Ödsmål, Kville sn, Bohuslän

Hällristning
Fiskare från
bronsåldern

Rock carving
Bronze age
fishermen

MEDDELANDE från
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Eutrophication and other Pollution Effects in North European Waters

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by

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Eutrophication and Hypertrophication.

The expression "eutrophication" is nowadays often encountered in marine science. It was first introduced by Weber (1907) for describing the nutrient rich conditions in North German peat-bogs as a contrast to oligotrophic or nutrient poor conditions. Naumann (1919) applied the term in limnology. Eutrophication means a development towards a more nutrient rich state regardless if this happens naturally or if it is caused by man. Naumann suggested that there exists a direct connection between the phytoplankton production and the nutrient conditions in the water. He also suggested that phosphorus and nitrogen have a decisive influence on the quantity and composition of the phytoplankton. This principle is still valid.

In pollution studies eutrophication is often used to describe the negative effects or overfertilization of the water. This is not the original meaning of the expression. The prefix "eu-" originates from Greek and means good. An eutrophication of an oligotrophic water body will increase the phytoplankton production and will have positive effects through the whole food chain improving e.g. fishing. If the fertilization of the water increases the biological production in the area so much that utilized oxygen cannot be replaced, negative effects may be created and we should speak about "hypertrophication" of the water.

Liebigs Law.

The famous German agricultural chemist Justus von Liebig introduced 1855 a law for the limits of a crop, called the Law of Minimum. This law states that a crop is limited by the nutrient salt present in the soil in minimum amount in proportion to the need of the plants. If we fertilize the soil with that nutrient, we can increase the crop yield.

Liebigs law can also be applied in the aquatic environment. When discussing the causes of eutrophication or hypertrophication of natural waters, Liebigs law is often referred to. One speaks readily about a certain limiting growth factor and says that every increase of its concentration in the water, will result in a proportional increase of the production of e.g. phytoplankton. The real effects are, however, much more complicated.

Fertilization with a nutrient salt will only be possible to the limit where another nutrient or other factor becomes limiting. Such factors may be light, temperature, vitamines, hormones, certain trace metals etc.

Mitschelich-Baules equation.

In 1916 Mitscherlich showed that when a limiting factor x, is increased, this increasing is not proportional to the increasing of the crop y, but to the difference between the maximum yield A, which will be obtained when the factor x is optimal, and the real increasing y. The relation was expressed through the following equation, where e is the base of the natural logarithm and c is a constant (Boguslawski 1958):

$$y = A(1 - e^{-ex}) \text{ or } dy/dx = c(A - y)$$

The same year Baule showed that the effect of the factor x is àlso depending on other limiting factors z, v etc. This interaction he formulated from Mitscherlichs equation as follows:

$$y = A(1 - e^{cx})(1 - e^{-c_1 z})(1 - e^{-c_2 v}) \text{ etc.}$$

Fig. 1 shows Mitscherlich-Baules equation for two factors x and z. The constants c and c_1 have for simplicity been given the same arbitrary value (0.7) (Rhode 1972). The effect of the increasing of a growth limiting factor is obviously depending both on its own concentration or intensity and on the effects of other simultanously acting factors.

This can be expressed in the following manner: The relative effect of a facor is largest when it is most in minimum in comparison to other factors. Its relative effect decreases with increasing concentration or intensity and approaches zero at its optimum, that is when the factor has maximum effect. Relative effect means growth or crop yield per concentration or intensity unit. It shows that e.g. a phosphate increase of 1 μg P/l water gives larger effects on the primary production with decreasing phosphate level and increasing nitrate level in the original water mass. The same is of course valid for nitrogen in connection with phosphorus and for all factors which may influence the yield.

In Nature not only one or two, but many factors, both chemical and physical as e.g. nutrients, trace metals, oxygen, pH, light, temperature, influence and limit the phytoplankton production and therefore, after a concentration or intensity increase may act as eutrophicants. Therefore it is not correct to speak about one minimum factor or the minimum factor. In reality there is always an interaction between all the growth factors, of which one, however, may be most limiting.

Effects of Sewage discharge.

In fresh water the availability of phosphorus generally is the most limiting factor among the nutrients. But after a high phosphorus increase e.g. through sewage discharge, nitrogen or some other factor may become more limiting than phosphorus in inland waters and brackish waters. In the oceans nitrogen is considered to be most limiting. It is a well known fact that both phosphate and nitrate decrease to values very close to zero in the surface water of large areas of the open oceans during the vegetative seasons. Sewage from urban areas contains large amounts of both nutrients and sewage water generally has an eutrophicating effects on coastal waters. Sewage thus is an important nutrient, but unfortunately it contains harmful factors as e.g. bacteria and virus which may cause diseases to higher living organisms. In fresh water areas cattle and Man may drink sewage contaminated water. Fishermen in the area may catch infected fish. In industrialized countries sewage may additionally contain different kinds of toxic matter, as heavy metals.

Hypertrophication may occur when large amounts of untreated sewage are discharged from densily populated communities, e.g. big cities, especially if the discharge occurs in a gulf or bay with restricted water exchange. The algal growth in the surface water and along the shores may increase so much that recreation areas are destroyed. In the deep water all oxygen may be utilized in oxidation of dead organic matter. The oxygen utilization is so fast that new oxygen cannot be supplied in a sufficient degree through diffusion from the atmosphere or through horizontal inflow from the open sea. Examples of such conditions are the archipelagos around Stockholm and Helsinki in the Baltic area.

According to Swedish investigations the discharge of easily oxidable organic matter from communities cause first a primary oxygen reduction in the recipient when the matter is broken down through oxidation. The nutrients which are set free in this process, will fertilize the water and cause a high plankton production. When this plankton dies and is broken down through oxidation, this process will cause a secondary oxygen reduction in the recipient. This reduction may be tbree to five time larger than the primary oxygen reduction (Fig. 2).

BOD in the Baltic and the North Sea.

Oxygen utilization in the water may also be increased directly without eutrophication or hypertrophication of the water. This happens e.g. when paper or pulp mills discharge large amounts of readily oxidable organic matter into the water. This matter often contains only small amounts of nutrient salts. The oxygen utilization of water is generally expressed as Biological Oxygen Demand (BOD). The BOD is measured after storing the sample for 5 or 7 days.

