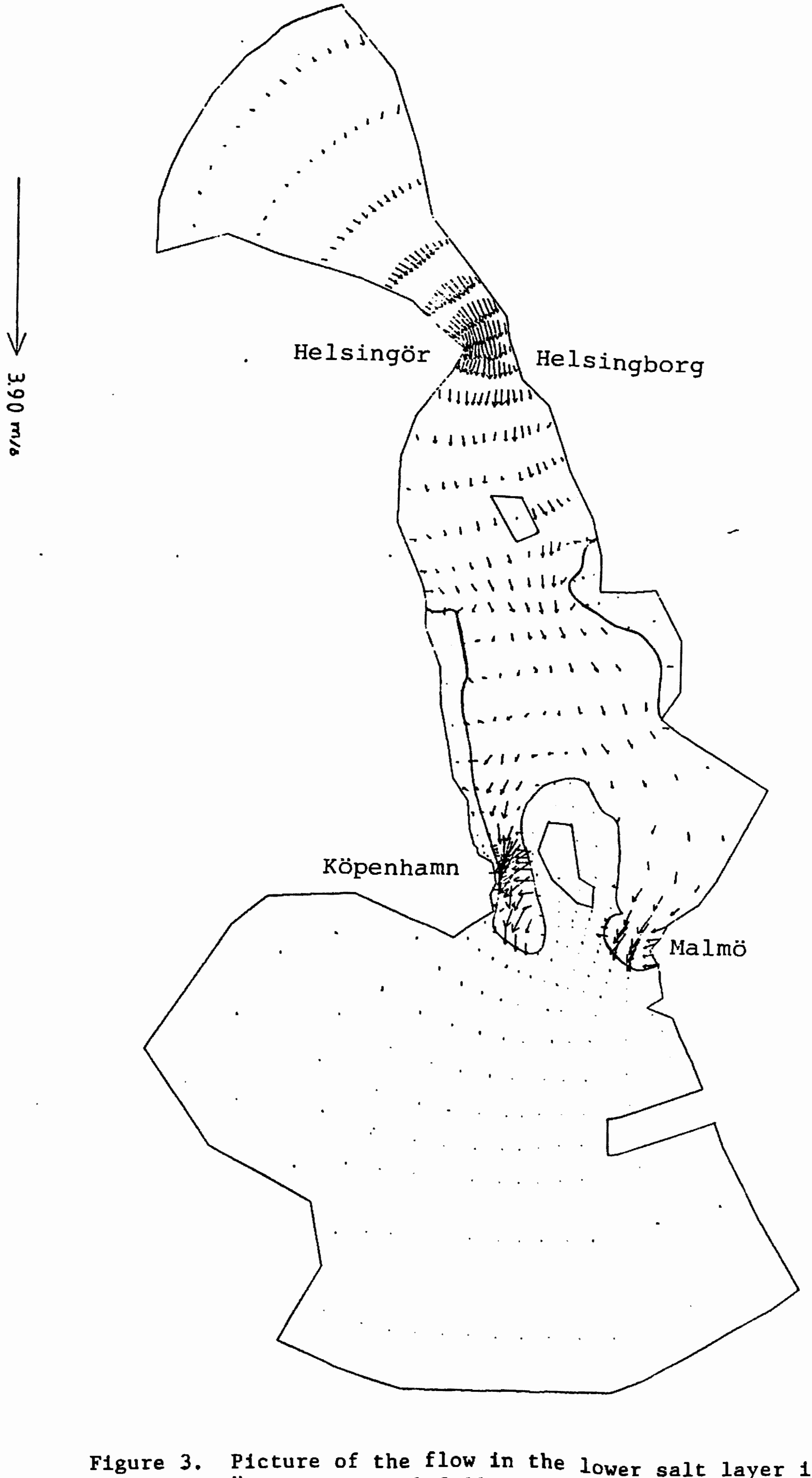


Figure 3. Picture of the flow in the lower salt layer in the Öresund Channel following 2 days' inflow without bridge/tunnel

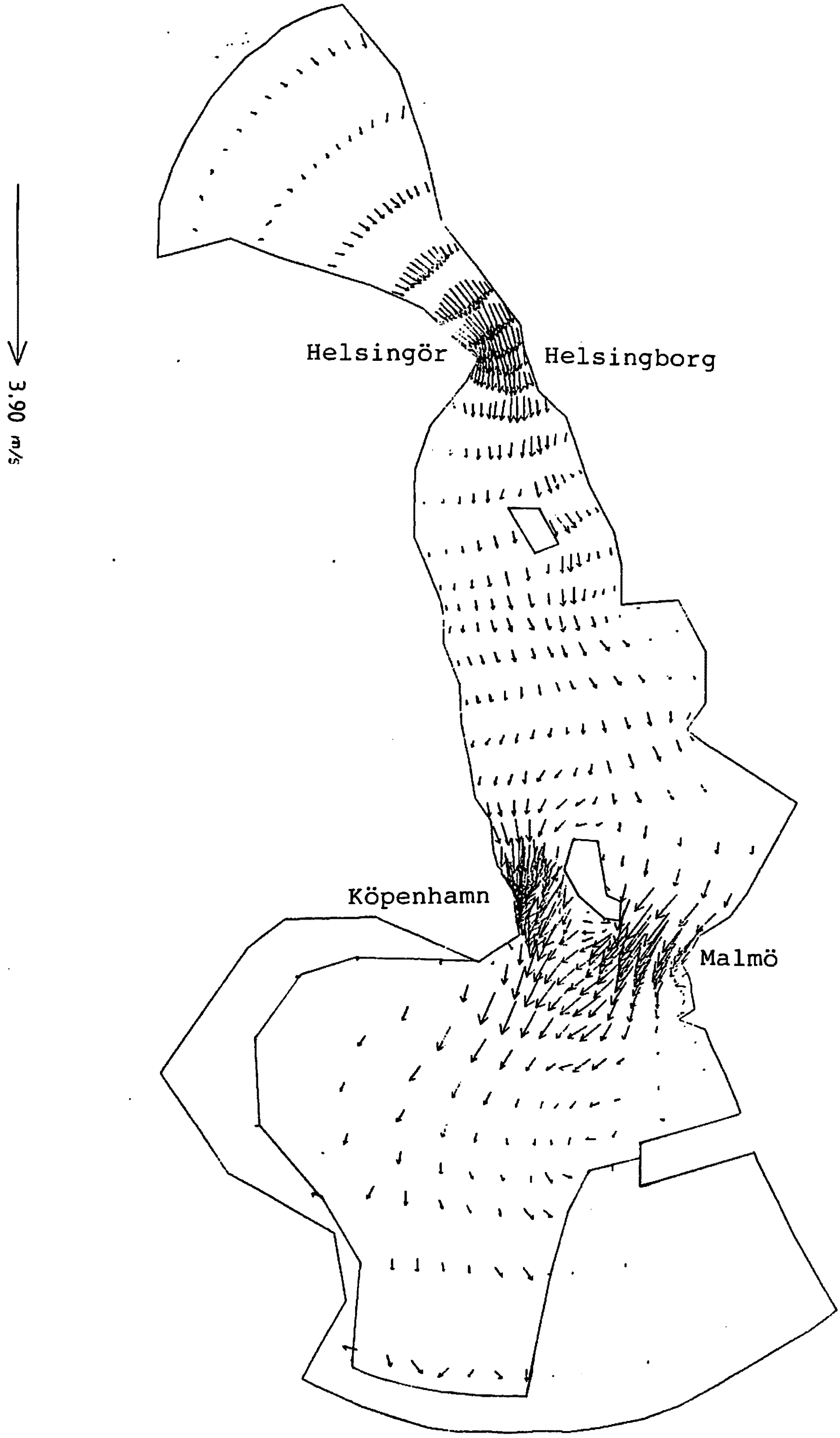


Figure 4. of the flow in the lower salt layer in the Öresund Channel after 6 days' inflow without bridge / tunnel

