CHAPTER 116

TRAPPING OF OUTFALL CONSTITUENTS BEHIND SILLS

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ABSTRACT

Communication between such coastal resipients of waste water as bays and fjords and the ocean is often through an outlet of small cross section

The combined effects of a topography with transverse ridges and a brackish surface layer creates a rather stagnant body of water. The ridge or sill deflects the tidal currents away from the bottom so that only the upper part of the water column is continually flushed The stability of the pycnocline prevents surface-generated turbulence from penetrating downwards, so the turbulence in the deep pool is weak.

A scheme has been proposed to store the nutrients of sewage outfalls behind the sill at Drøbak in the Oslo-fjord The storage capability of that fjord was estimated for a conservative outfall constituent by means of a one dimensional dispersion equation From the analysis the gains of deep outfalls through diffusors compared with surface outfalls can be estimated for various periods between deep water inflows, which are observed to occur.

INTRODUCTION

Topographic traps

The effect of a given waste water release on the coastal

environment depends to a large extent on the coastal morphology Indentations as well as promontories tend to create sheltered water bodies with long residence times in large scale circulations This tendency is often enhanced by the constricted outlet of many bays and fjords

A very efficient kind of constriction is the transverse bottom ridges or sills which are characteristic of the coastal inlets carved by glaciers and known as fjords. A longitudinal section of a fjord (Oslofjord) is shown in Fig. 1 Several sills divide the deep fjord into smaller sub-basins of varying size It is obvious that this type of topography prevents large bodies of water from participating in the normal movements of coastal waters. In fact, only two significant transport processes seem to exist in the deep basins One, the vertical diffusion, is continuous, while the other is a discrete process of flood-like inflows.

Inflows. Occasional renewal of the water occurs whenever the water density at the sill level exceeds the density of the bottom water inside the sill The water mass occupying the basin is then forced upwards by densimetric displacement, and a complete or partial renewal of the basin water takes place within a relatively short period of time The inflowing volume depends on the density surplus and its duration and is governed primarily by meteorological variables such as wind and atmospheric pressure (upwelling).

Vertical diffusion The density surplus responsible for the initial inflow is caused by a salinity surplus and a temperature defect, compared with the overlying layers Thus a salinity gradient is established for a slow diffusive transport of salt upwards, and a temperature gradient for a similar transport of heat

downwards. With time this diffusion depletes the density surplus of the basin water, and the stage is set for a repeat performance, beginning with a new inflow.

Fig 2 shows observed salinities in the two innermost basins of the Oslofjord during 1962-65, demonstrating the two processes described above, and first by GADE (5).

The pycnocline lid

Even on open coasts pycnoclines develop near river mouths, but the fjords are particularly prone to stratification, for topographic and climatic reasons A regular feature of any fjord is therefore a pycnocline which is usually very stable in the summer half of the year

The pycnocline acts as a lid on the deep pool. Vertical circulation that would go right to the bottom in water of constant density, is replaced by a layered flow The shear motion in the pycnocline filters out most of the horizontal momentum, so that only very weak flows are set up below the pycnocline

The effect of the density gradient on the surface-generated turbulence is equally strong. When entraining or eroding water of higher density, some of the turbulent energy is converted into potential energy In this way the pycnocline acts as a sink of turbulence

The combined effects of topography and layering thus create bodies of water with a rather special flow regime, characterized by long residence times and a low exchange with the surface layer

Sewage disposal behind sills

The sheltered deep basins inside the sill at Drøbak (Fig 1) have been proposed for disposal of sewage from Oslo (6,7). The reasoning is that nutrients can be stored in these basins without causing algal blooms, in contrast to the disposal through shallow outfalls presently in use. A high production of algae is undesirable for two reasons, first because it decreases the esthetic and recreational value of the fjord, and secondly because the organic debris exhausts the oxygen supply at the lower depths.

The usefulness of this scheme hinges on the inflows discussed above. A renewal of the deep water must take place before the steady state of maximum storage has been reached, for which the supply through the sewers equals the vertical diffusion of a nutrient

A MODEL FOR CIRCULATION AND DIFFUSION OF DISCHARGED SEWAGE

Earlier work

A model for the mixing and the convection in a confined region induced by a source of buoyancy has been advanced by BAINES and TURNER (1) Neglecting the effect of turbulence in the environment on the rising plume, they obtained asymptotic solutions of the density distribution valid at large times. The model proposed by CEDERWALL (2) for mixing and convection induced by discharged sewage follows closely that of BAINES and TURNER, but is mostly concerned with the distribution of disposed pollutants

The simplifying assumptions made by CEDERWALL agree well with those first introduced by the authors of this paper (3), however, he neglects the diffusion of constituents through the halocline into the surface layer

The present model

A cross section of the fjord is shown in Fig 3 The source of the constituent is the effluent outfall at level z = 0, and its strength is $Q_o c_o$, where Q_o is the volume flux and c_o the concentration. Because of its buoyancy, the effluent jet will rise to the level h in the pycnocline Here the density of the surrounding fluid equals that of the jet, and the diluted effluent is trapped in a submerged field referred to as the cloud.