BOD values for the discharge of sewage and industrial wastes have been computed for the North Sea (ICES 1974) and for the Baltic (Dybern 1974). The values are around 10^6t/year and 1.2×10^6/year respectively. The volume of the North Sea is about 64 000 km^3 and of the Baltic 22 000 km^3. This gives a BOD_7 of 0.01 mg/l/year for the North Sea and 0.052 mg/l/year for the Baltic, if the BOD load would be evenly distributed in the whole water mass. These numbers are not alarming when one considers that 1 l water contains around 10 mg oxygen and that the diffusion rate of oxygen through the sea surface is very fast. The North Sea water has a renewval time of only few years, but the renewal time of the Baltic water is as high as 35 years. Also with this slow renewal time the oxygen supply would be sufficiently fast if the water were not stratified. The stratification is mainly caused by a permanent halocline, which prevents termohaline convection. This causes oxygen depletion in the deep water below the halocline. The increased load of oxygen utilizing organic matter during the last decades may be one of the reasons for the hydrogen sulfide formation in the bottom water of the Baltic deep basins. Fig. 3 shows the estimated BOD load of the Baltic according to Dybern (1974). Table I shows the estimated BOD loads and discharge of different types of wastes discharged into the North Sea (ICES 1974).

Discharge of easily oxidable organic matter from industries.

The Idefjord between Norway and Sweden is an example on a fjord into which large amounts of easily degradable organic matter from a pulp mill are discarged. The Idefjord is around 25 km long and forms a 90° angle at the Norwegian town Halden (Fig. 4). In the entrance area are two sills. Inside these are two main basins. The sill depth is 8.5 - 9.5 m and the maximum depth of the basins are around 40 m. There are several fresh water discharges, but only two of them have importance, the Tista which discharges at Halden and brings large amounts of wastes to the fjord and the Berbyelva in the innermost part of the fjord, which discharges water of good quality. The long and narrow form of the fjord and the high sills in the entrance area prevent effective water exchange. The fresh water supply causes formation of a halocline and this makes the deep water inside the sills very sensitive to discharge of wastes. The pulp mill is located in Halden (point 11 in Fig. 4). The discharge from the mill contains large amounts of organic and inorganic solid matter (9 000 t of organic matter/year and 4 300 t of inorganic matter/year). The water discharge is about 2 m^3/s. The water contains in addition harzes, acids and metals. The sewage water from the city of Halden contains 40 kg P and 230 kg N/day, but because the primary production in the fjord is practically zero, this fertilization has no effect. The bottom of the fjord is almost dead and large amounts of fiber material have been deposited there (Dybern 1972). All oxygen of the water below the halocline has disappeared and large amounts of hydrogen sulfide have been formed (Fig. 5). The hydrogen sulfide layer sometimes extends up to the surface. Occasionally the water of the fjord is partly renewed through inflow of water from the Skagerack, but reducing conditions return in the water in few weeks (Fig. 6). Fig. 7 shows the discharge of lignosulphonic acid from the paper mill (Engström 1975). Plans to improve the situation in the Idejord are being prepared by the Norwegian authorities.

Discharge of toxic elements.

Recently there has been a lot of big headlines in Scandinavian newspapers about a Finnish oil tanker, which on its way back to the Persian Gulf, intended to dump some 7 tons of arsenic enclosed in barrels into deep water somewhere in the Atlantic outside the Cape Town. Due to the pressure of the public opinion in Scandinavia, the tanker was forced to deliver the arsenic barrels back to Finland. Especially television, radio and newspapers in Sweden were very indignant and upset over the planned dumping.

It is easy to raise the public opinion against dumping of toxic material and single cases may get quite a lot of publicity, but the more serious dumpings or discharges of toxic waste are easily forgotten after the first alarms and may go on for long times.
In Sweden the "Rönnskärsverken" outside Skelleftehamn at the Bothnian Bay has since 1930 discharged large amounts of heavy metals and arsenic into the water. Rönnskärsverken is owned by the Boliden Company and processes copper ore and prepares from the byproducts e.g. arsenic, arsenic salts, zinc, selenium, sulfuric acid, nickel sulfate, gold and silver. At present the discharge of arsenic is 1 500 t/year. This discharge should be compared to the planned Finnish dumping of 7 tons into deep water in the open ocean.
The Bothnian Bay is a semienclosed sea area with a very slow renewal time of the water. The volume of the basin is only 1 540 km^3

and it is the innermost part of the Baltic, which has an average renewal time of its water around 35 years. Table II shows the main content of the waste water from the Rönnskärsverken reported by the company.

Table II

(from Lithner 1974)

Tons/year

As	Zn	Pb	Cu	Cd	Hg	Se	Cr	Ni	Te	F	SO_2	H_2SO_4	Fe
1500	144	25	50	9.7	1.1	4	2.4	2	0.7	86	1200	600	300-500

Kg/year

Mn	Co	Bi	Sn	Tl	Ag	Ga	In	Au
5600	2400	1200	1000	560	480	300	240	16

The discharge has been decreased from 3200 t in 1967 to 2200 t in 1968 and is at present 1 500 t.

Investigations have shown high values of arsenic in the bottom sediments close to the Rönnskärsverken. The lower levels of animal population on the sea floor has been damaged in an area of 40 km^2 around the discharge point.

Arsenic in the form of arsenate reacts with molybdate in the same manner as phosphate and forms a similar blue colour when reduced. Therefore arsenate normally is included in the phosphate analysis. In sea water arsenate is only some percent of the phosphate and it is not reported separately. It is, however, possible to distinguish between phosphate and arsenate in a simple way, because phosphate reacts much faster than arsenate with molybdate. If the sample is measured after 5 minutes and again after one hour, the difference between the readings will give the arsenate. Such measurements in the Bothnian Bay show that more than 50 % of the total value in the ordinary phosphate analyses may be arsenate.

Fig. 8 shows a longitudinal section of the Gulf of Bothnia and the distribution of arsenate in the water according to Dahlin (1975). The Rönnskärsverken is located at point F8 in the figure. The arsenate is spreading with the outflowing surface water into the Bothnian Sea (to the left in the figure).

Recovery of a sea area.

Sometimes we may see in a newspaper that a sea area is "dead" and never can recover. The Baltic has e.g. several times been declared to be in such a state that it never can be saved. This is of course an exaggeration. If necessary measures are taken, a sea area can always recover. Nature will in due time restore the conditions if the cause of the pollution is removed.