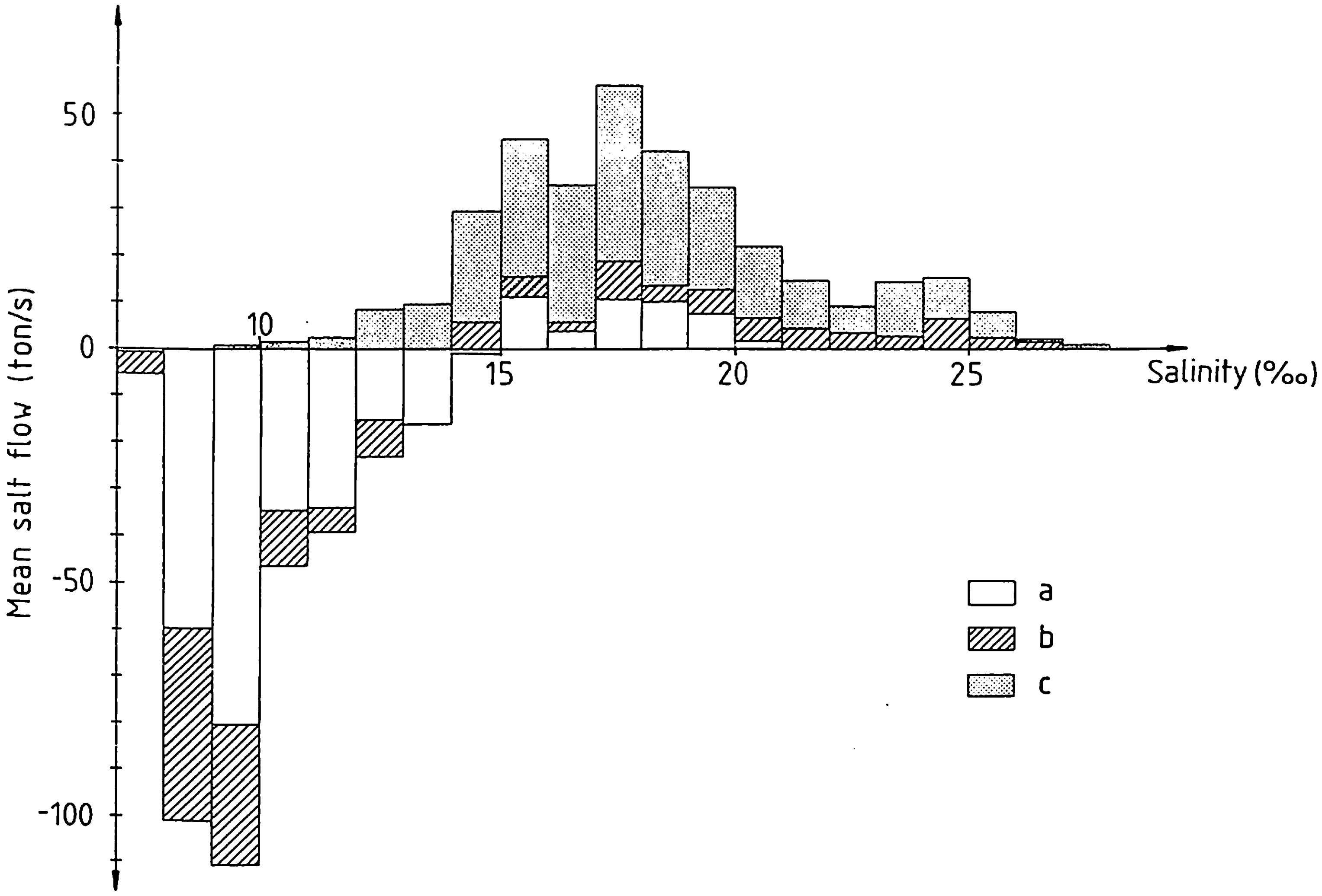


Figure 5. Supply of salt water to the Baltic Sea proper, divided into various salinity intervals (a= upper layer in the Belt Sea, b = via Öresund, c = lower layer in the Belt Sea).

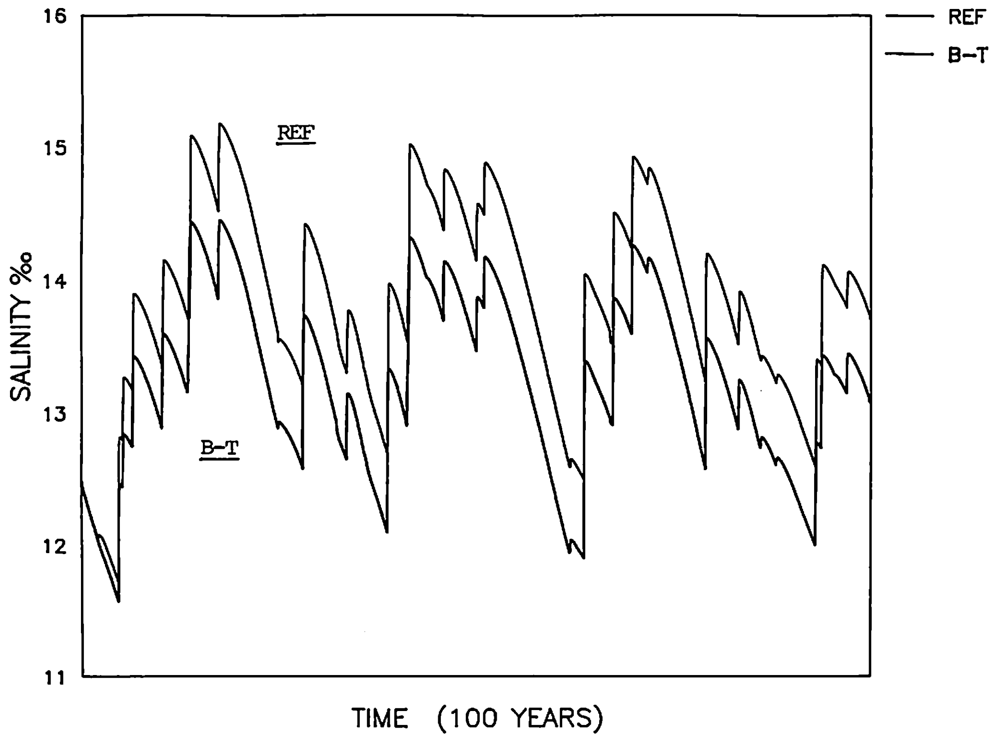


Figure 6A Salinity variations over 100 years at a depth of 250 m from model simulations without (REF) and with Öresund bridge / tunnel (B-T)

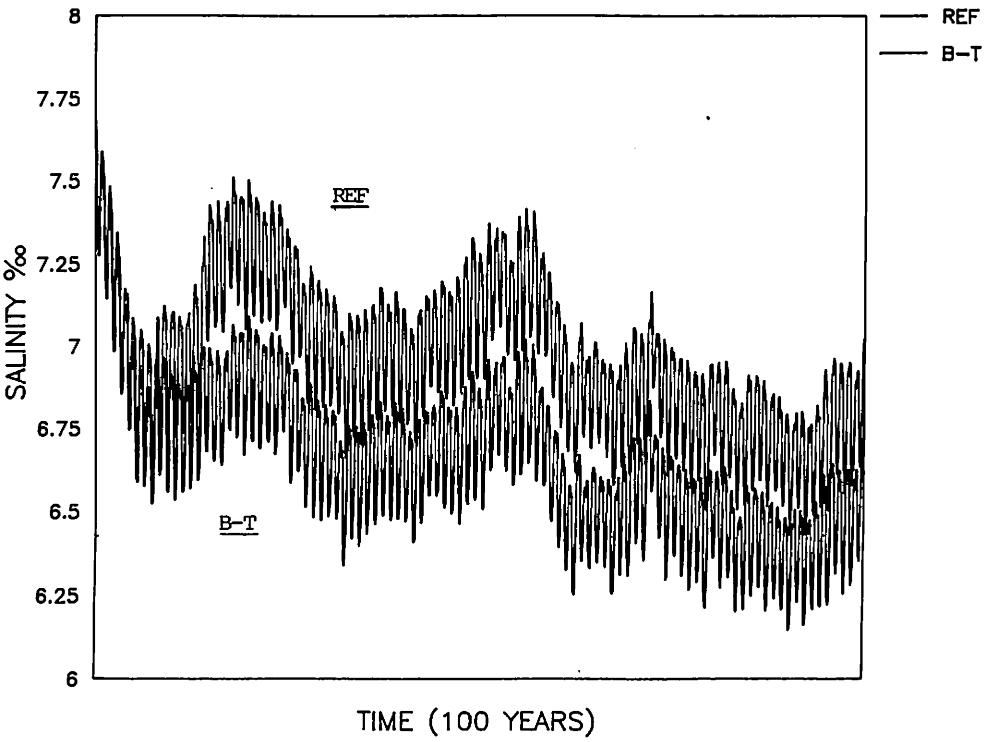
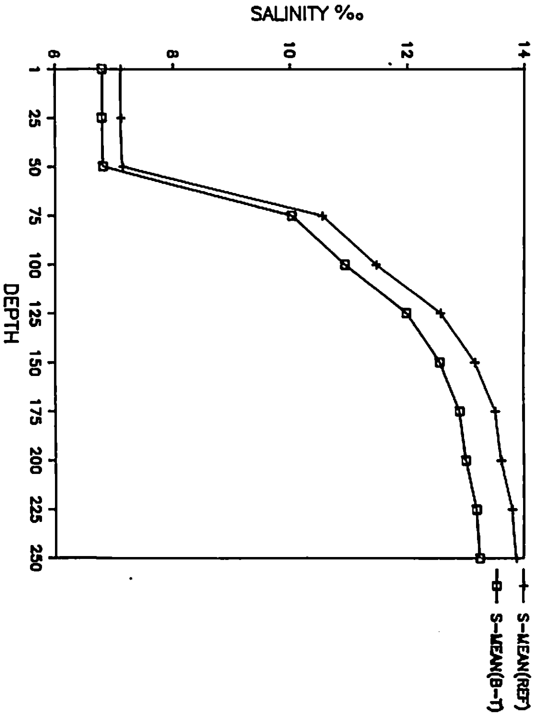


