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ABSTRACT

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The results of a study on the physical and biological conditions in Hopavågen and Straumen are presented. The data were collected during the period 1983–1994.

The hydrographic data show that the deep water of Hopavågen is stagnant during most of the year. The tidal current is not strong enough to generate turbulence and vertical convection in the deepest parts of Hopavågen. This results in oxygen depletion and the formation of hydrogen sulphide. Total convection may take place during cold periods, but it is not certain whether this occurs every winter.

The inflow and outflow of the tide through the narrow and shallow channel gives rise to a tidal movement in Hopavågen with an amplitude and timing which differs significantly from the normal tidal movement in the main fjord. It is shown that the mean water level in Hopavågen rises and falls, following the spring/neap cycle in the main fjord.

The littoral zone in Hopavågen differs from the normal pattern found in very sheltered localities. There are no sublittoral laminarians, no distinct fucoid zone, and the abundance of mussels and barnacles is much less than is normal for sheltered localities. It is suggested that the abnormal tidal movement and grazing by sea urchins are the major causes of these unusual distribution patterns.

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1 INTRODUCTION

Hopavågen (UTM ref. 32/520270) is a landlocked bay in Agdenes, Sør-Trøndelag, Western Norway (Fig. 1). A narrow and shallow channel (Straumen) connects Hopavågen with the main fjord.

Various studies in landlocked marine basins have been carried out in Norway (e.g. Strøm 1936, Glenne & Simensen 1963, McClimans 1973, Lande 1974, Gulliksen 1977, Jensen et al. 1985, Stokland 1987, Stokland & Berge 1988, Skei 1988, Stokland 1992). A common feature in most of these basins is a shallow sill, which may partly or completely prevent renewal of the deep water in the basin.

Between 1971 and 1980 The Foundation of Scientific and Industrial Research (SINTEF) carried out field experiments in Hopavågen as a part of the project "Feedback Control of Schooling Fish". These studies resulted in the collection of data on the hydrographical and biological conditions found in Hopavågen (Balchen 1979, 1981).

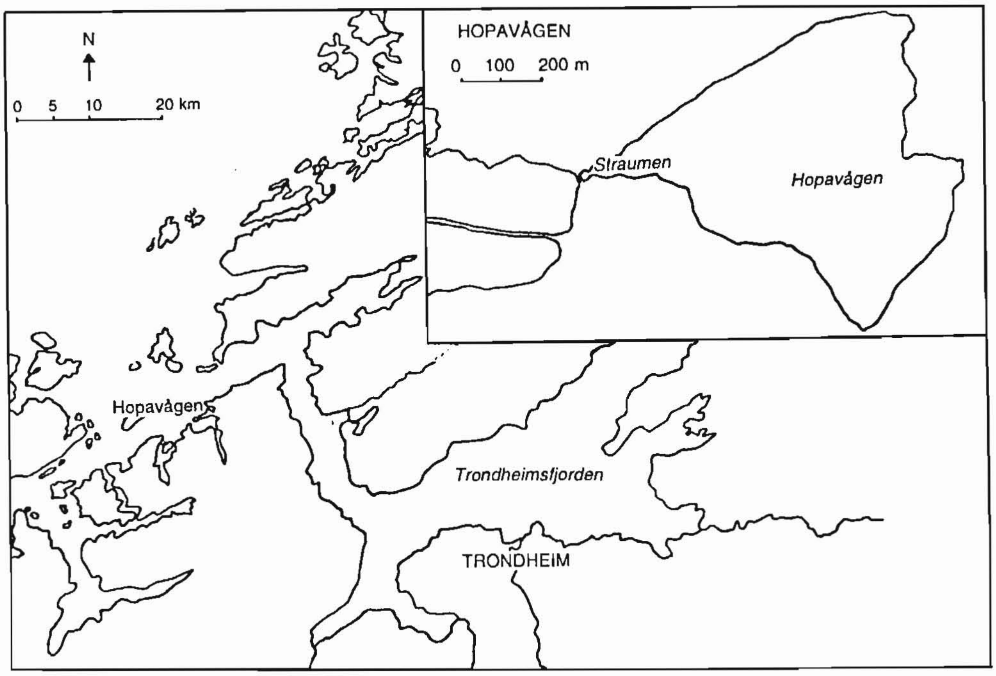

Fig. 1. Map of the coast of Sør–Trøndelag with Hopavågen.

The freshwater runoff from the areas surrounding Hopavågen is restricted to a few small streams. The volume of the freshwater is insignificant compared with the daily inflow of sea water through Straumen.

There is little human activity around Hopavågen and its catchment area. Apart from sewage discharges corresponding to 5–6 p.e., and some agri–cultural discharges from a farm, Hopavågen is unpolluted. Using revised estimates of the nutrient discharge from different sources (Holtan & Åstebøl 1991), the total discharges per year of nutrients into Hopavågen may be estimated as ca 10 kg tot–P and ca 290 kg tot–N.

Hopavågen was formerly known for its excellent fishing. Good catches of plaice (*Pleuronectes platessa*) with individual weights of up to 7 kg, coal fish (*Pollachius virens*) and herring (*Clupea harengus*) were frequently reported (Mr O.A. Olsen, pers. comm.). However, from the middle of this century the catches gradually diminished. Today, the fishery in Hopavågen is of no economic importance.

In a report published by the Regional Director of Fishery in Trøndelag (Fiskerisjefen i Trøndelag 1987), Hopavågen was indicated as a suitable site for the production of juvenile marine fish species. Furthermore, it was suggested that the sheltered conditions in Hopavågen might provide suitable conditions for shellfish farming. In 1994 a small scale experiment on the settlement and growth rate of *Mylilus edulis* was started.

Since 1977 the University of Trondheim has used Hopavågen and the adjacant areas for field courses for undergraduate biology students, in–service training courses for teachers and other specialist courses. Two secondary schools in Trondheim have also used the area for biology field work. Since 1987 a College of Engineering in Trondheim has carried out annual field work in Hopavågen as a part of the student courses in aquatic biology and coastal management.

This paper presents data on the biological and physical conditions found in Hopavågen and Straumen, collected during the period 1983–1994.

2 MATERIAL AND METHODS

The hydrographic measurements include measurements of the temperature, salinity and in some cases also dissolved oxygen. At fixed hydrographic stations, temperature and salinity were measured *in situ* with a YSI SCT–Meter. Dissolved oxygen was measured *in situ* with a YSI Dissolved Oxygen Meter. The temperature and salinity of the deepest parts of Hopavågen were measured in samples from water bottles.

The description of the bottom topography is based on depth soundings using an echo sounder, carried out from a rowing boat following transects marked on a map (scale 1:5000) (Fig. 2). Samples of the bottom sediments were taken by means of bottom grabs. Observations on the occurrence of hydrogen sulphide were made from the water samples collected by the water bottles and from the sediments sampled with the grabs.

In the descriptions of the physical conditions present in the tidal zone, the classification of Klemsdal (1979) was used. Observations of tidal movements were carried out by recording the water level on a metal pole with centimeter–markings, that was placed ca 5 m from the shore.

Qualitative plankton samples were taken from rowing boats using different plankton nets (mesh size 10 μ and 500 μ), at depths varying between 0 m and 30 m. Qualititive samples of bottom fauna were taken by means of a rectangular iron dredge (60 x 20 cm).

Table 1. Sampling and registrations carried out in Hopavågen 1983–1994

Date	Hydro–graphic measure–ments	Depth soundings	Sediment samples	Descrip–tion of tidal zone	Descrip–tion of tidal movements	Plankton samples	Benthos samples
01.09.83	x	x		x			x
05.09.85	x			x		x	x
23.05.87	x	x	x	x	x	x	x
27.05.88	x	x	x	x		x	x
11.05.89	x	x		x		x	x
05.09.91	x	x			x	x	x
10.09.92	x	x		x	x	x	x
26.09.92	x						
02.09.93	x					x	
19.06.94						x	
27.08.94						x	

3 RESULTS AND DISCUSSION

3.1 Topography and sediments

The area of Hopavågen is ca 370,000 m^2 and its total drainage area is ca 1.9 km^2. Echo sounding recordings were made along 13 transects as shown in Fig. 2. A bottom profile, based on recordings between A and B, is shown in Fig. 3.