The Gullmarsfjord at the Swedish west coast may serve as an example. The innermost part of the Gullmarsfjord has two arms, Saltkällefjorden and Färlevfjorden. The Örekil river discharges into the Saltkällefjorden. A paper mill at Munkedal discharges its waste into the Örekilsälven. Until the middle of the 1960:ies the factory discharged sulphite waste liquor and 25 tons of dry substance/day. The sulphite liquor could be traced to the mouth of the Gullmarsfjord 30 km from the discharge point. The effects of the discharge were catastrophic for plants and animals in the shore areas. The bottom of the Saltkällefjord was practically dead. In 1966 the factory decided to stop the fabrication of paper mass and instead buy it elsewhere and only fabricate paper. After that year several km of the shore were fast recolonized by plants and animals. The shore fauna had almost completely recovered after three years. The bottom fauna recovered in 5-6 years. Fig. 9 shows recolonization of macroscopic bottom fauna at three localities in the Saltkällefjord after closing of the sulphite factory. (Rosenberg 1974).

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Table I. Summary of the input data in Tables 1-4

Pollutant (tonnes/year)	Source: Domestic	Source: Industry	Source: Dumping	Atmosphere (preliminary data)
BOD	546 × 10^3	459 × 10^3	?	?
COD	882 × 10^3	?	?	?
Nitrogen	199 × 10^3	219°	?	?
PO_4 Phosphorus	36 × 10^3	73°	?	?
Organochlorine pesticides	0.66	?	?	?
PCBs	6.56	?	?	?
Zinc	25.4 × 10^3	15.4 × 10^3°	?	100 × 10^3‡
Copper	3.9 × 10^3	1.84 × 10^3°	?	13 × 10^3
Manganese	61.4 × 10^3	?	?	6 × 10^3
Lead	?	3.16 × 10^3°	?	15 × 10^3
Mercury	22	119°	?	?
Cadmium	?	112°	?	2.3 × 10^2
Iron	?	176 × 10^3°	75 × 10^3+	150 × 10^3
Acids	–	493 × 10^3°	225 × 10^3	?
Volume of discharge/rainfall (m^3/year)	2 680 × 10^6	1 795 × 10^6°	?	46 000 × 10^7

° Data very incomplete

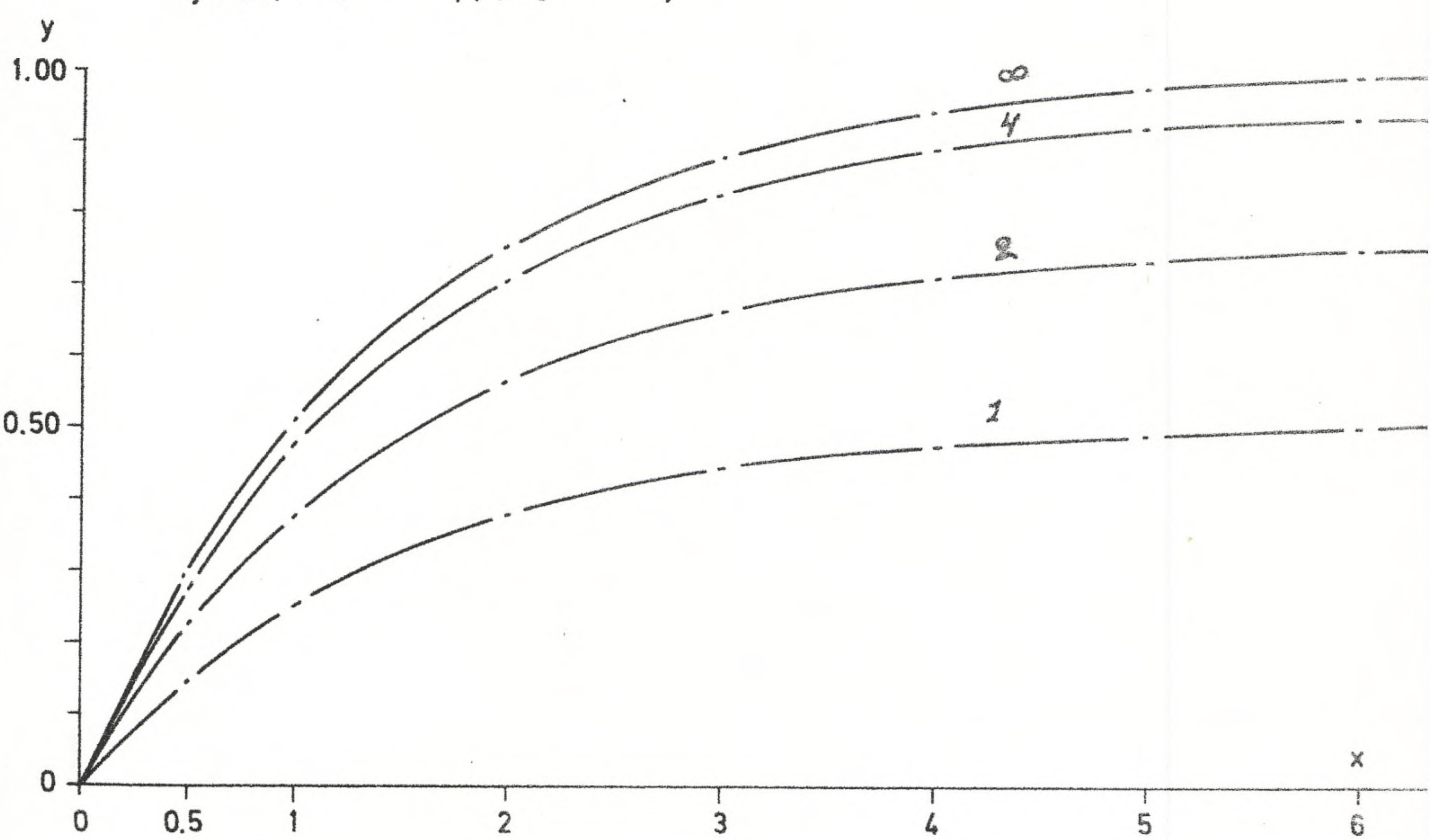
\+ Titanium dioxide waste only and assumes 10% acid and 10% $FeSO_4$