Figure 6B Salinity variations over 100 years at a depth of 1 m from model simulations without (REF) and with Öresund bridge / tunnel (B-T)



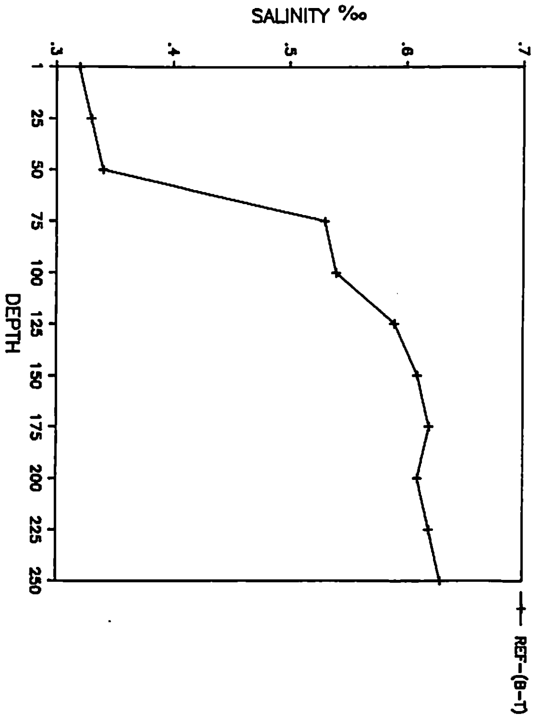
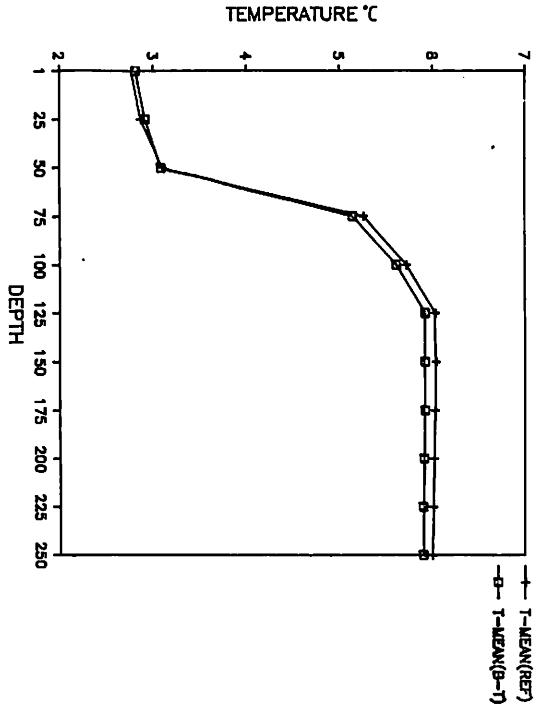


Figure 7A Vertical salinity distribution, based on monthly mean values for January from 100 year simulations without (S-MEAN (REF)) and with Öresund bridge/tunnel (S-MEAN (B-T))

Figure 7B Salinity differences between observations plotted in Fig. 7A (REF - (B-T))



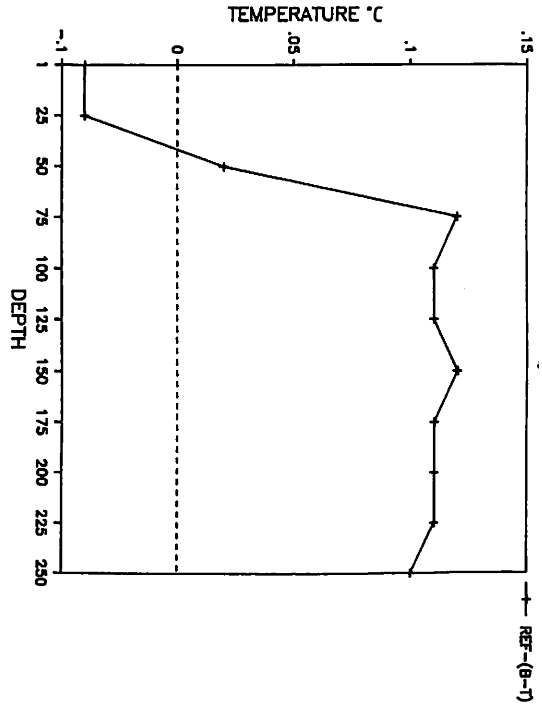


Figure 8A Vertical temperature distribution, based on monthly mean values for January from 100 year simulations without (T-MEAN (REF)) and with Öresund bridge/tunnel (T-MEAN(B-T))

Figure 8B Temperature differences between observations plotted in Fig. 8A (REF - (B-T))