Assumptions In order to simplify the analysis we introduce the following assumptions

1 There is no exchange in the deep waters after the complete renewal that we choose as initial condition

2. The density profile is not significantly affected by the induced circulation of sewage

3 The vertical constituent flux is given by

$$-D_z \frac{dc}{(dz)} A_z \qquad (1)$$

where D_z is the diffusion coefficient, dc/dz the concentration gradient and A_z the horizontal area

4. The effluent is trapped just below the halocline and instantaneously spread into a thin layer which will be successively convected and diffused downwards as new sewage reaches the trapping level

5. Any two scalar components are transported by the same mechanism. Thus the concentration distribution of the constituent across the halocline in steady-state condition is just a scaling of the salinity distribution, or

$$\left[\frac{\partial c}{\partial z}\right]_{h^+} = \frac{\Delta c}{\Delta s}\left[\frac{\partial s}{\partial z}\right]_{h^+} \qquad (2)$$

where Δc and Δs are the difference in concentration of the constituent. z=h is the trapping level and h^+ refers to "just above" and accordingly h^- to "just below" The time lag to reach steady-state from initial conditions is of the order of one week and may be neglected (3). The vertical constituent flux upwards to the surface layer is then given by

$$-\left[D_z \frac{1}{\Delta s} \cdot \frac{\partial s}{\partial z} \cdot A_z\right]_h + c(h,t) = Q_v c(h,t) \qquad (3)$$

For simplicity the concentration of the constituent in the surface is assumed to be zero

6. The amount of sewage discharged to the fjord during a year is small compared with the fjord water available for dilution.

7. The freshwater runoff is sufficient to maintain a density stratification, but does not induce appreciable upward entrainment (CARSTENS (4))

The dispersion equation

The convection and mixing within the trapped cloud outside the plume is now described by the one dimensional dispersion model

$$\frac{\delta c}{\delta t} - U\frac{\delta c}{\delta z} = \frac{\delta}{\delta z}\left(D_z \frac{\delta c}{\delta z}\right) \qquad (4)$$

where $U = Q(z)/A(z)$ is the induced convective velocity and $Q(z)$ the plume flow rate at level z. Eq. (4) can be solved numerically together with the continuity equation for the constituent within the cloud

$$Q_o c_o + \int_o^z cdQ - Q_v c(h,t) + U(z)A_z(z)c(z,t) - D_z \frac{\delta c}{\delta z} A_z = \int_z^h \frac{\delta c}{\delta t} A_z dz \qquad (5)$$

which for z=h has the following form

$$Q_o c_o + \int_o^z cdQ - Q_v c(h,t) + U(z)A_z(z)c(z,t) - \left[D_z \frac{\delta c(h,t)}{\delta z} A_z\right]_h = 0 \qquad (6)$$

The first term is the source, the second term accounts for the recirculation of the constituent, and the third term is the constituent flux into the surface layer. The fourth and the fifth terms, respectively, represent the convective and the diffusive downward flux.

A straight forward numerical treatment of Eqs. (4) and (6) is not feasible at present. We have not completely solved the problem of supporting convenient mathematical

models with sound physical arguments. We shall, however, use Eqs. (5) and (6) to estimate the time history c(h,t) of the cloud concentration at the trapping level. We feel our solutions for small and for large values of t are acceptable, but we do not yet have a solution for intermediate values of t.

Solution for small t For small t the thickness of the cloud is small compared with the height h. Hence, the recirculation of the constituent may be neglected

$$\int_0^h cdQ \approx 0, \text{ and } U(h)\cdot A_z(h) \approx Q_o S_o \qquad (7)$$

where S_o is the dilution at the trapping level. For small t we may also assume the vertical distribution of the constituent concentration above the trapping level to be a mirror image of that below. Thus, the upward diffusive flux equals the downward flux and

$$-\left[D_z \frac{\delta c(z,t)}{\delta z} A_z\right]_{h^-} \cdot c(h,t) = Q_v c(h,t) \qquad (8)$$

With these assumptions Eq (6) has the solution

$$\frac{c(h,t)}{c_o} = \frac{Q_o}{(1+\alpha)Q_v + Q_o S_o} \qquad (9)$$

where $\alpha \approx 2$ for small t As the concentration in the surface layer is assumed to be constant=0, α decreases with growing t. Fig. 4 shows Eq. (9) for a particular case in the Oslofjord.