‡ There is considerable doubt about the validity of this figure

Fig. 1

Mitscherlich – Bautes equation for the influence of the growth factors

$$y = A(1 - e^{-0.7x})(1 - e^{-0.7z})$$



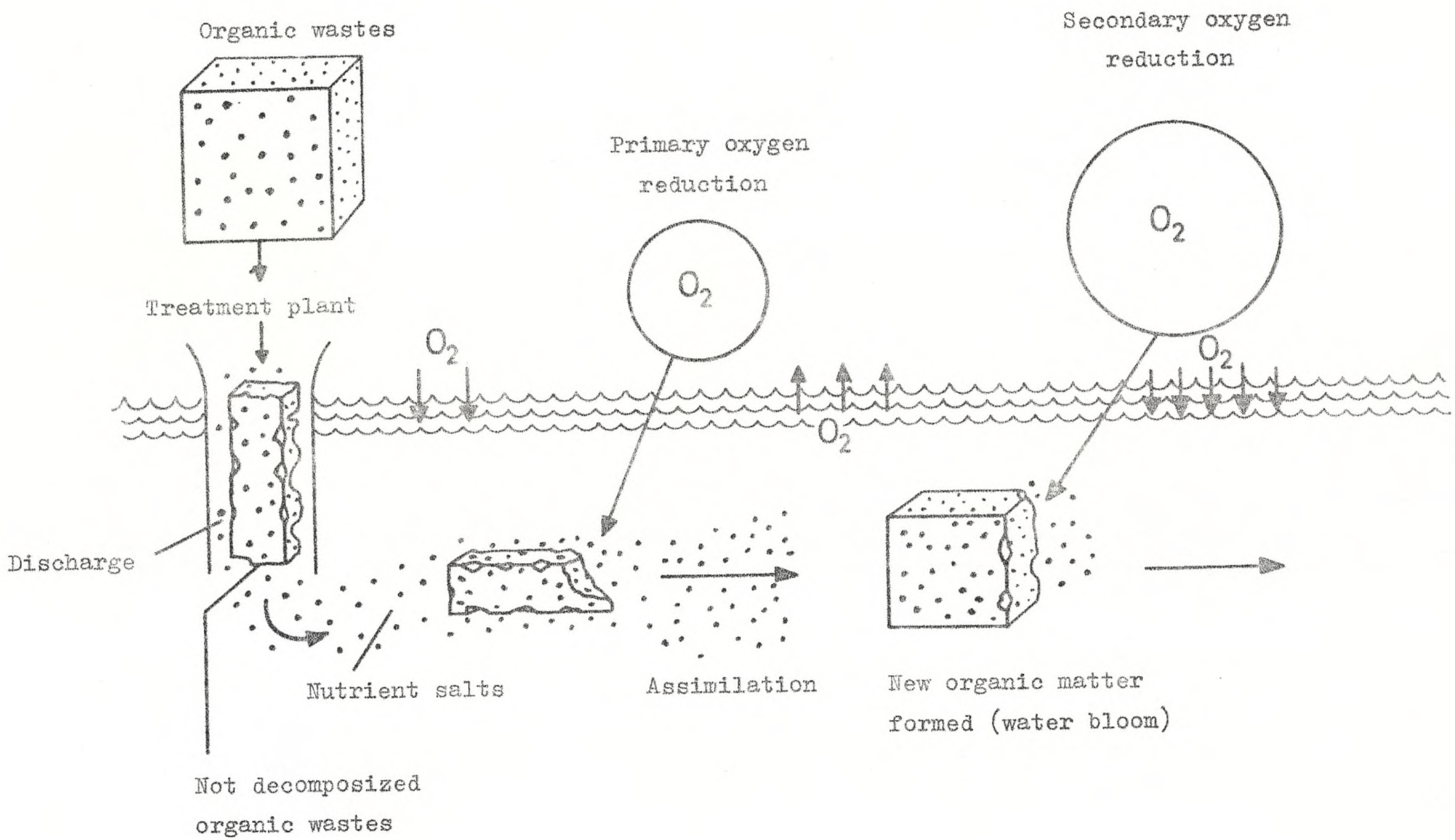
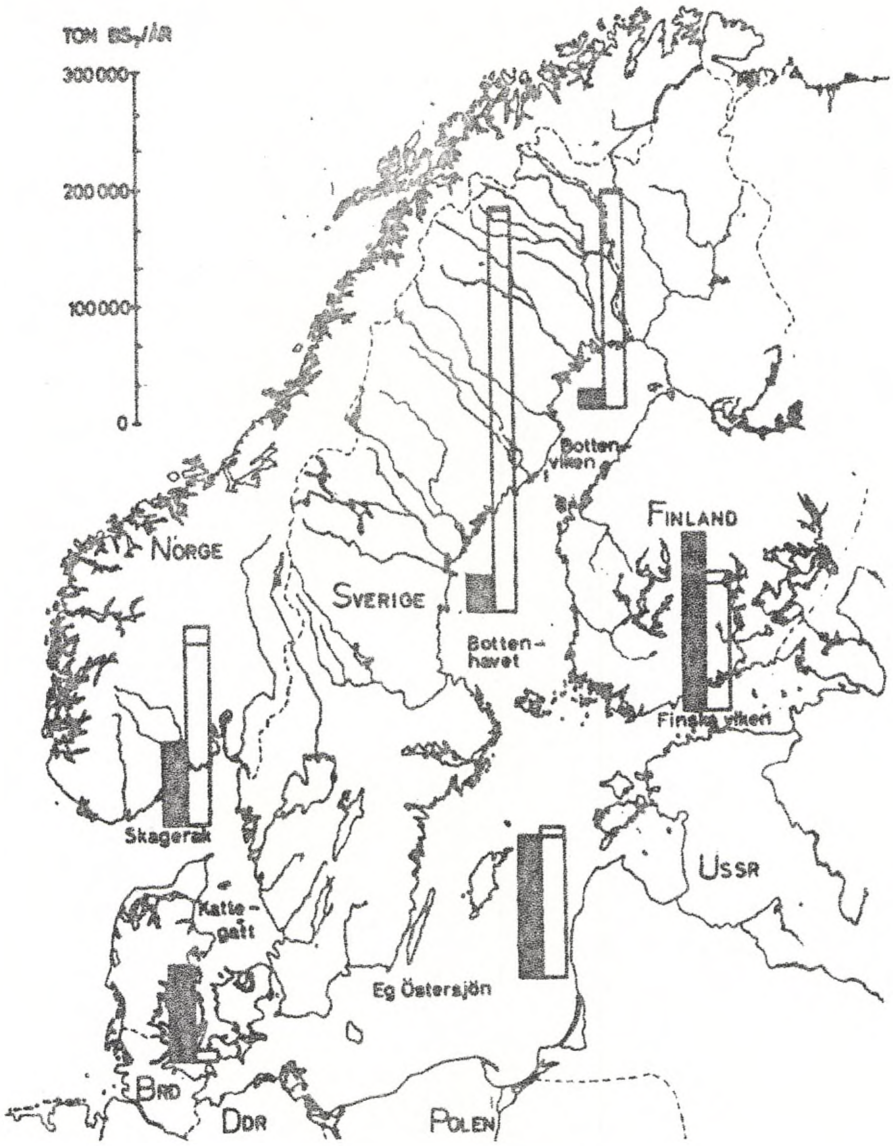
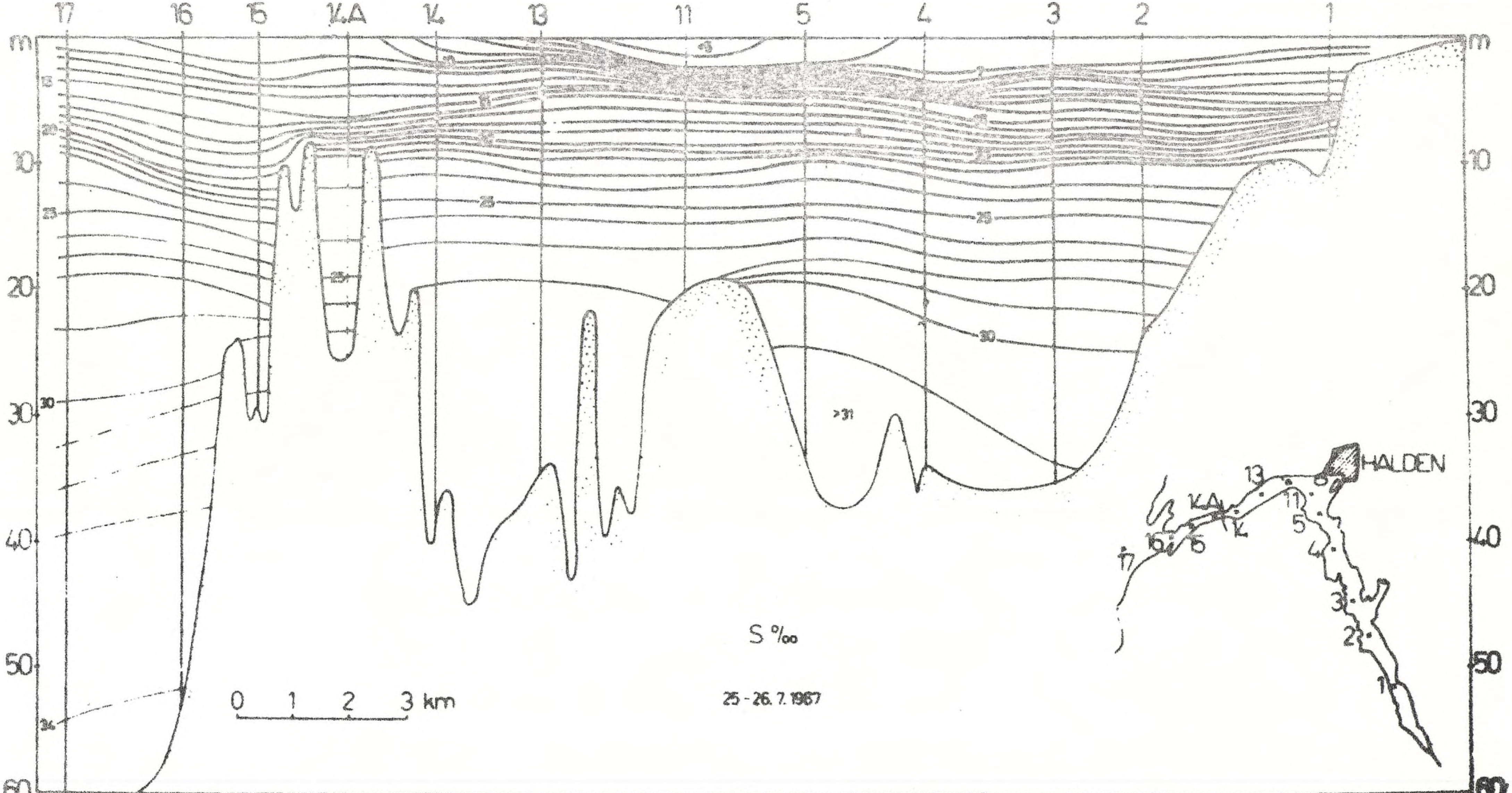