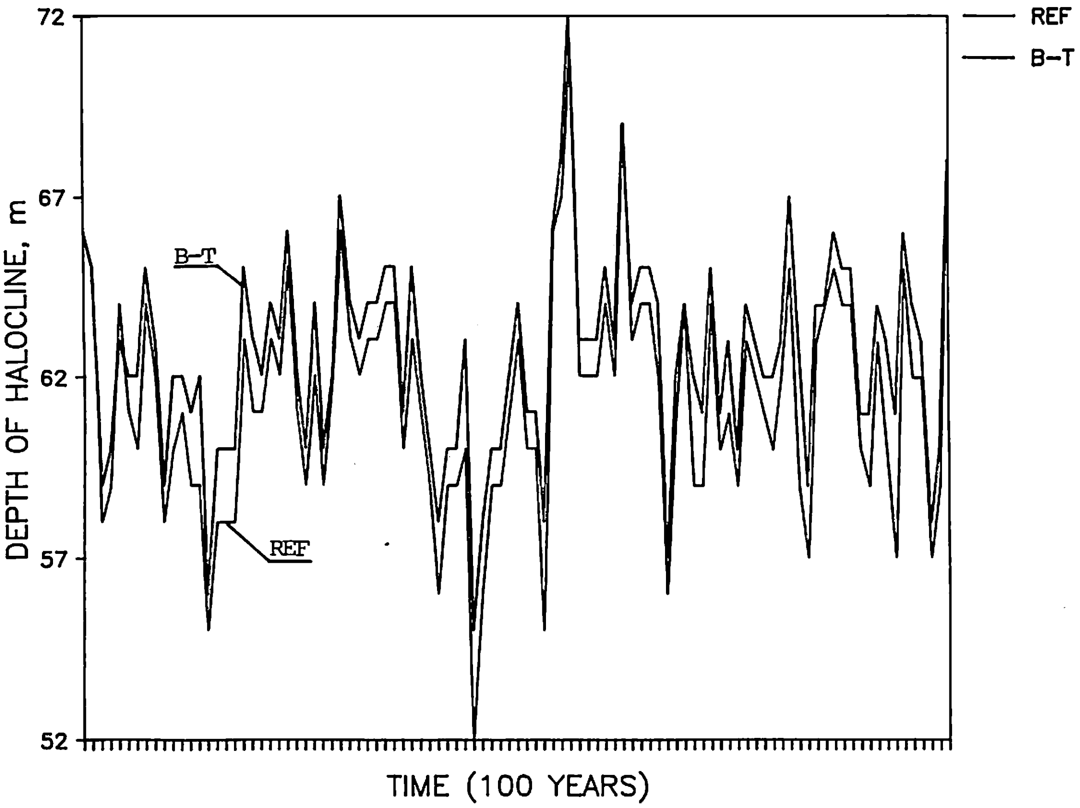
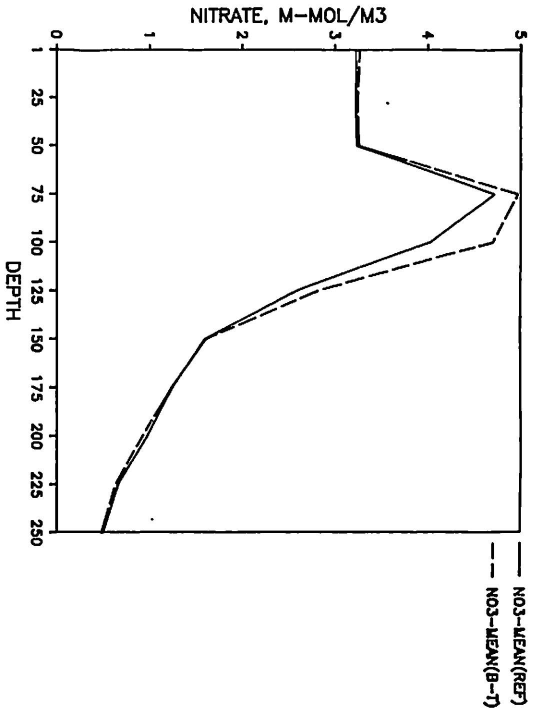


Figure 9 The maximun depth to the halocline through the year. From 100 year simulations without (REF) and with Öresund bridge / tunnel (B-T).



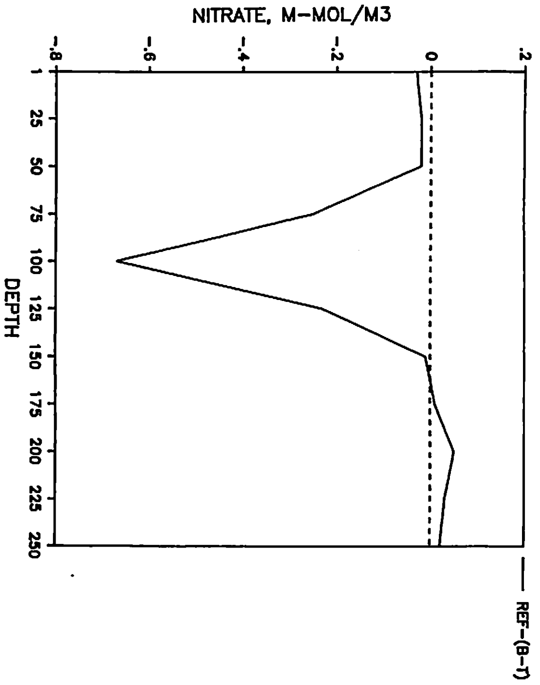
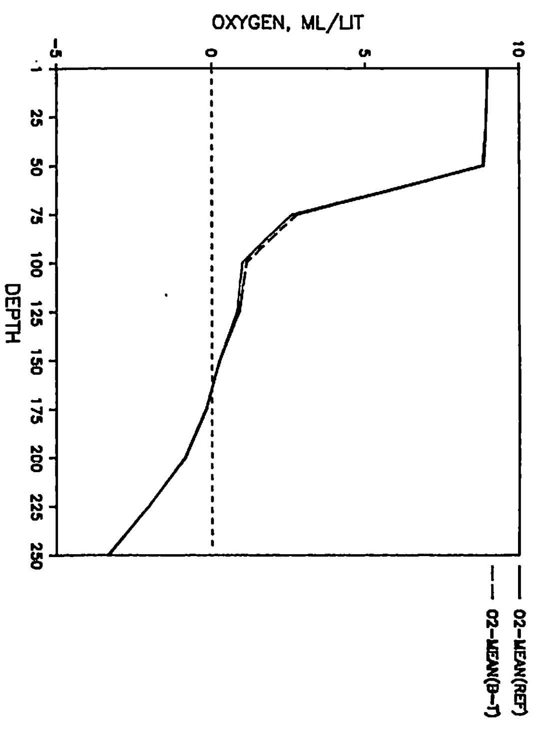


Figure 10A Vertical nitrate division, based on monthly mean values for January from 100 year simulations without (NO3 - MEAN (REF)) and with Öresund bridge / tunnel (NO3 - MEAN (B-T)).

Figure 10B Nitrate concentration differences between observations plotted in Figure 10A (REF-(B-T))



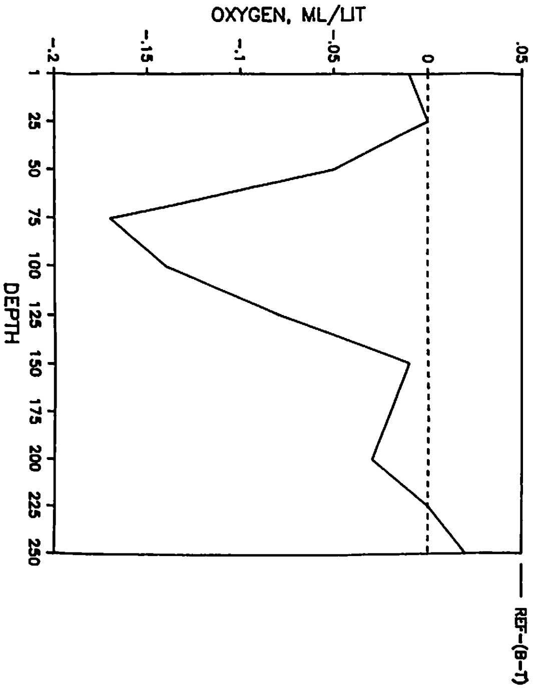


Figure 11A Vertical oxygen distribution, based on monthly mean values for January from 100 year simulations without (O2-MEAN (REF)) and with Öresund bridge/tunnel (O2-MEAN (B-T))

Figure 11B Oxygen concentration diffenences between observations plotted in Figure 11A (REF-(B-T))

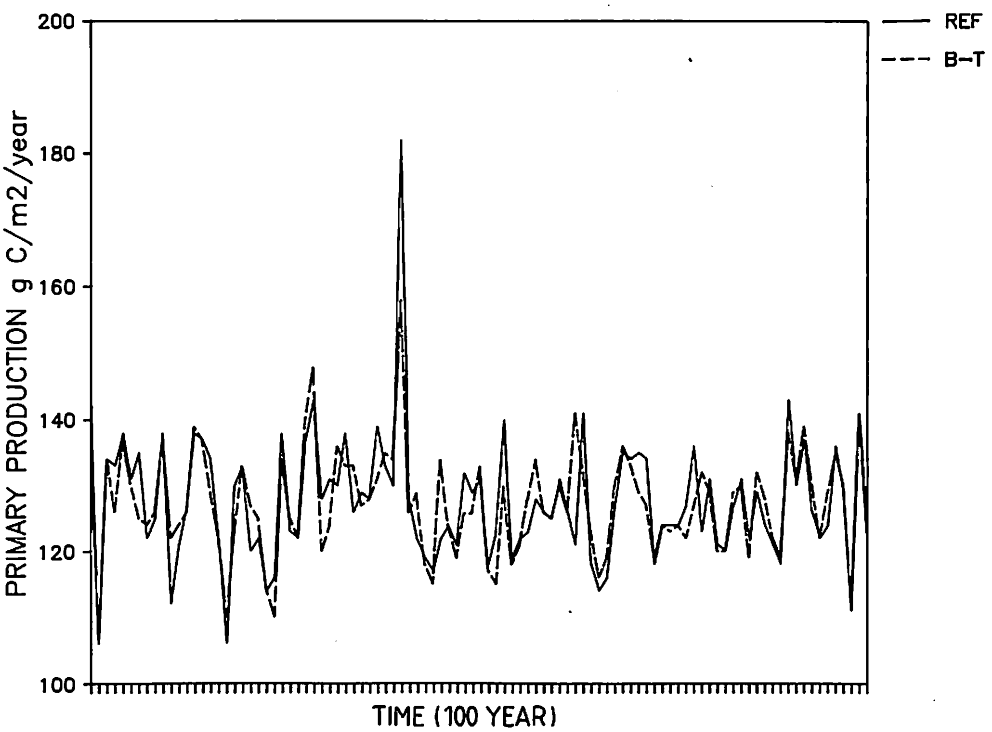


Figure 12A Yearly primary production variations in the simulations without (REF) and with Öresund bridge/tunnel (B-T)