Hopavågen shows the following features:

1 The greatest depth measured in Hopavågen is 31 m (see Figs 2 and 3).

2 About one-third of the total area of Hopavågen has a depth exceeding 25 m. Assuming that one-third has a depth between 0 and 12 m and one-third a depth between 12 and 25 m, the average depth will be 18 m. This will give Hopavågen a volume of ca 6.66×10^6 m^3.

3 In the northern and northeastern part of Hopavågen the slope may be as steep as 30 degrees. In the southern part the shore is more gently sloping.

4 The depth of the sill is ca 1.0 m at low tide. The maximum volume above the sill depth (1.70 m at maximum high tide) is ca 630,000 m^3.

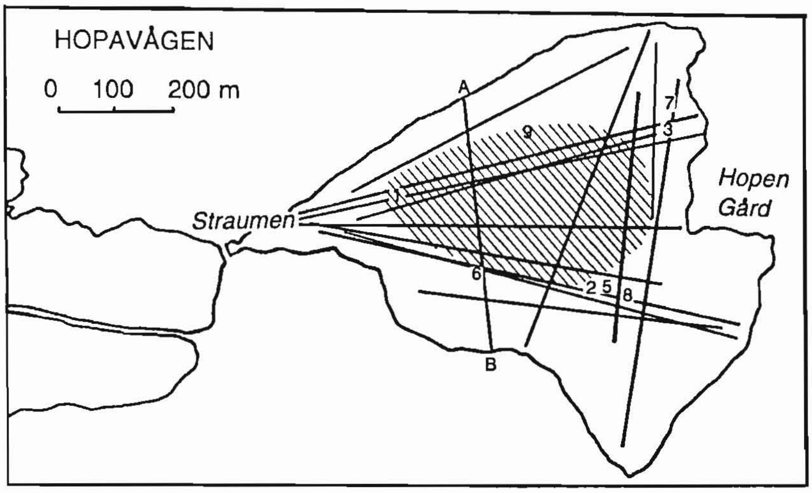

Fig. 2. Bottom topography of Hopavågen. The area marked indicates the deepest part of Hopavågen (depth exceeding 25 m). The positions of the sediment sampling sites are marked 1–9. Black lines indicate echo sounding transects.

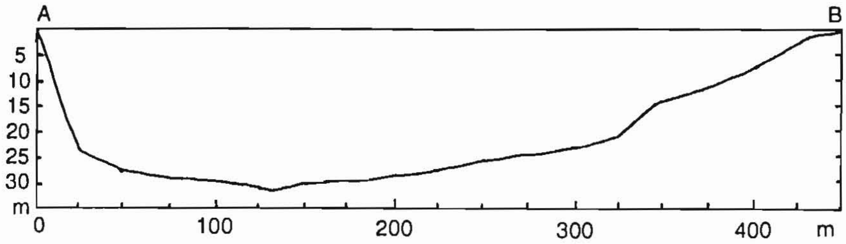

Fig. 3. Bottom profile of Hopavågen through A and B (see Fig. 2).

Coarse sediments were found only near Straumen. All other sediment samples consisted of silt and fine sand. The smell of hydrogen sulphide was noticed in all the bottom samples and in two of the samples taken from deepwater (Table 2).

Table 2. The main characteristics of the sediment samples and deepwater samples (*) of Hopavågen

Sample	Date	Classification of sediment particles	Occurrence of organic matter	Smell of hydro-gensulphide
1	23.05.87	fine/coarse sand	yes	weak
2	23.05.87	fine sand/silt	yes	strong
3	23.05.87	fine sand/silt	yes	weak
4	23.05.87	fine sand/silt	yes	strong
5	27.05.88	fine sand/silt	no	strong
6	27.05.88	fine sand/silt	yes	weak
7	27.05.88	fine sand/silt	no	weak
8(*)	05.09.91	-	-	strong
9(*)	10.09.92	-	-	strong

3.2 Tidal movements

The tide curves in Fig. 4 are based on the following observations:

1 The exact time of high water and low water on 22.05.87 and 23.05.87.

2 Highest and lowest water level in Hopavågen on 22.05.87 and in the main fjord on 22.05.87 and 23.05.87, measured against a fixed reference point.

3 The direction of the tidal current in Straumen and the time at which the tide turned on 21.05.87 and 22.05.87.
4 The predicted time of high and low water in the main fjord (Norges Sjøkartverk 1987).

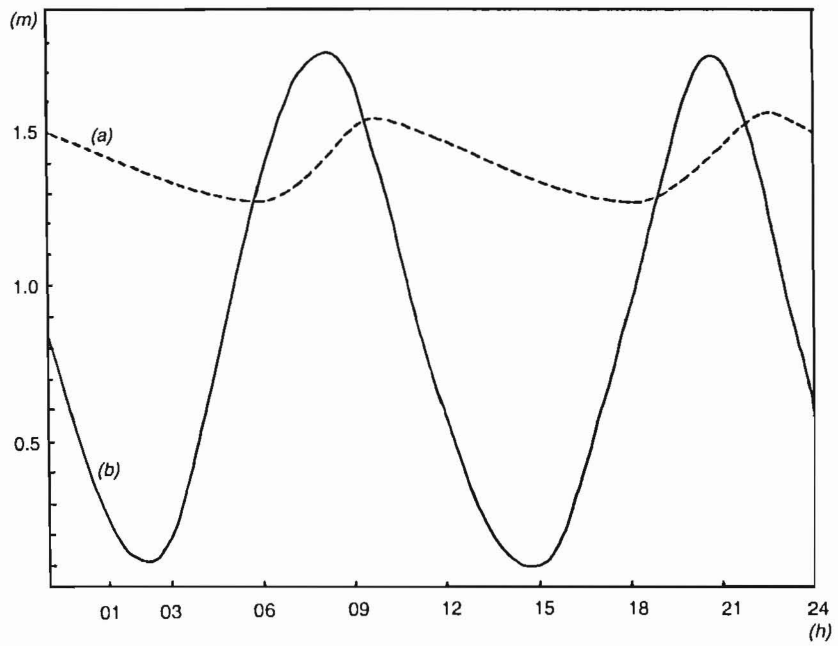

Fig. 4. Tide curves in Hopavågen (a) and in the main fjord (b) on 22.05.1987.

The situation in Hopavågen and the main fjord on 22.05.1987 can be summarized as follows:

- The tidal range in Hopavågen was 0.32 m. The tidal range in the main fjord was 1.68 m.
- The highest water level in Hopavågen was 0.19 m below the high water level in the main fjord.
- The lowest water level in Hopavågen was 1.17 m above the low water level in the main fjord.
- Between the time of low water in the main fjord and the time of low water in Hopavågen, there was a delay of 4 h 30 min.
- Between the time of high water in the main fjord and the time of high water in Hopavågen the delay was 1 h 47 min.

- The water level in Hopavågen took approx. 4 hours to rise and fell over a period of approx. 8.5 hours.
- The tidal current into Hopavågen was stronger than the current out of Hopavågen.

The curves in Fig. 4 do not oscillate around the same axis. This means that the mean water level is higher in Hopavågen than in the main fjord. Variations in the tidal range in the main fjord therefore result in varying delays to the tide in Hopavågen. During May 1987, when measurements were recorded, the tidal range was only slightly different from the mean tidal range in Trondheimsfjorden (1.83 m). A smaller tidal range in the main fjord (neap tide) results in an even shorter inflow period, and a longer outflow period. A larger tidal range (spring tide) on the other hand, causes a longer inflow period and a shorter outflow period. Dalen (1971) found that low tide in Hopavågen was 5 hours after low tide in the main fjord, while high tide had a delay of 1 h 10 min, but he gives no information about the tidal range in Hopavågen.

In 1991 the tidal movement in Hopavågen was recorded by reading the water level on the pole with centimeter markings. The water level was noted every 30 minutes over 10 hour period (see Fig. 5). The resulting tide curve showed the expected shape, with a small irregularity near low water. This irregularity may be due to a sudden change in the wind direction or other local conditions. Lewis (1964) refers to such irregularities as "shallow water effects". Because the tidal range is small, a relatively small deviation from normal conditions, caused by local factors, may have a notable effect on the tide curve.

On 05.09.1991 the tidal range in Hopavågen was 0.55 m. The interval between high water and low water was 7 h 45 min. This agreed with what was expected: There was a longer inflow period and a shorter outflow period than was found when measurements were taken on 22.05.1987. This was due to there being a larger amplitude in 1991.