Organic wastes
Treatment plant
Discharge
Not decomposized
organic wastes
Nutrient salts
Primary oxygen
reduction
O2
O2
O2
Assimilation
Secondary oxygen
reduction
O2
O2
New organic matter
formed (water bloom)

Fig. 2

Fig. 3

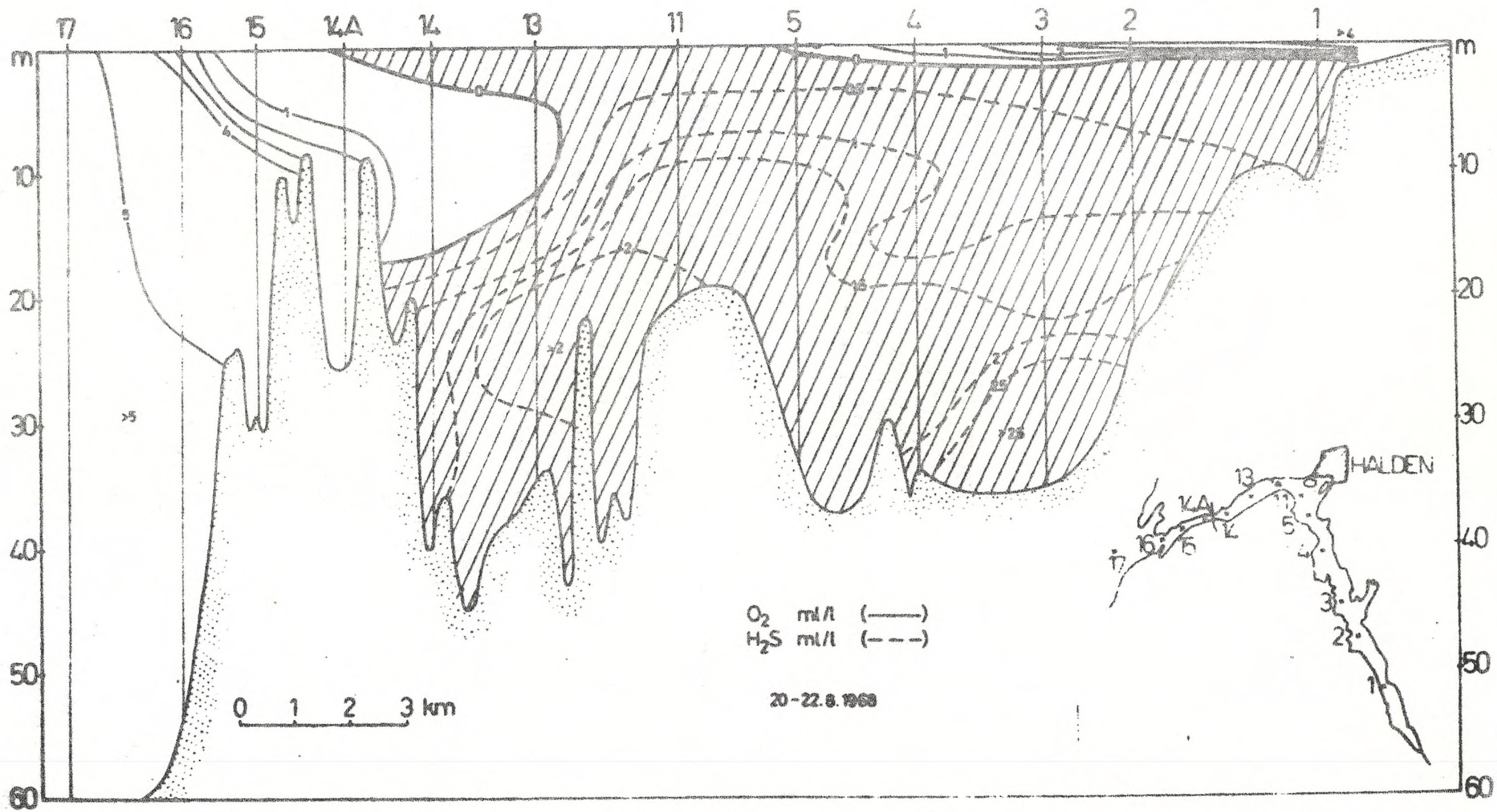


The discharge of oxydable organic matter along the coasts of the Baltic, the Kattegatt and the Skagerack expressed as BOD_7. Black bars show sewage from communities. Transparent bars show discharge from industries (the part below is from pulp, paper and other wood processing industries. The small part above is from other industry).



17
16
15
14A
14
13
11
5
4
3
2
1
m
10
20
30
40
50
60
HALDEN
S ‰
25 - 26. 7. 1967
0 1 2 3 km

Fig. 4


17
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4
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2
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m
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20
30
40
50
60
>5
0 1 2 3 km
O_2 ml/l (——)
H_2S ml/l (– – –)
20-22.8.1968
HALDEN