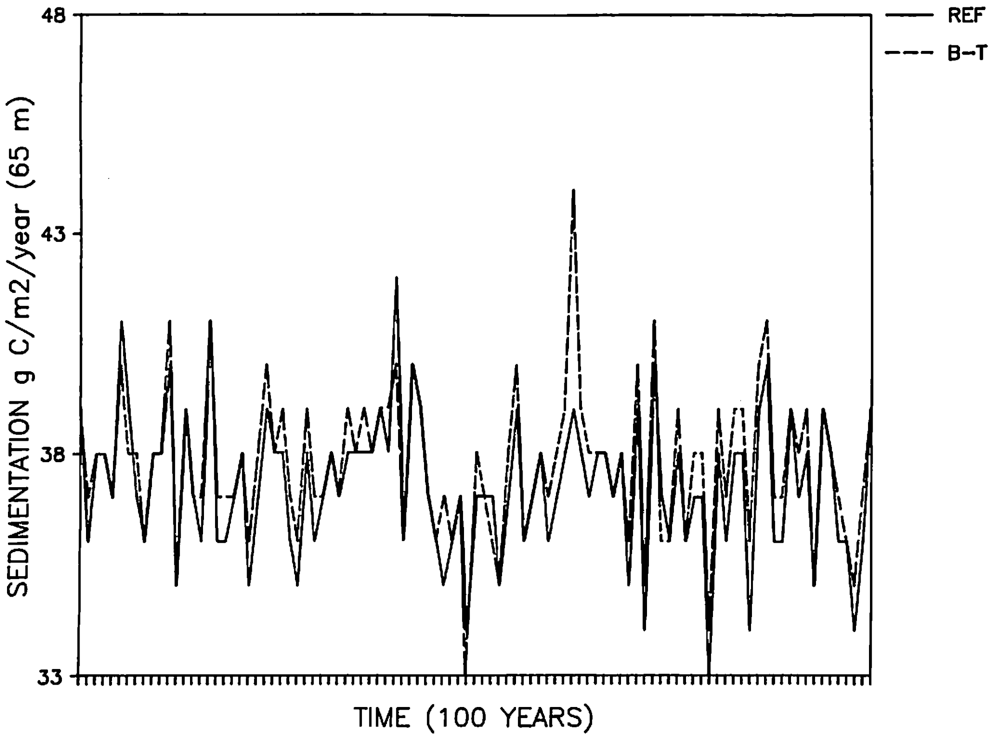


Figure 12B Sedimentation varations through the halocline (65 m) in the simulations without (REF) and with Öresund bridge/tunnel (B-T)

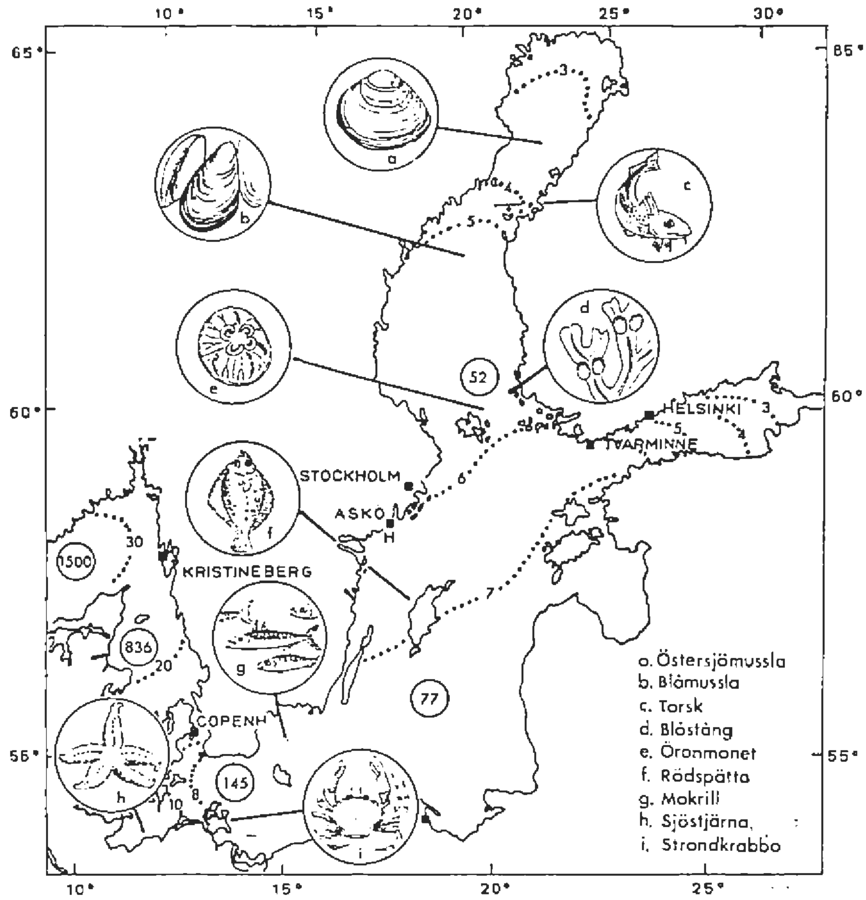


Figure 13 The salinity decreases towards the inner parts of the Baltic Sea, at the same time as the marine animals and plants vanish. The picture shows the salinity of the surface and the approximately innermost spreading boundary of some characteristic species and the number of macroscopic species of animal.

a) Baltic mussel
b) Sea mussel
c) Cod
d) Bladder wrack
e) Jelly-fish
f) Plaice
g) Mackerel
h) Starfish
i) Crab

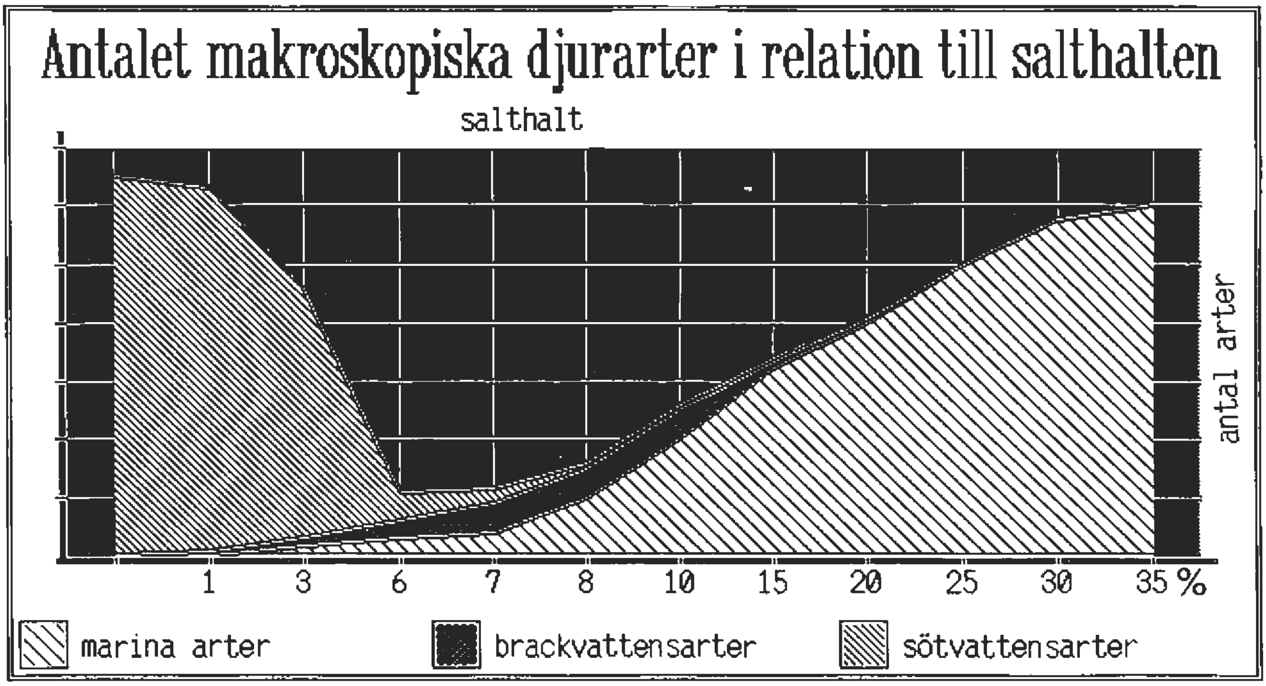


Fig 14. Antalet makroskopiska djurarter i förhållandet till vattnets salthalt.