One year later on 10–11.09.1992, the water level in Hopavågen was measured every hour over a twelve hour period. The tidal range was 0.70 m, and the interval from low tide to high tide was 4 h 30 min. As expected, the large range compared with that found in 1991 and in 1987, resulted in a shorter outflow period than in either 1987 or 1991.

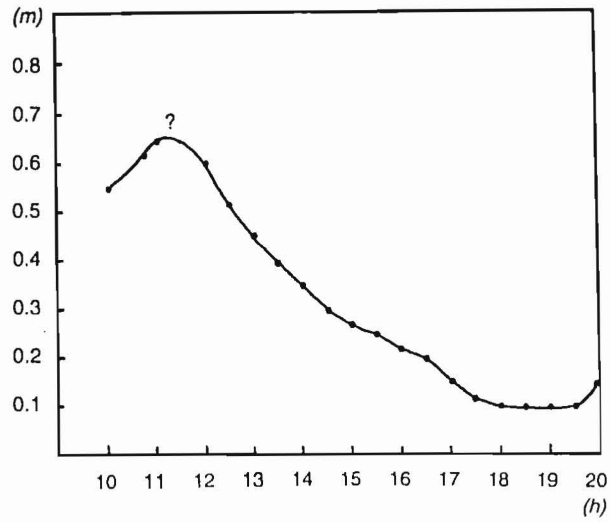

Fig. 5. Tidal curve for Hopavågen on 05.09.1991, based on water level readings taken every 30 minutes. The highest level and time of high water (?) is estimated on base of the other readings.

Normally the semi–diurnal tidal curves of open coasts show a characteristic sinus–shape. The curves normally have a varying amplitude, but they always oscillate around a fixed axis. In land–locked bays, "lochs" etc., however, deviations from the normal curve can easily occur. Lande (1973) describes "abnormal" tidal movements in Prestvaagen, a land–locked bay in Verrabotn, Nord–Trøndelag. Lewis (1964) describes tidal anomalies in lochs in Scotland, and states that such deviations may have significant effects upon littoral communities.

During neap tides in the main fjord (amplitude ca 0.70 m), the high water level will not reach high enough to enable inflow into Hopavågen. Therefore, during a neap tide, water runs out of Hopavågen all the time and the water level in Hopavågen in fact falls. This is counteracted when the amplitude increases towards the time of the spring tide. The larger amplitude results in a shorter outflow and a longer inflow period. The water level in Hopavågen will then rise again. This means that during a lunar cycle the axis in the tidal curve of Hopavågen oscillates around a varying level.

The tidal movements in Hopavågen may be characterized by the following features:

1 The period from low to high tide is shorter than the period from high to low tide.
2 The period from low tide to high tide is shorter during a period of neap tides than during a period of spring tides. The period from high tide to low tide is longer during neap tides than during spring tides.
3 The mean water level in Hopavågen is higher during spring tides than during neap tides in the main fjord.
4 The tidal range in Hopavågen is larger during spring than during neap tides in the main fjord.
5 Observed tidal ranges between 0.32 m and 0.70 m give a total exchange of between 118,400 and 259,000 m^3 water for each tide cycle. The volume of water exchanged by the tide currents represents between ca 24 and 41% of the volume above the sill depth and between ca 2 and 4% of the total volume of water.

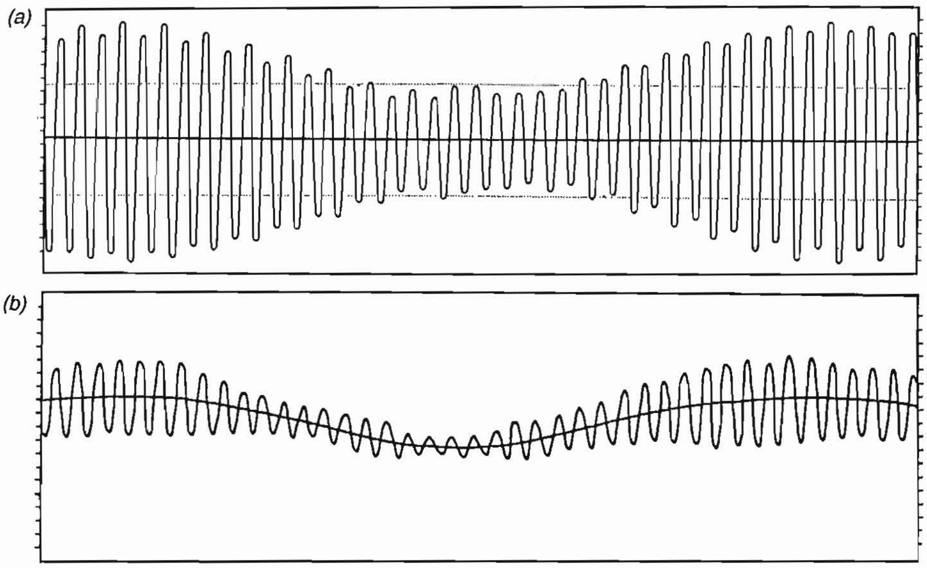

Fig. 6. Simplified models of tidal movements. (a) The "normal "curve for open coasts. (b) A hypothetical curve for Hopavågen.

3.3 Hydrography

Hydrographic stations were located in different areas of Hopavågen: in the western part, the northern part and the southern part. The exact positions of the stations varied slightly from year to year. However, most of the stations were located in the areas 1, 2 and 3, as shown in Fig. 7. Each of the numbers in Fig. 7 represents the year in which measurements were taken. In 1992 two hydrographic stations were located in area 1. In the analysis and presentation of the hydrographic measurements the data are grouped together by area into areas 1, 2 and 3 (Figs 8–16).

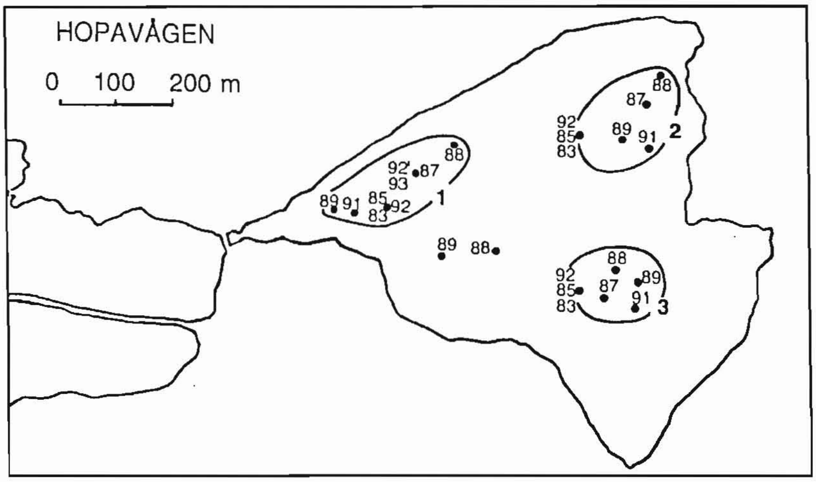

Fig. 7. Map of Hopavågen, showing the hydrographic stations grouped into the three areas: area 1, area 2 and area 3 (see text for further explanation).

It seems that some of the curves from the same date are displaced in relation to the co–ordinate axes. This might be due to the non–calibration of the different instruments being used. Irregularities of this kind can only be identified when another series of observations are made with different instruments but at approximately the same time. In investigations where only a single set of measurements are made, it is hard to uncover these kinds of error. In the present study, however, it is not difficult to identify and correct these irregularities.

The results of the measurements made in May 1987, 1988 and 1989 show a stratification in the upper layers of water, while the deep water has a uniform low temperature and high salinity. The stratification is due to the relatively high temperature and low salinity of the surface water. During the summer the stratification of the surface layers becomes more pronounced, while the conditions in the deep water remain stable. Observations made by the Foundation of Scientific and Industrial Research (SINTEF), show that the temperature of the water masses beneath ca 20 m increases only slightly from ca 4.5°C at the beginning of June to ca 6°C by the middle of September (Olsen 1974).

The observations made in September 1983, 1985, 1991, 1992 and 1993 show that the stratification of the upper layers weakens during the autumn. A pycnocline at a greater depth prevents deep water from taking part in the vertical convection of the upper layers. During late autumn and winter colder and relatively more salty water progressively enters Hopavågen through Straumen. This water creates unstable conditions which presumably spread to the deeper water.