Fig. 5

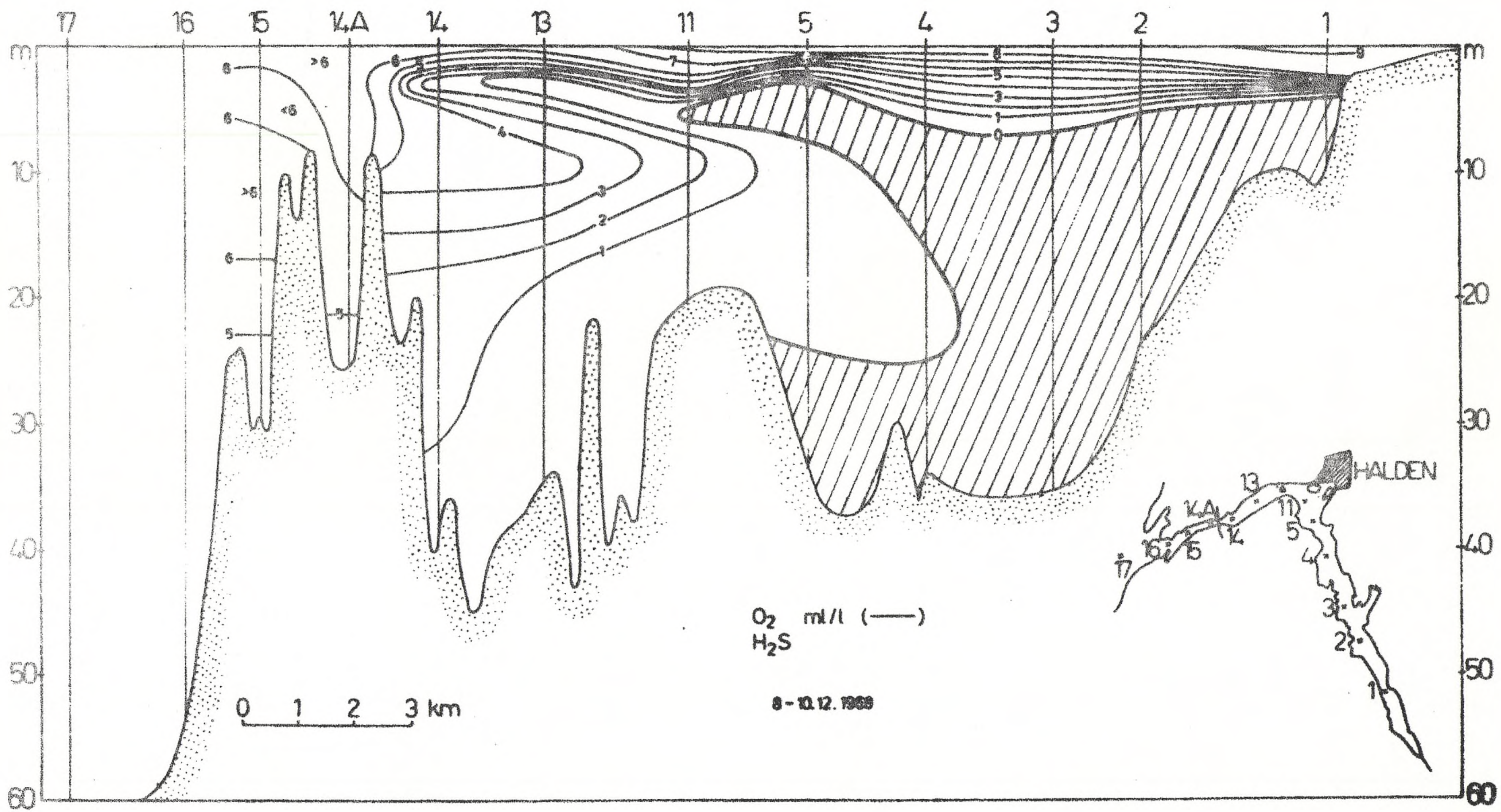
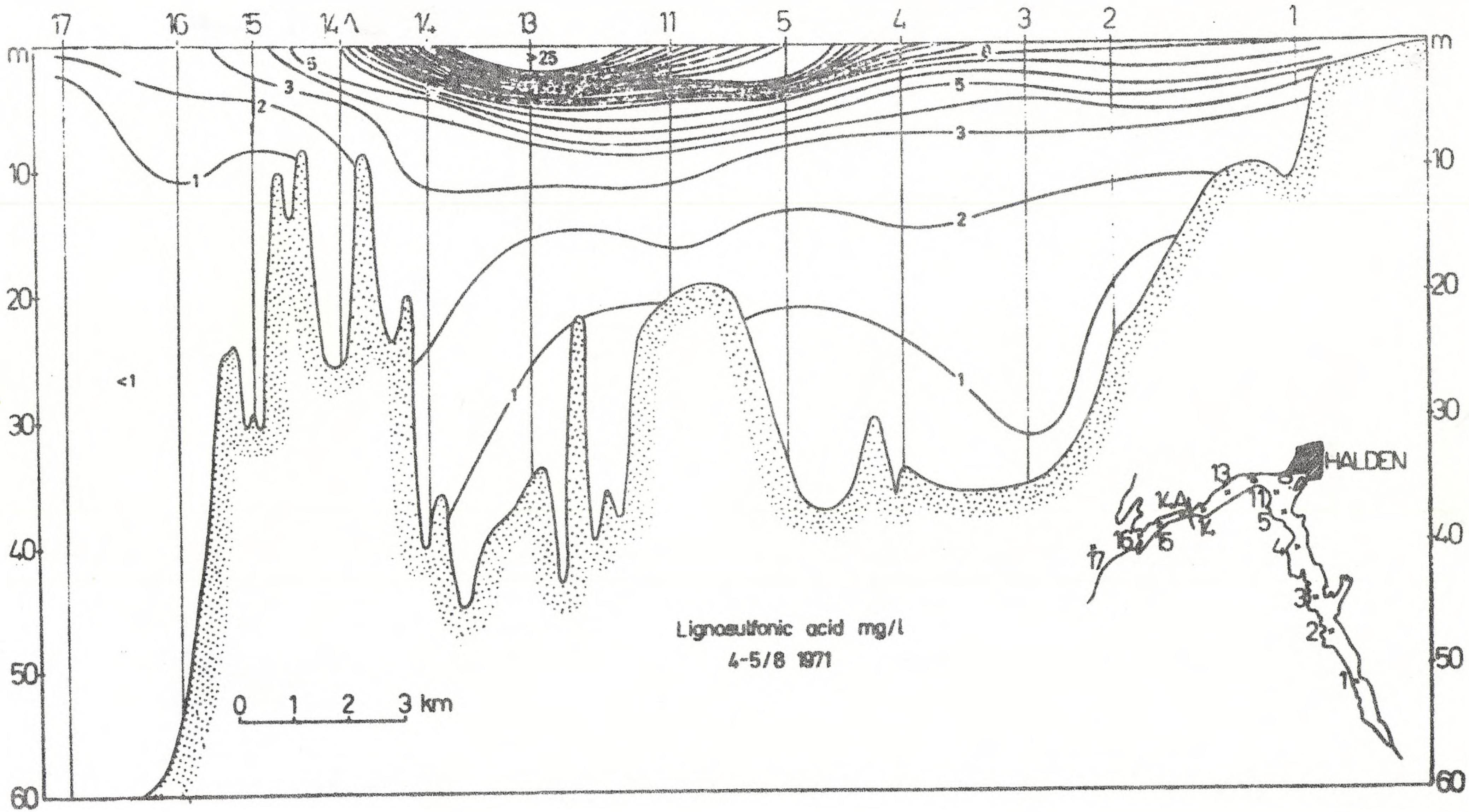

17 16 15 14A 14 13 11 5 4 3 2 1
m
10
20
30
40
50
60
HALDEN
O_2 ml/l (——)
H_2S
8 - 10.12.1969
0 1 2 3 km

Fig. 6


Lignosulfonic acid mg/l
4-5/8 1971
HALDEN
0 1 2 3 km
17
16
15
14A
14
13
11
5
4
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2
1
m
10
20
30
40
50
60
>25
<1