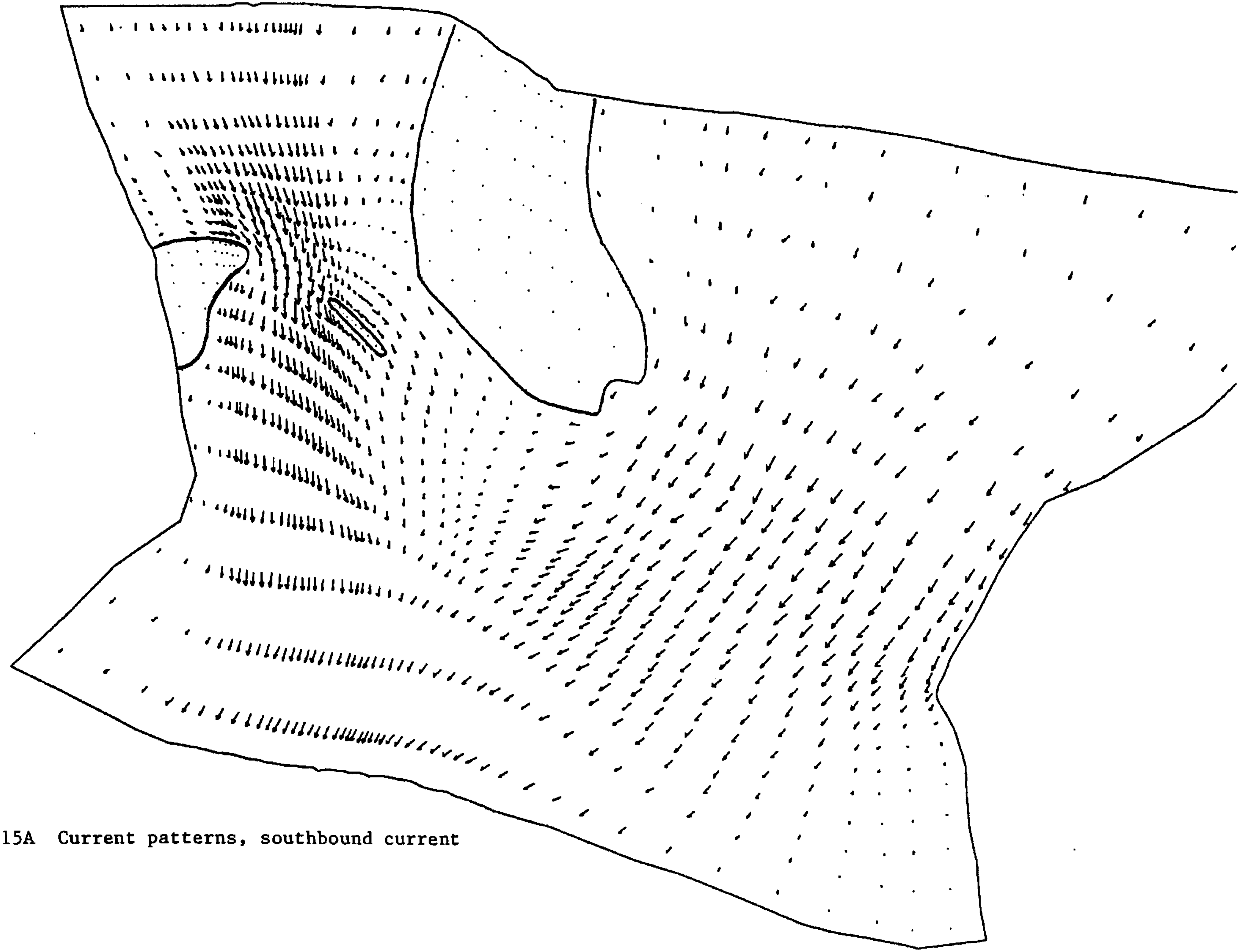


Figure 15A Current patterns, southbound current

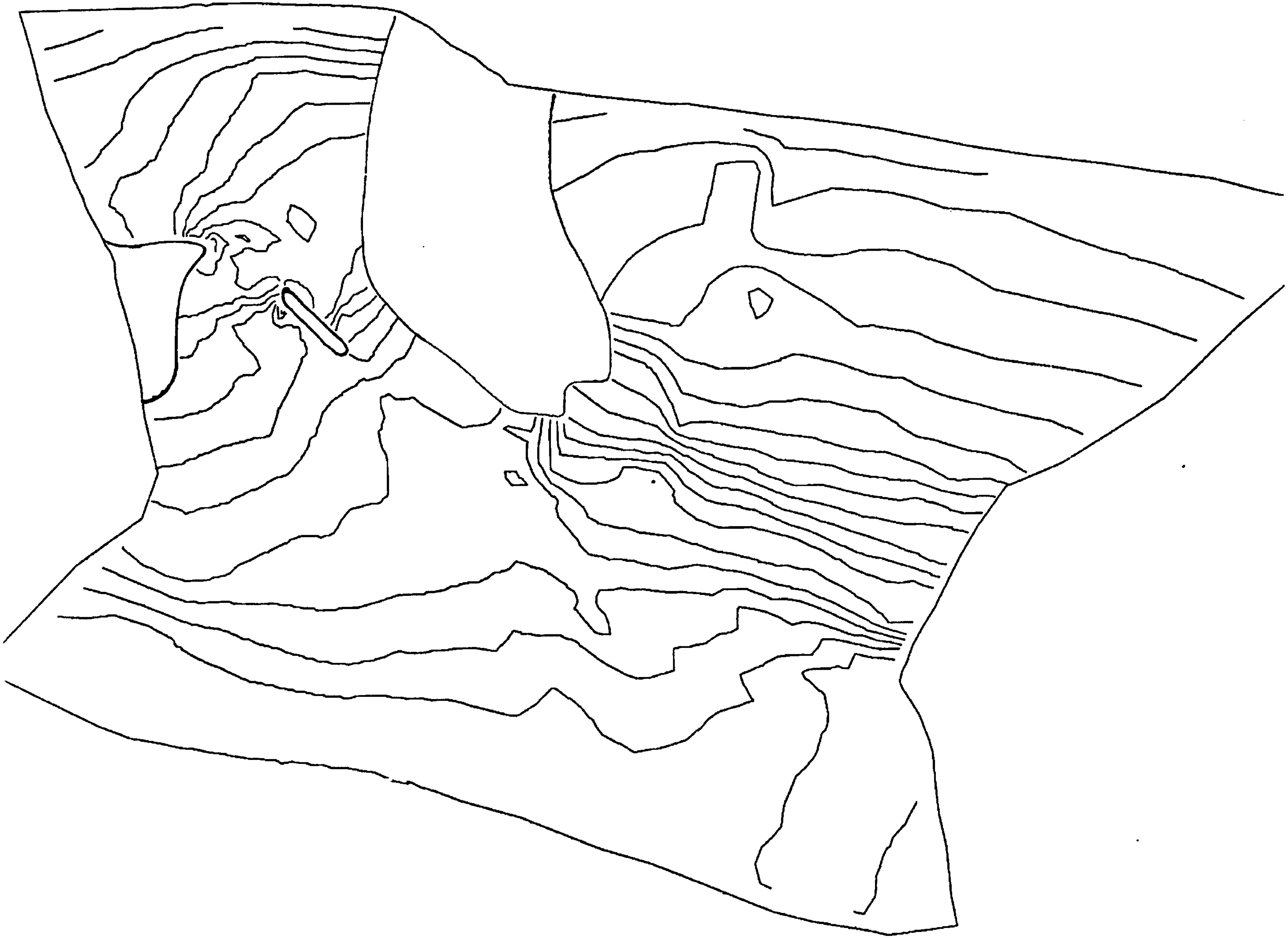


Figure 15B Sea level, southbound current. It is 20 cm sea level difference between the north and the south boundary