The hydrographic conditions in Hopavågen are characterized by stagnant deep water during most of the year. This results in oxygen depletion, as was observed in May 1987 and September 1991. Furthermore, a strong smell of hydrogen sulphide was noted in both the sediment and water samples taken from the bottom in all three areas in May and in September (see Table 2). Hydrogen sulphide is probably formed throughout the entire central part of Hopavågen (depth > 25 m, see Fig. 2).

The tidal current is obviously not strong enough to generate turbulence and vertical convection in the deepest parts of Hopavågen. In this respect the situation in Hopavågen differs from the situation in for example the outer basins of Barmanfjorden (Lande 1974, Stokland 1992) and Borgenfjorden (Gulliksen 1977).

It seems obvious that an eventual convection that includes the deep water masses could only take place during the winter when the surface water is cooled and its density increases. Normally, the winter temperature of the surface water in the main fjord ranges from ca 3 to 6°C and the salinity is not lower than ca 30 ppm (Jacobsen 1974). Inflow of this "heavy" fjord water during the winter months might break down the stratification in Hopavågen and cause a vertical convection, that in some cases would also include the deeper water. Observations of the vertical distribution of the temperature in February 1971 (Balchen 1971), showed a homogeneous water mass from the surface to the bottom. There were no signs of oxygen depletion or the formation of hydrogen sulphide. This suggests that a total convection might have taken place at that time. It is not certain whether a convection like this occurs every winter.

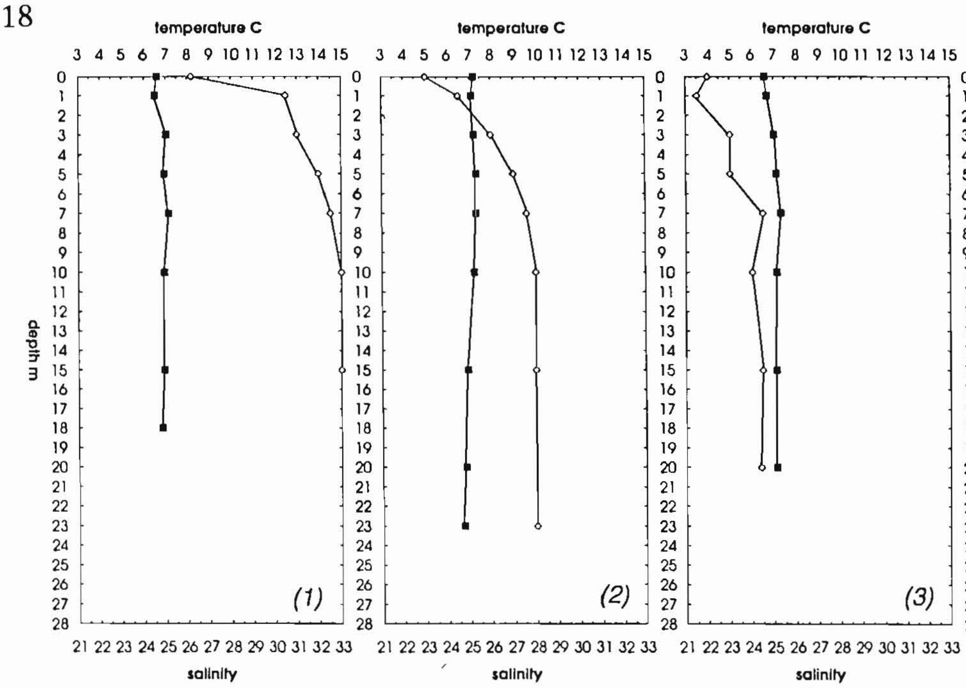

Fig. 8. Vertical distribution of temperature (n) and salinity (_) in the areas 1, 2 and 3. Date: 11.05.1989.

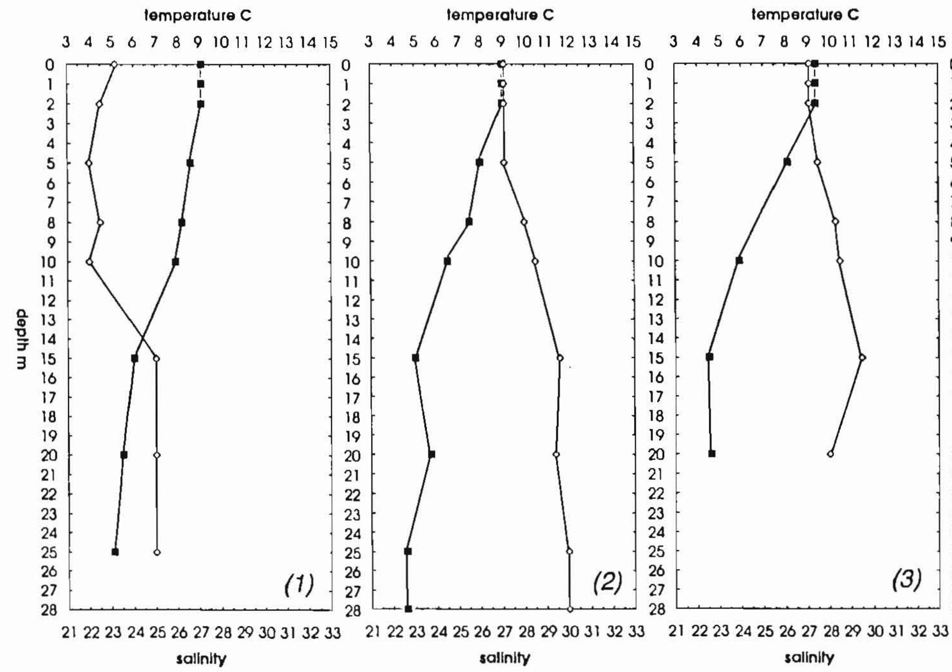

Fig. 9. Vertical distribution of temperature (n) and salinity (_) in the areas 1, 2 and 3. Date: 23.05.1987.

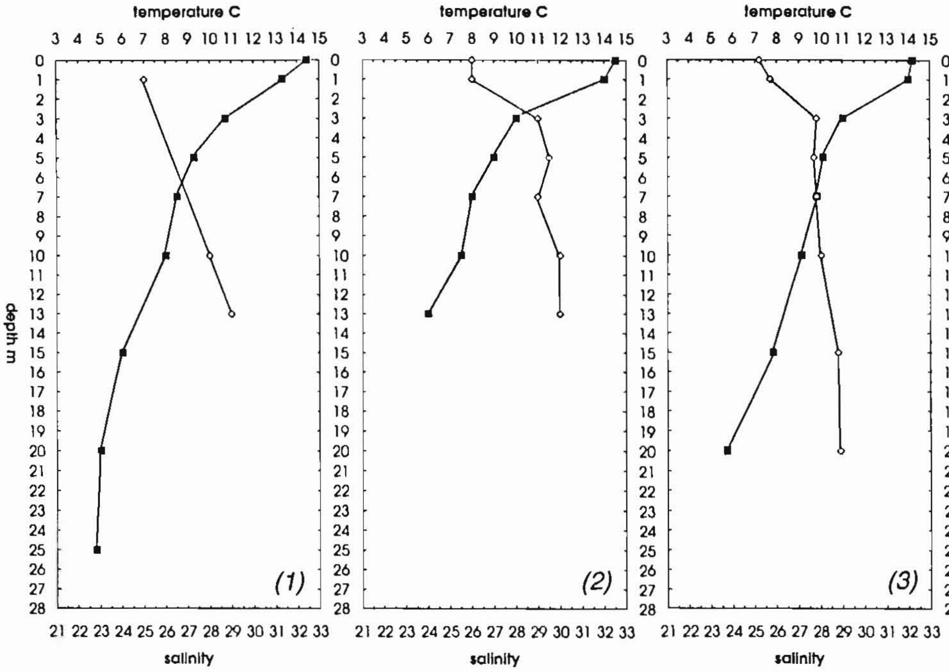

Fig. 10. Vertical distribution of temperature (n) and salinity (_) in the areas 1, 2 and 3. Date: 27.05.1988.