Fig. 7

AsO_4 µgat/l · 10^{-2} 74 11 18-20

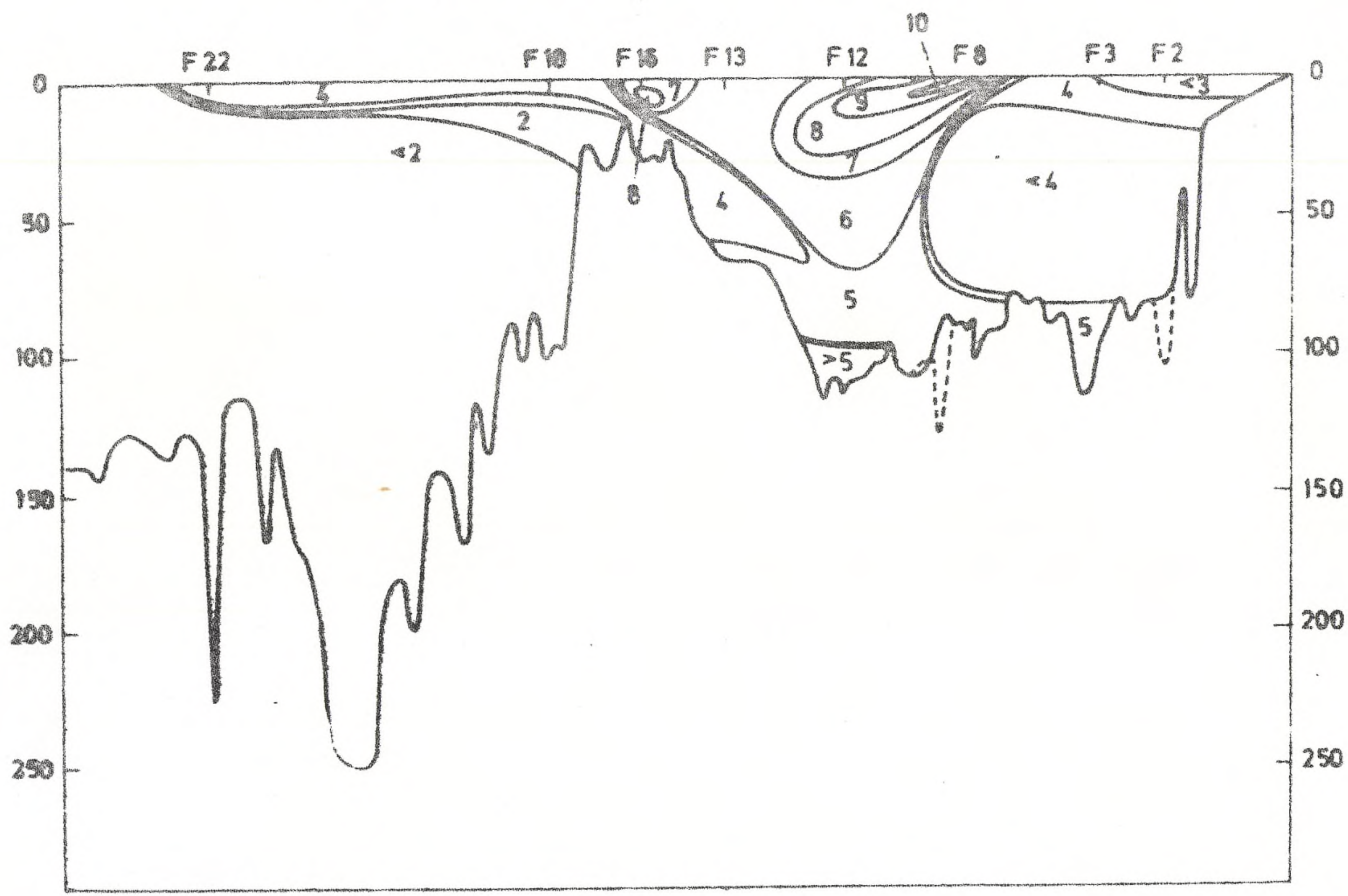

Fig. 8

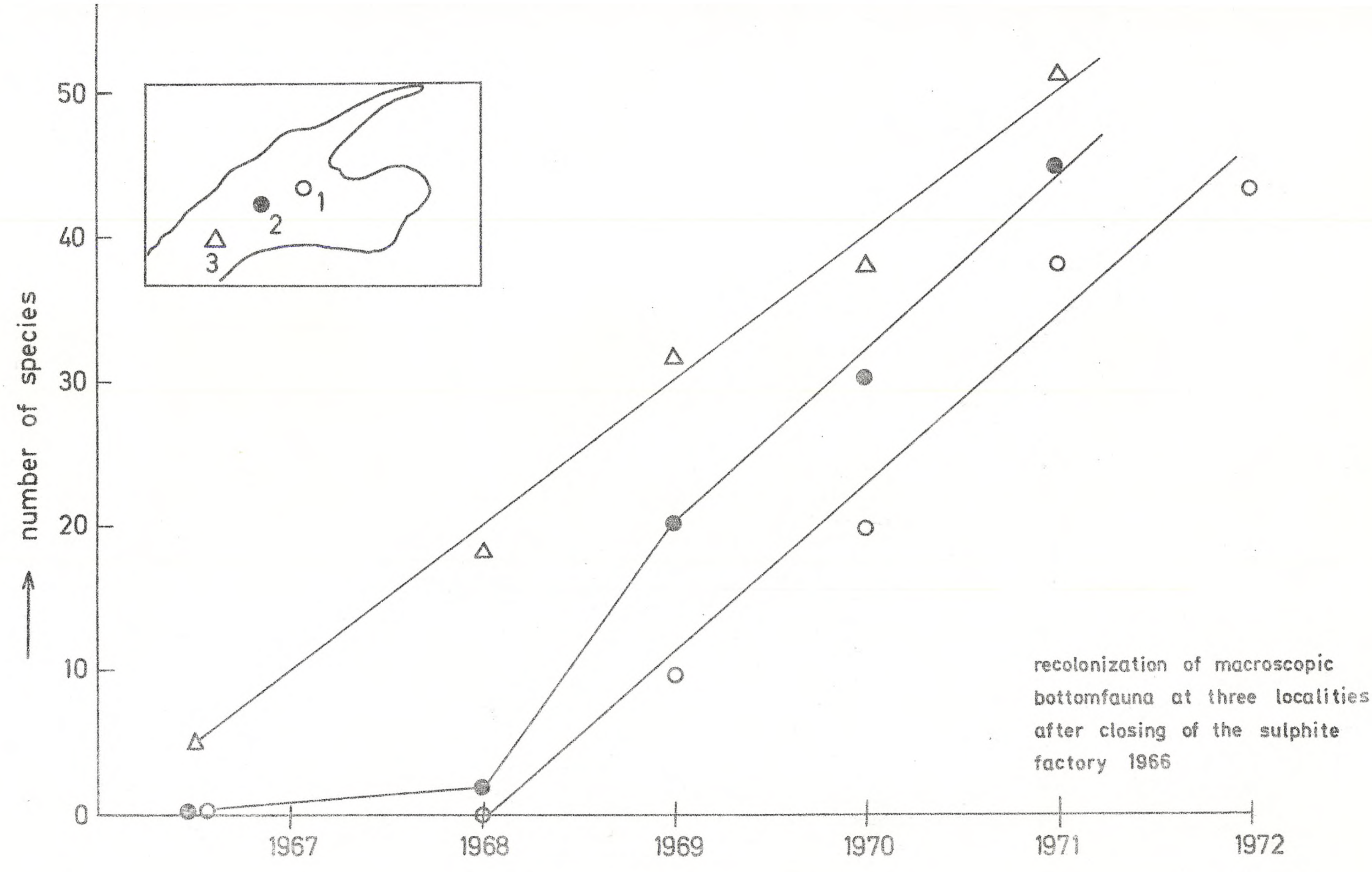
number of species
50
40
30
20
10
0
1
2
3
1967
1968
1969
1970
1971
1972
year
recolonization of macroscopic bottomfauna at three localities after closing of the sulphite factory 1966

Fig. 9