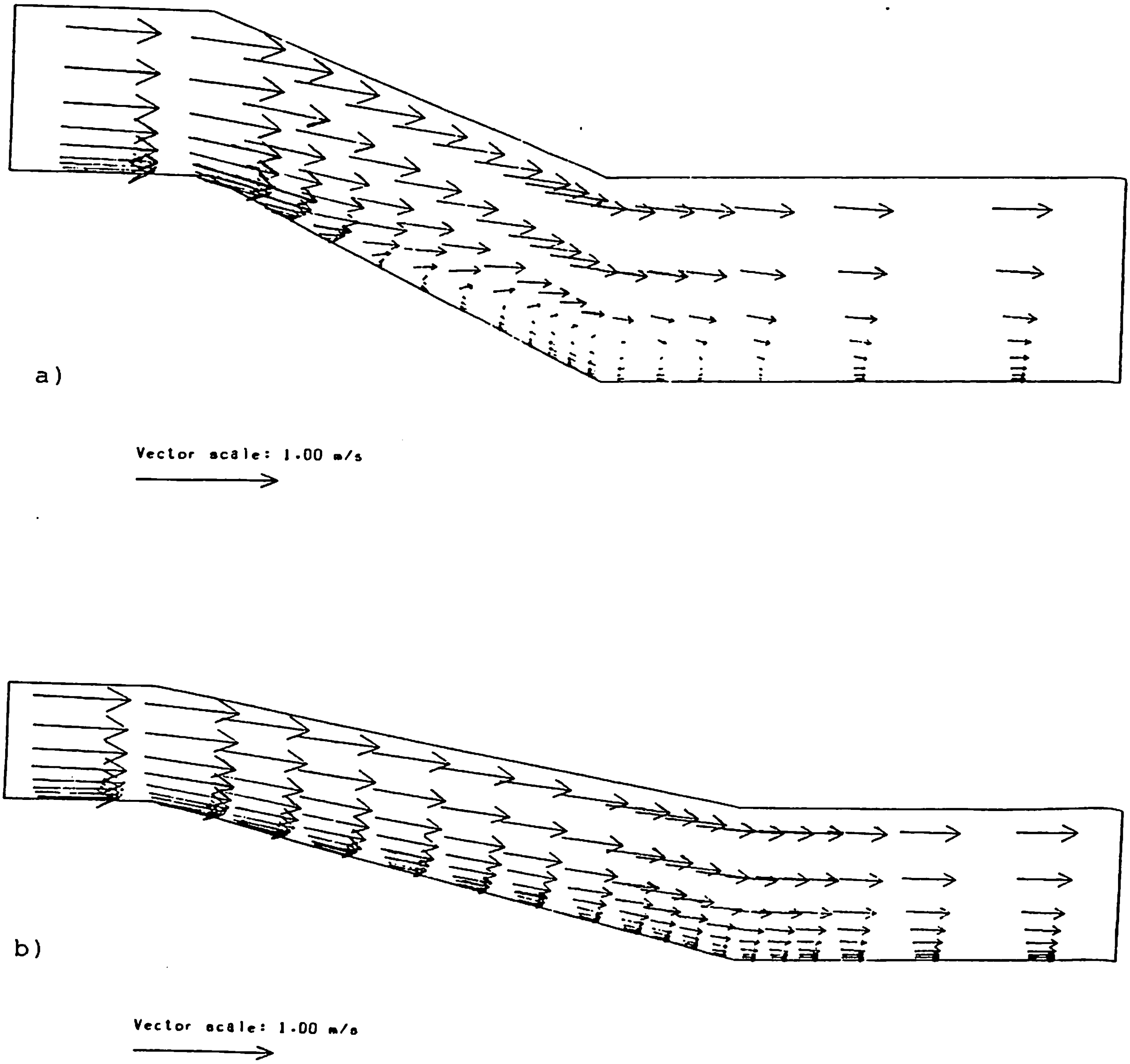


Fig 2/1 Velocity field at the upstream part of the recess

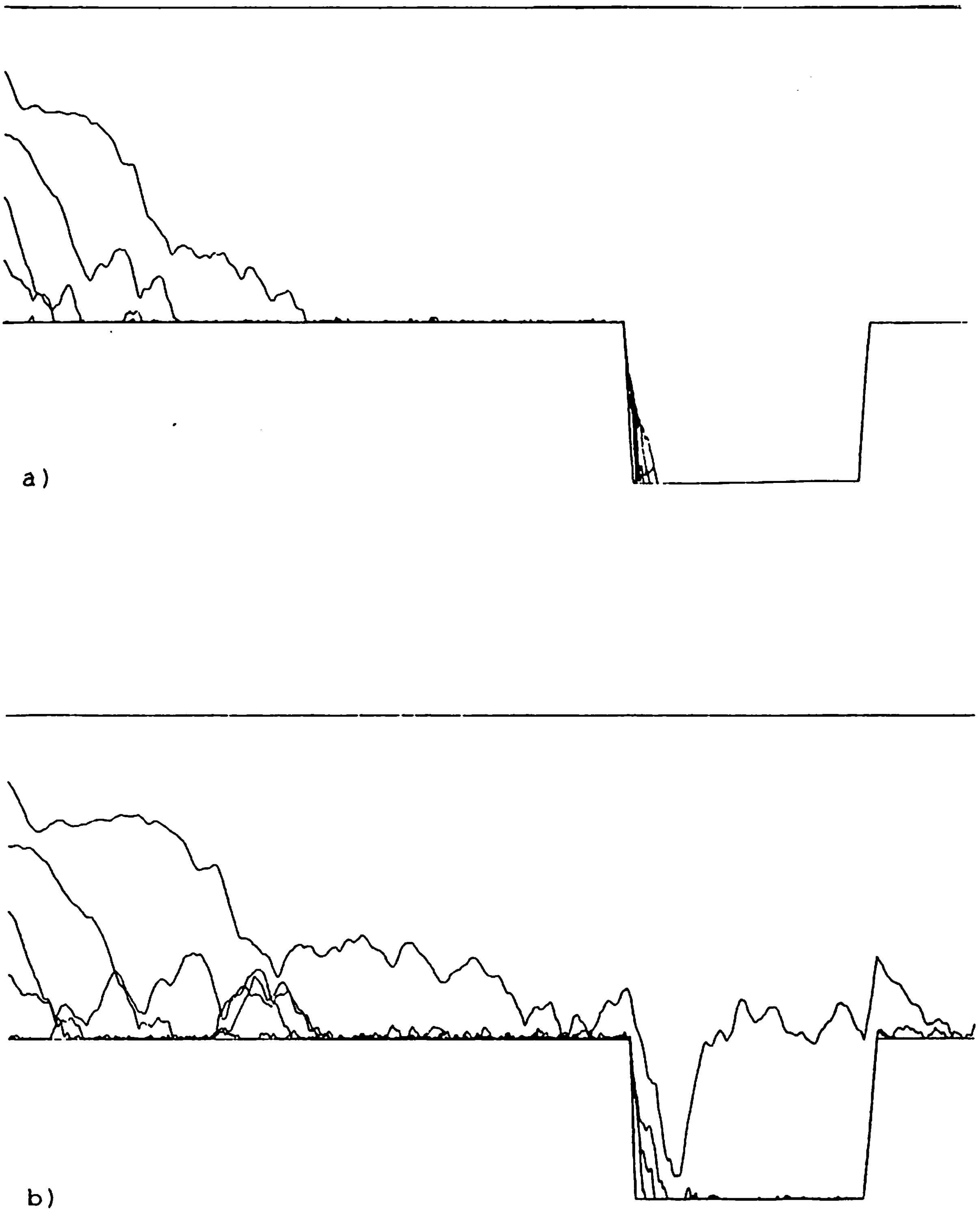


Fig 2/2 Course of five particles

a slope of 1:2, current velocity 0.5 m/s
a slope of 1:2, current velocity 0.8 m/s