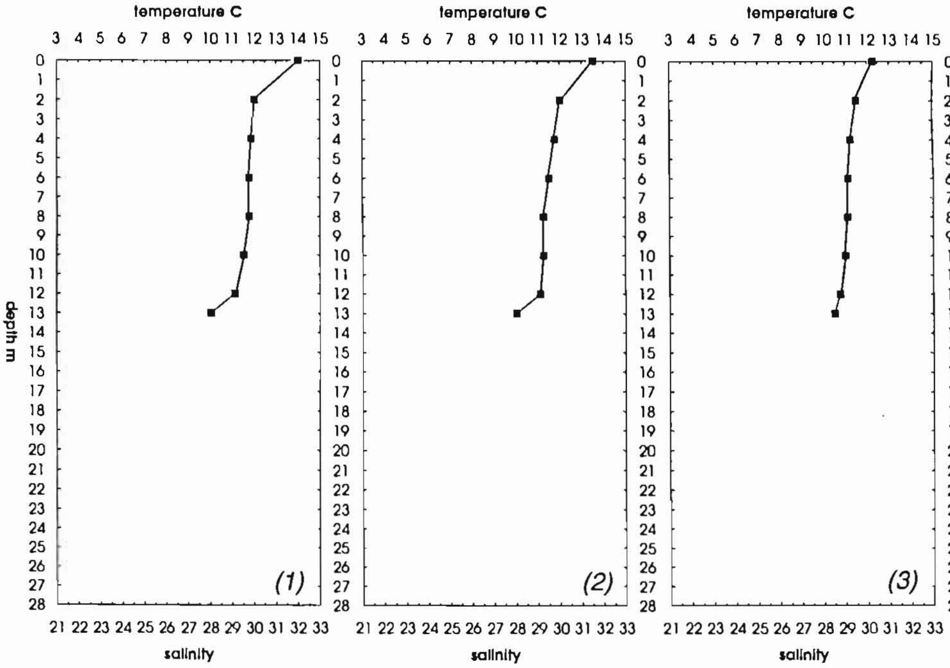

Fig. 11. Vertical distribution of temperature (n) in the areas 1, 2 and 3. Date: 01.09.1983.

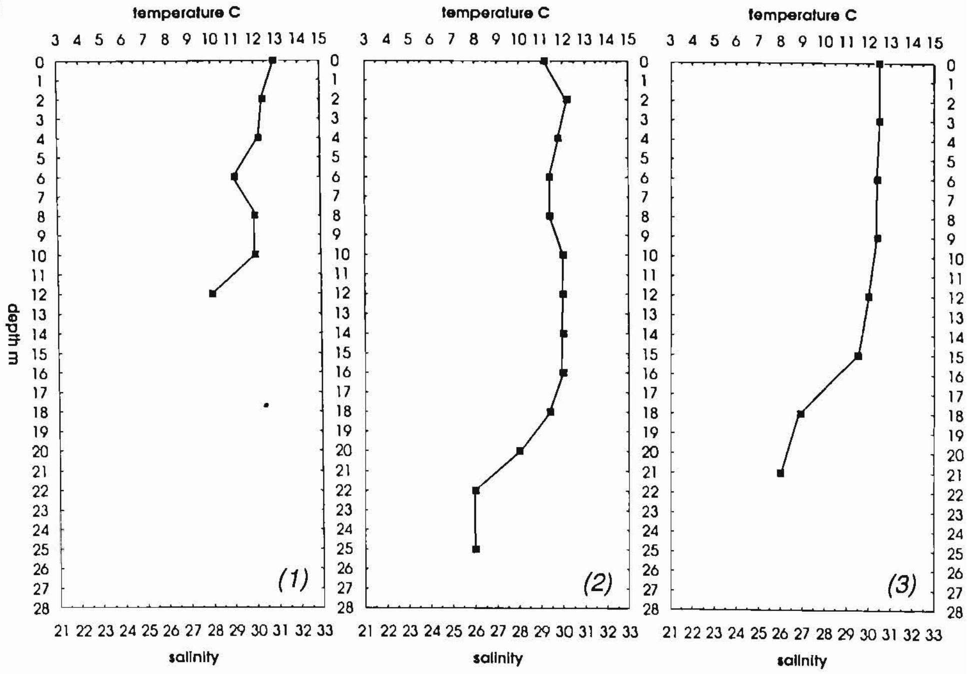

Fig. 12. Vertical distribution of temperature (n) in the areas 1, 2 and 3. Date: 05.09.1985.

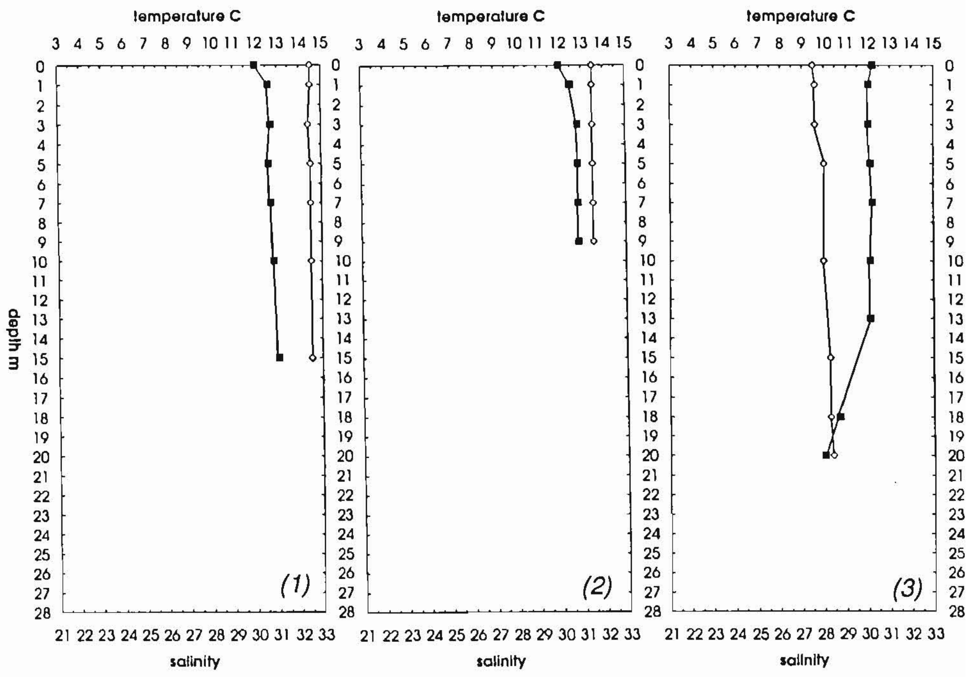

Fig. 13. Vertical distribution of temperature (n) and salinity (_) in the areas 1, 2 and 3. Date: 05.09.1991.

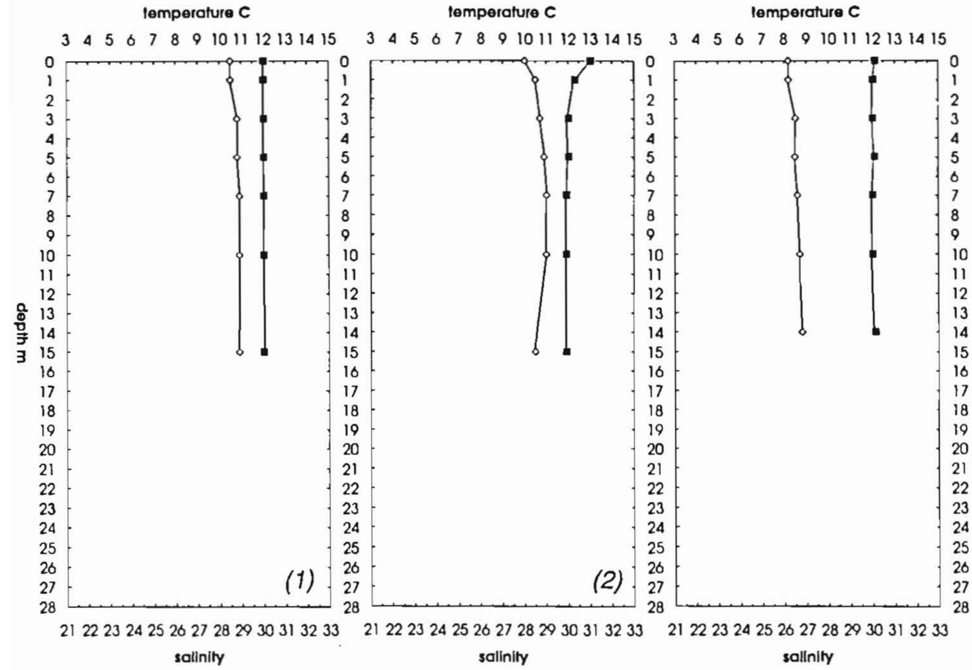

Fig. 14. Vertical distribution of temperature (n) and salinity (_) in the areas 1, 2 and 3. Date: 10.09.1992.

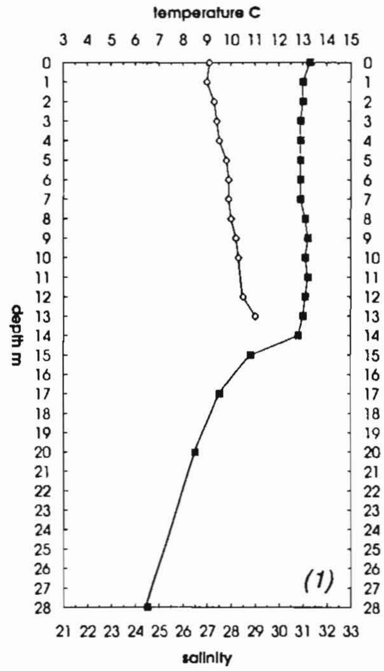

Fig. 15. Vertical distribution of temperature (n) and salinity (_) in area 1. Date: 26.09.1992.

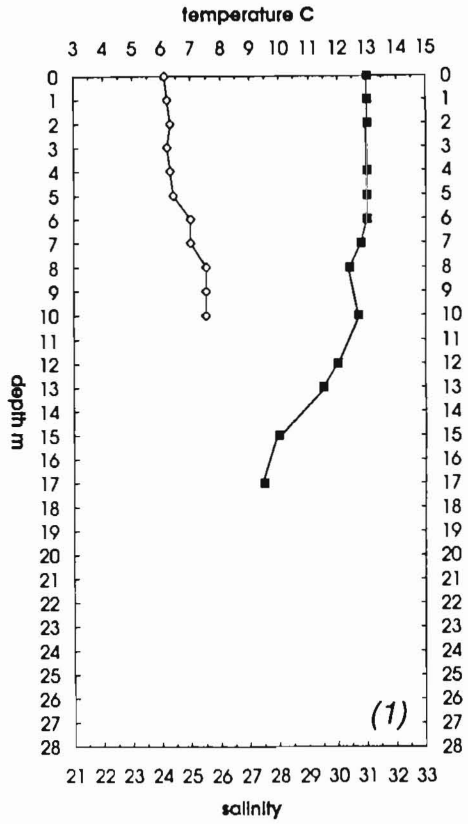

Fig. 16. Vertical distribution of temperature (■) and salinity (◇) in area 1. Date: 02.09.1993.

3.4 Zooplankton

Although no systematic comparisons have been made, it has generally been noted that the numbers of different taxa in plankton samples from Hopavågen are lower than those in samples from the surface layer of the main fjord, taken at about the same time. This may indicate that if the majority of the zooplankton in Hopavågen have originated from the main fjord, as suggested by Olsen (1974), the inflow of fjord water over the shallow threshold has a "sorting-effect".

Table 3. Zooplankton organisms identified in plankton samples from Hopavågen

Tintinnida indet.
Hydroida indet.
Bolinopsis infundibilium
Ctenophora indet.
Rotifera indet.
Turbellaria indet.
Polychaeta indet. (larvae)
Podon sp.
Evadne nordmanni
Ostracoda indet.
Calanoid copepods (all stages)
Calanus finmarchicus (all stages)
Mysidacea indet.
Natantia indet. (larvae)
Brachyura indet. (larvae)
Paguridae indet. (larvae)
Cirripedia indet. (nauplii)
Gastropoda indet. (larvae)
Bivalvia indet. (larvae)
Bryozoa indet. (cyphonautes)
Asteroida indet. (larvae)
Echinoida indet. (larvae)
Ophiuroidae indet. (larvae)
Oikopleura sp.
Sagitta elegans
Chaetognatha indet.
Pisces indet. (larvae)

3.5 Benthic fauna

The dominant organisms in the dredge catches from Hopavågen were the echinoderms *Strongylocentrotus droebachiensis* and *Ophiura albida*, hermit crabs (Paguridae indet.) and the serpulid worm *Pomatoceros triqueter*. In shallow water large populations of the horse mussel *Modiolus modiolus* were observed.

Table 4. Benthos in Hopavågen. Dredge catches from soft and intermediate bottom

POLYCHAETA
Pomatoceros triqueter
Spirorbidae indet.
Terebellidae indet.
Pectinaria sp.
Polychaeta indet.

NEMERTINI
Nemertini indet.

CRUSTACEA
Paguridae indet.
Galathea intermedia
Carcinus maenas
Crangon crangon
Caprellidae indet.
Gammaridae indet.
Balanus balanus
Verruca stroemi

BRYOZOA
Bryozoa indet.

MOLLUSCA
Polyplacophora indet.
Acmaea testudinalis
Aporrhais pespelicani
Turitella communis
Gibbula cineraria
Buccinum undatum
Velutina velutina
Natica sp.
Trophonopsis sp.
Nudibranchiata indet.

Modiolus modiolus
Anomiidae indet.

Pectinidae indet.
Cerastoderma edule
Dosinia sp.
Abra alba
Cyprina islandica
Cultellus pellucidus
Hiatella arctica

ECHINODERMATA
Asterias rubens
Ophiopholis aculeata
Ophiura albida
Ophiuroidae indet.
Strongylocentrotus droebachiensis
Echinus esculentus
Echinocardium cordatum

CHORDATA
Ciona intestinalis

3.6 The littoral zone of Hopavågen

The topography and substrate of the littoral zone in Hopavågen ranges from gently sloping mud flats to steep cliffs (Fig. 17). Besides topography and substrate, wave exposure is the most influential factor affecting the distribution of littoral organisms. Using the relationships between exposure and the distribution of littoral organisms, it is possible to devise biologically-defined exposure scales for rocky shores in a particular area. In Norway biologically-defined exposure scales were devised by Dalby et al. (1978), van Marion (1978) and Osland (1985). The scales describe the overall biological characters of shores with different degrees of exposure, ranging from very exposed to very sheltered.

Hopavågen is a very sheltered locality, but the littoral zone in Hopavågen differs in several aspects from the normal pattern usually found in very sheltered localities:

1 Sublittoral laminarians are absent from Hopavågen.
2 There is no fully developed fucoid zone in the eulittoral zone. The normal fucoids of the littoral zone are locally scarce.

3 The abundance of *Mytilus edulis* is much lower than one would expect under very sheltered conditions. It seems that the settlement of larvae has not been successful for several years.
4 The abundance of *Semibalanus balanoides* is much lower than one would expect under very sheltered conditions.

A common feature of benthic algae, mussels and barnacles is that they are sessile organisms. However, it is clear that the distribution of mobile intertidal animals such as *Nucella lapillus, Patella vulgata* and *Littorina*-species in Hopavågen on the other hand is normal. These species are abundant throughout the whole area on suitable substrates.

The hydrographic measurements showed that the temperature and salinity of the surface water in Hopavågen mainly follows the variation found in the surface layers of the main fjord. Yet in the adjacent area outside Straumen the littoral community is normal. This indicates that that the hydrographic conditions are unlikely to be causing the abnormal pattern of organisms found in the littoral zone in Hopavågen. Furthermore, the variations of temperature and salinity in Hopavågen are much smaller than those found in the inner parts of Trondheimsfjorden. The inner parts of the fjord show normally developed populations of laminarians, fucoids, mussels and barnacles.

Sessile littoral organisms may be damaged or dislodged from the substrate by sea ice. Ice formation however, has not taken place in Hopavågen since 1942 (Mr O.A. Olsen, pers. comm.), and ice erosion therefore cannot explain the unusual distribution pattern of littoral organisms in Hopavågen.

The sea urchin *Strongylocentrotus droebachiensis* grazes heavily on organisms in the sublittoral and eulittoral zone in the Hopavågen area. The sea urchin is very abundant both in and outside Hopavågen. A significant increase in the number of sea urchins, resulting in the disappearance of the laminarian vegetation, was observed by local fishermen in the early seventies (Mr O.A. Olsen, pers. comm.). Initially the sea urchins seemed to avoid the strong current in Straumen, but in the middle of the eighties *Strongylocentrotus droebachiensis* became more abundant in Straumen, resulting in a marked reduction of the laminarian vegetation there. In the same period severe effects of sea urchin grazing were reported from other places along the Norwegian coast (Sivertsen & Bjørge 1980, Sivertsen 1987).