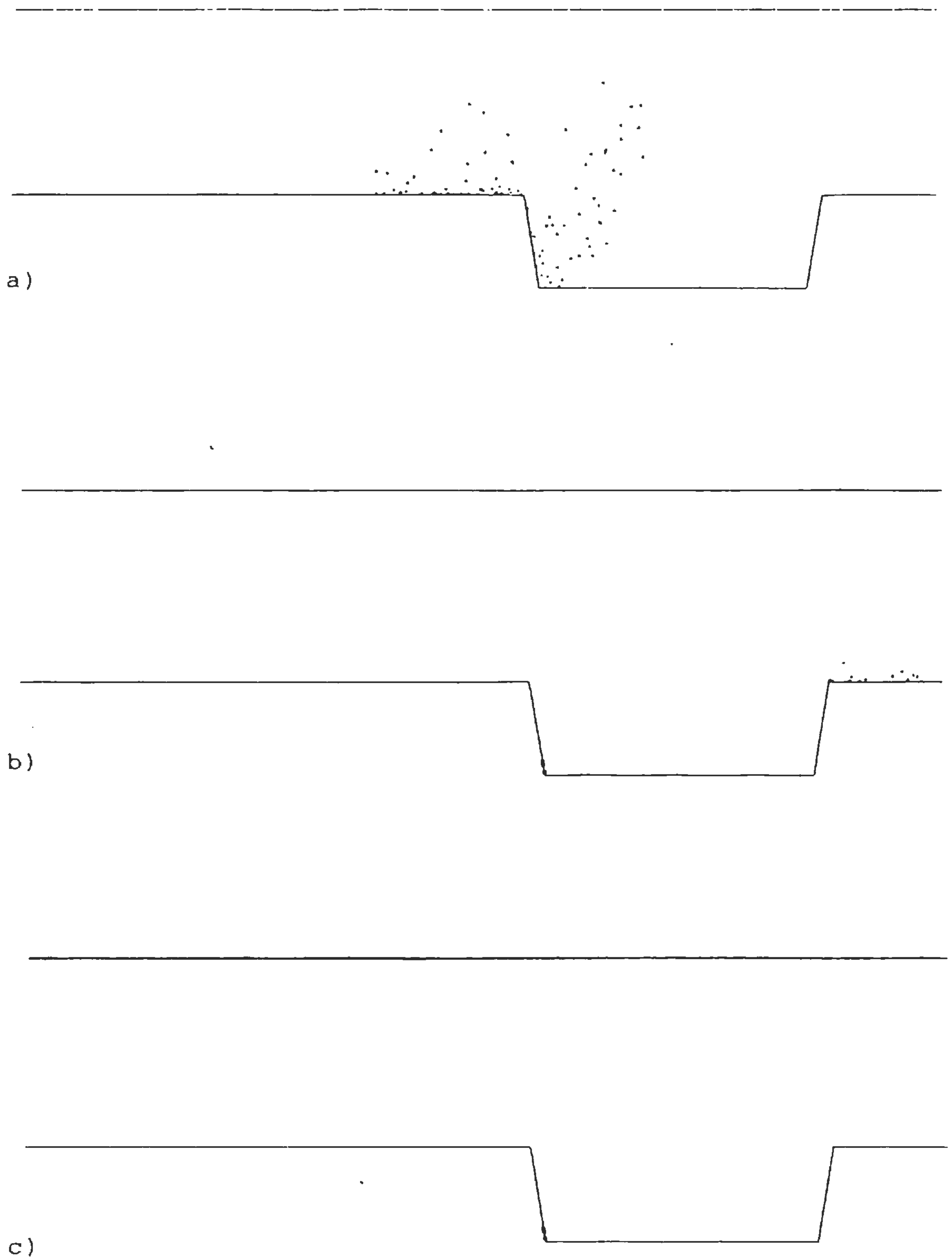


Fig 2/3 Time development of a spreading situation, slope 1:4 current velocity 1.4 m/s

a) after 15 min
b) after 30 min
c) after 45 min

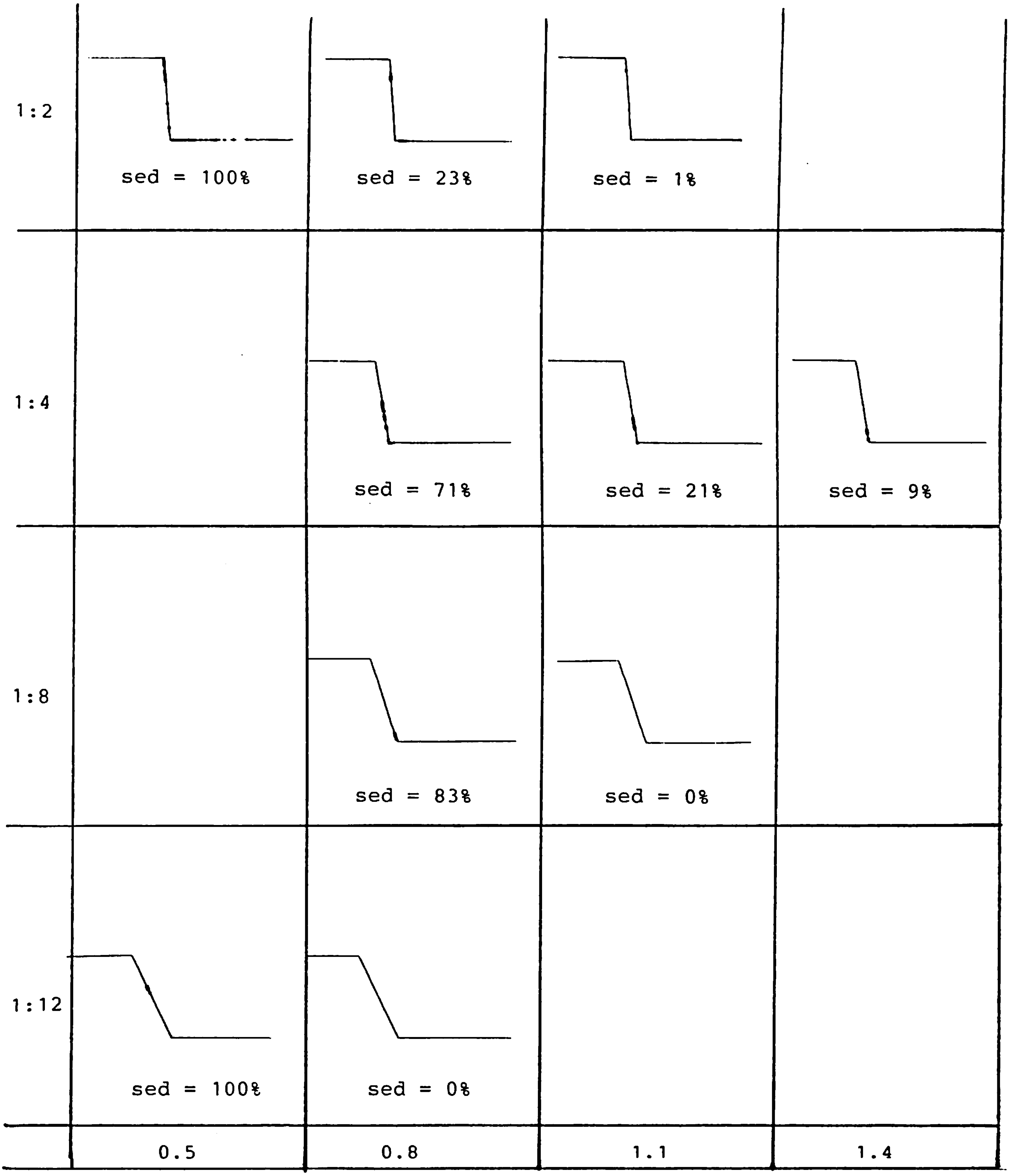


Fig 2/4 Summary of different model simulations: Sedimentation as a function of slope and current velocity (m/s)

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