Strongylocentrotus droebachiensis primarily grazes on benthic algea in the sublittoral zone (see review by Hawkin & Hartnoll 1983), but may occasionally graze on fucoids in the lowermost parts of the eulittoral. The unselective rasping of sea urchins may even deplete barnacles at low levels (Lewis 1964). It seems very likely that the absence of sublittoral algae in Hopavågen is caused by the grazing of sea urchins. The eulittoral zone in Hopavågen may also be partly affected by the grazing of sea urchins. However, outside Straumen the sea urchins are at least as abundant as inside Straumen. There are, however, no signs of such grazing effects in the eulittoral zone outside Straumen.

The most outstanding physical differences between the areas outside and inside Straumen refer to the exposure gradient and the tidal movement. Lewis (1964) points out that abnormal tidal movements may have a dramatic effect upon the intertidal organisms. Many sessile intertidal organisms face great problems when the tidal rhythm differs from the semi-diurnal pattern. Larval stages of sessile animals seem to be particularly sensitive. The cyprid-larvae of *Semibalanus balanoides* are far more sensitive to prolonged periods of exposure than the metamorphosed individuals. Other intertidal organisms show the same tendency (Newell 1979). The hypothetical tidal curve for Hopavågen (Fig. 6b) shows that the conditions are highly risky for organisms which depend on an approximate semi-diurnal tidal rhythm. Free dwelling organisms, such as the common intertidal gastropods, can simply avoid this problem by adjusting their position on the shore. Sessile organisms in the sublittoral zone are not affected by this problem either. This is clearly demonstrated by the dense populations of *Modiolus modiolus* in Hopavågen.

Grazing and the abnormal tidal movement seem to be the major problems faced by the intertidal organisms of Hopavågen. Grazing is likely to be the major problem at lower levels, while the abnormal tidal movement is the major problem at higher levels.

The mean water level in Hopavågen is ca 0.5 m above mean sea level. That means, in a geological perspective, that Hopavågen is near the point of being separated from the sea by geological uplift. Calculating on an average

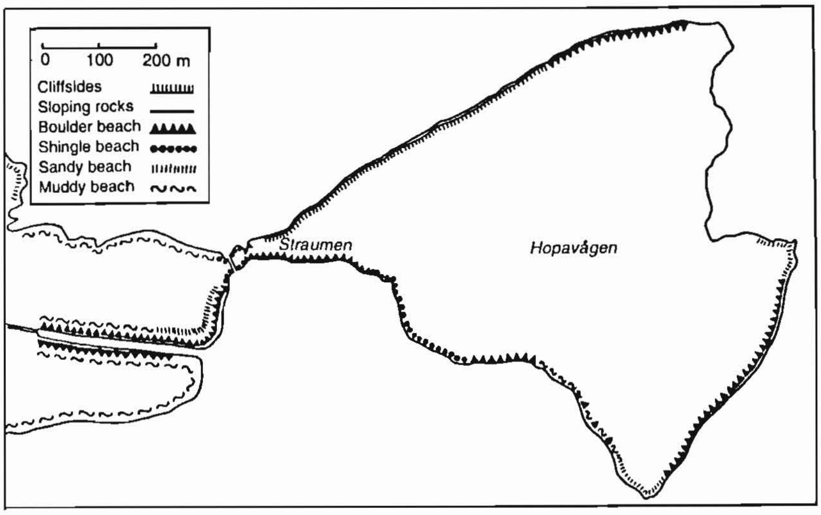

Fig. 17. Substrate and topography of the shoreline of Hopavågen.

uplift rate of 2.1 mm per year (Bakkelid & Skjøthaug 1984), and discounting the effects of sea level variation and varying sedimentary rates, Hopavågen may become separated from the sea in about 700 years. Estimates based on observations at Agdenes during the last fifty years (O.A. Olsen, pers. comm.), indicate that the uplift rate in recent time may be as high as 4–5 mm per year. In this perspective, the abnormal tide regime and the resulting abnormalities in the littoral community, may be interpreted as showing an early stage in the transition of Hopavågen from a landlocked bay to a fully formed lake. In the landlocked fjord Lakselvvatn in Northern Norway, the mean water level is 1.5 m above mean sea level (Jensen et al. 1985), and Lakselvvatn therefore presumably represents a later stage in lake formation. Lakselvvatn has a fully developed fresh water littoral fauna above 2 m deep. The freshwater runoff from two rivers is however greater than in Hopavågen. Lindholm (1982) describes landlocked basins on Åland, representing different stages in lake formation. The conditions in the Baltic Sea (low salinity and small tidal range) differ however from the conditions on the Norwegian west coast.

Anoxic conditions in the deep water may also be explained as a result of land uplift. It has been suggested that a relatively high land uplift rate in recent time may have caused a significant decrease of the water renewal in parts of Borgenfjorden, North-Trøndelag (McClimans 1981).

3.7 The littoral zone of Straumen

The narrowest part of Hopavågen has a width of only 7–8 m and a depth of ca 1.5 m at low tide. Towards the main fjord the tidal stream runs through a ca 200 m long tidal sand/mud flat. Towards Hopavågen, a few meters inside the narrowest part of Straumen, the depth increases suddenly to ca 5–6 m. Still further towards Hopavågen a ca 50 m long shallow bar indicates that the velocity of the water current decreases.

When 259.000 m^3 water is forced into Hopavågen by the rising tide during a period of only 4 h 30 min., the average inflow is almost 1000 m^3/min. With an estimated area of the cross section through the narrowest part of Straumen of ca 18 m^2, the average velocity of the current during a rising tide is ca 0.9 m/s. Dalen (1971) reported measuring velocities exceeding 2 m/s.

Common benthic macroalgae in the tidal zone of Straumen are *Pelvetia canaliculata, Fucus spiralis, F. vesiculosus, Ascophyllum nodosum, Fucus serratus, Scytosiphon lomentaria, Dumontia incrassata, Chordaria flagelliformis* and *Halidrys siliquosa.* Common subordinate algae species are *Corralina officinalis, Chondrus crispus, Gigartina stellata, Palmaria palmata, Hildenbrandia prototypus, Phymatholithon* sp. and *Cladophora rupestris*.

The sublittoral macroalgal community is dominated by *Laminaria digitata*, with the scattered occurrence of *Alaria esculenta*. The *Laminaria*–stipes are heavily overgrown with epiphytic and epizoic organisms. The surfaces of stones and bedrock have a pinkish colour resulting from the presence of an almost complete cover of calcareous algae (*Lithothamnium* sp., *Phymatholithon* sp., *Lithophyllum orbiculatum*). The algae *Ceratium rubrum, Polysiphonia* sp., *Desmarestia aculeata, D. viridis, Leathesia diformis* and *Codium fragile* are common species between the laminarians.

The invertebrate fauna of Straumen (see Table 5) shows a high diversity compared with the fauna in most of the shallow waters in the Trondheimsfjord area. A characteristic feature is the presence of a relatively large number of filter feeders, favoured by the strong tidal current. Another interesting feature is the presence of typical sublittoral organisms at high levels. It is for example not uncommon to find *Buccinum undatum* crawling upon exposed stones in Straumen and *Alcyonium digitatum* can easily be found between stones around the water mark at low tide. This phenomena, a general uplift of the upper limits of some species, is well–known from very exposed localities on the outer coast. In the intermediate and inner parts of the fjords this phenomena is restricted to localities with very strong currents.

Table 5. Marine invertebrates found in Straumen in the period 1983–1994. Recordings marked with (*) are recordings from the tidal stream outside the bridge over Straumen

PORIFERA
- *Cliona celata*
- *Halichondria panicea*

CNIDARIA
- *Hydractinia* sp.
- *Laomedea flexuosa*
- *Dynamena pumila*
- *Clava squamata*
- *Coryne pusilla*
- *Sarsia eximia*
- Hydroidae indet.
- *Alcyonium digitatum*
- *Tealia felina*
- *Metridium senile*
- Actinaria indet.

NEMERTINI
- *Linneus longissimus*
- Nemertini indet.

POLYCHAETA
- Polynoidae indet.
- *Arenicola marina* (*)
- Terebellidae indet. (*)
- *Nereis* sp. (*)
- *Spirorbis* sp.
- *Pomatoceros triqueter*
- *Serpula vermicularis*
- Polychaeta indet.

CRUSTACEA

Balanus balanus
Semibalanus balanoides
Mysidacea indet.
Caprellidae indet.
Gammaridae indet.
Amphipoda indet.
Idothea sp.
Isopoda indet.
Crangon crangon
Galathea sp.
Paguridae indet.
Carcinus maenas
Hyas araneus

PYCNOGONIDAE

Pycnogonum littorale

BRYOZOA

Electra pilosa
Membranipora membranacea
Alcyonidium sp.
Bryozoa indet.

MOLLUSCA

Polyplacophora indet.
Patella vulgata
Acmaea testudinalis
Gibbula cineraria
Lacuna divaricata
Littorina obtusata
Littorina littorea
Littorina rudis
Hydrobia sp.
Velutina velutina
Natica sp.
Nucella lapillus
Buccinum undatum
Nudibranchiata indet.

Anomidae sp.

Musculus discors
Musculus niger
Modiolus modiolus
Mytilus edulis
Mya arenaria (*)
Cerastoderma edule (*)
Hiatella arctica
Pholas candida (*)

ECHINODERMATA
Cucumaria frondosa
Psolus sp.
Echinus esculentus
Strongylocentrotus droebachiensis
Henricia sp.
Asterias rubens
Marthasterias glacialis
Crossaster papposus
Ophiotrix fragilis
Ophiocomina nigra
Ophiopholis aculeata

CHORDATA
Ciona intestinalis
Styela rustica
Ascidiacea indet.

3.8 Fish

The following species of fish species have been recorded from Hopavågen between 1983 and 1994:

Gadus morhua, Pollachius virens, Merlangius merlangus, Pollachius pollachius, Trisepterus minutus, Clupea harengus, Platychthys flesus, Microstomus kitt, Pleuronecta platessa, unidentified flounder (hybrid?) (Pleuronectidae indet.), *Coryphoterus flavescens, Pomatoschistus minutus, Spinachia spinachia, Pholis gunellus, Labrus bergylta* and *Ctenolabrus rupestris*.

According to local fishermen (Mr O.A. Olsen, pers. comm.), the cod in Hopavågen is considered to be of "poor quality".

The condition factor (k) of 31 individuals of *Gadus morhua* from Hopavågen was calculated, based on measurements of weight and length, using the following relationship:

$k = m.100 / l^3$,

where m is the weight in grams and l is the length in cm (Fig. 18). The length ranged from 19 to 70 cm.

The condition factor of cod normally varies between different localities. This usually indicates different nutritional conditions, but there may also be genetic causes. The results from Hopavågen correspond well with measurements made in Borgenfjorden (Denstadli 1972, Mork 1976).

The stomach contents of all the specimens (31) recorded in Fig. 18 were examined. Reptantia were found in 80% of the stomachs (Fig. 19). The cod has very general feeding habits, but may specialize on a prey that temporarily or locally is abundant (Mattson 1990). In Hopavågen the relatively high abundance of Paguridae is clearly reflected in the cod stomachs.

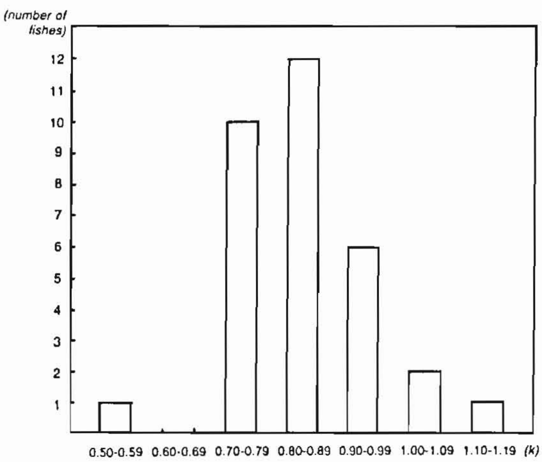

Fig. 18. Condition factor (k) of *Gadus morhua* from Hopavågen. 15 individuals caught on 11.05.1989 and 16 individuals caught on 05.09.1991.

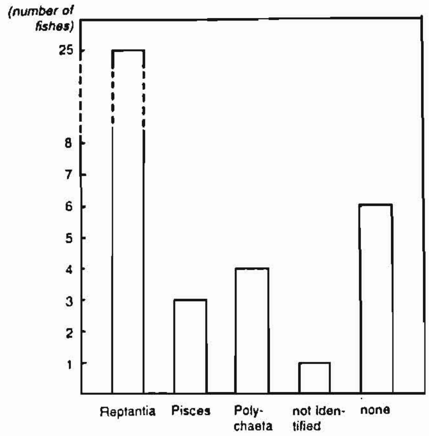

Fig. 19. Stomach contents of *Gadus morhua* from Hopavågen. 15 individuals caught on 11.05.1989 and 16 individuals caught on 05.09.1991.

4 CONCLUSIONS

The hydrographic measurements in Hopavågen show that the renewal of deep water is restricted, resulting in anoxic conditions. Total deep water renewal may occur during the winter, but it is not certain if this happens every winter. These anoxic conditions are due to the presence of a shallow sill in Straumen. Similar conditions are found in other landlocked fjords on the southern and western coast of Norway (Strøm 1936, Stokland 1987, Skei, 1988, Stokland & Berge 1988) and on the coast of Northern Norway (Jensen et al. 1985).

Hopavågen is a poll with a very large volume of water compared with the polls which are usually considered as suitable for juvenile fish production (Svåsand & Øyestad 1986, Jensen 1987a, b). The large volume and relatively great depth may cause practical problems. In addition the poor circulation and the formation of hydrogen sulphide in a large proportion of Hopavågen may also cause other problems. The conditions in the deep layers might eventually be improved by substituting some of the old deep water with fresh intermediate water from outside Hopavågen. A "natural" circulation could be generated by releasing brackish or fresh water or compressed air into the deep layers of poorly circulating waters (Molvær et al. 1985). As another solution the volume of tidal water entering and leaving Hopavågen might be increased by enlarging the narrowest part of Straumen. According to McClimans (1978), an inlet gives a maximum energy production when the tidal range within the basin is 0.707 times as large as the external tidal range. In Hopavågen this ratio is *ca* 0.2. Nevertheless, it is not at all certain that increasing the energy in the tidal current towards its maximum, would cause enough mixing to produce large scale circulation in Hopavågen.

With regard to shellfish farming the poor circulation and the large volume of water play a minor role. Whether or not Hopavågen is a suitable locality for shellfish farming depends among other factors on the growth rate the shellfish might achieve there. Dense populations and high growth rates of *Mytilus edulis* are usually found in the intermediate and inner parts of a fjord, areas with a relatively high surface temperature in summer and relatively low surface salinity (Brattegard 1966, Lande 1973, Rustad 1980). In this respect Hopavågen does not seem to provide optimal conditions. Moreover, the almost total absence of a *Mytilus edulis* population in Hopavågen may result in poor settlement of larvae.

In a research and educational context, Hopavågen and Straumen are very interesting. Straumen offers optimal conditions for the study of specialized marine invertebrates and communities in tidal rapids. Hopavågen is an interesting locality showing features of the early stages in natural lake formation due to land uplift. As an outdoor research and training laboratory, Hopavågen has outstanding qualities. The sheltered conditions offer good facilities for hydrographic and biological studies, summer and winter, in all kinds of weather.

5 SUMMARY

Hopavågen is a landlocked marine basin, connected with the main fjord through a narrow shallow channel, Straumen. The shallow sill of this basin affects the hydrographical and biological conditions in several ways:

1. The renewal of the deep water is restricted. This results in anoxic conditions and the formation of hydrogen sulphide.

2. The tidal range of Hopavågen is much smaller than in the main fjord.

3. The tidal movement inside Straumen differs from the «normal» tidal movements of open coasts by having a longer outflow than inflow period. During neap tides there may be no inflow at all.

4. The mean water level of Hopavågen is highest during spring and lowest during neap tides in the main fjord.

5. The tidal anomaly in Hopavågen gives rise to an abnormal intertidal community pattern. There is no fully developed fucoid zone and the abundance of *Mytilus edulis* and *Semibalanus balanoides* is much lower than one would expect under such sheltered conditions. The varying mean water level seems to discourage sessile intertidal organisms, while the free–living organisms appear to be unaffected. The strong tidal current within Straumen has given rise to the development of a highly specialized community of organisms typically found in tidal rapids, these include many filterfeeders.

6 ACKNOWLEDGEMENTS

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