Solution for large t. The effluent cloud is successively convected and diffused downwards. In order to get a rough estimate of the transport velocity we consider only the convection and neglect the diffusion. We then have to find the rate of advance of the first

front. If we take U_o as the front velocity and z_o as the front level, it follows from continuity that

$$U_o = \frac{Q(z_o)}{A_z(z_o)} \tag{10}$$

and the travel time T is given by

$$T = \int_{z_o}^{h} \frac{dz}{U_o} = \int_{z_o}^{h} \frac{A_z}{Q}\, dz \tag{11}$$

For a particular diffusor arrangement (S_o=50) in the Oslofjord with Q_o=10 m^3/s and h=60, T required for z_o=0.1 h may be calculated to about 14 months

For t>14 months most of the deep water has recycled once and the effluent may be assumed to be approximately uniformly mixed into the deep water In this case of ideal mixing we have

$$c(h,t) = c(z,t) = c(t)$$

$$\int_{o}^{h} \frac{\delta c}{\delta t} A_z dz = \frac{\delta c}{\delta t} \int_{o}^{h} A_z dz = \frac{\delta c}{\delta t} V \tag{12}$$

where V is the deep water volume between the levels z=0 and z=h. We also have U(0)=0. With z=0 Eq. (5) then takes the form

$$Q_o c_o - Q_v c(t) = \frac{\delta c}{\delta t} V \tag{13}$$

which has the solution

$$\frac{c}{c_o} = \frac{Q_o}{Q_v}\left(1-e^{-\frac{Q_v t}{V}}\right)$$

Fig. 4 shows Eq. (14) for a particular case in the Oslofjord

$$Q_o = 10\ m^3/s,\ S_o = 50,\ D_z = 3 \cdot 10^{-5}\ m^2/s$$

$$\frac{1}{\Delta s}\frac{ds}{dz}_h = 0{,}15/m,\ A_z(h)=1{,}1\cdot10^8 m^2,$$

$$V=4{,}2\cdot10^9 m^3$$

CONCLUSIONS

A transverse ridge or sill on the bottom shelters the water mass below the sill depth from tidal flushing. A pycnocline provides additional sheltering from surface-generated turbulence, and so the body of water behind a sill and below a pycnocline is characterized by long residence times.

The buildup of the concentration of an outfall constituent released in such a stagnant body of water was investigated for the special case of the Oslofjord, based on a set of assumptions leading to a general one-dimensional dispersion equation.

Solutions were obtained for small and large periods of constituent release, respectively. The solution for small t assumes a rapid horizontal spread compared with the vertical transport The solution for large t assumes ideal mixing. A tentative "probable curve" has been inserted for intermediate times.

From the analysis the gains of deep outfalls through diffusors compared with surface outfalls can be estimated for various periods between deepwater inflows.

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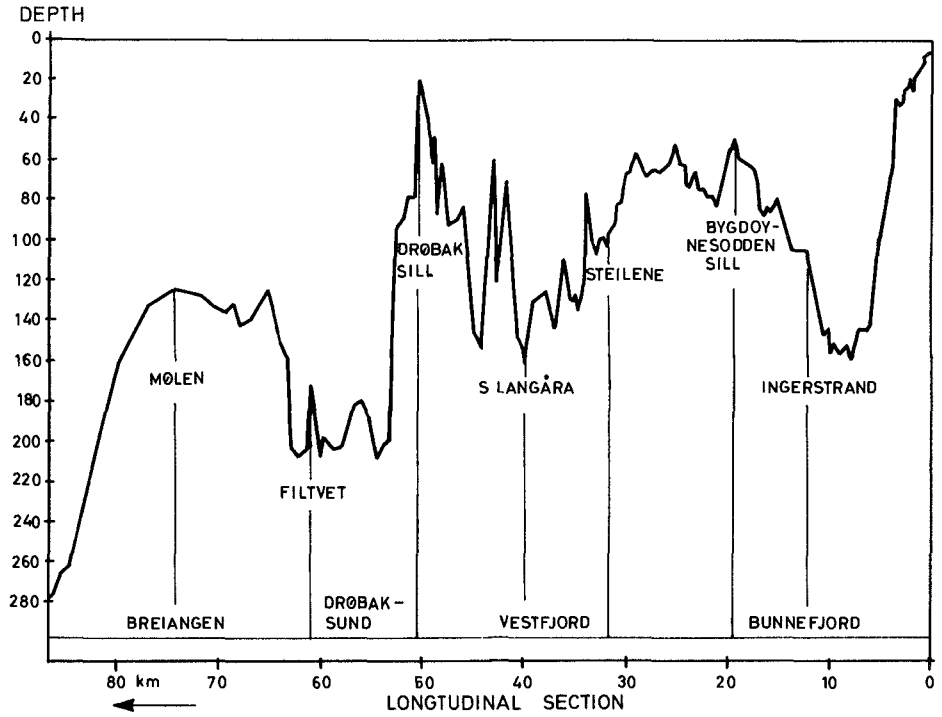

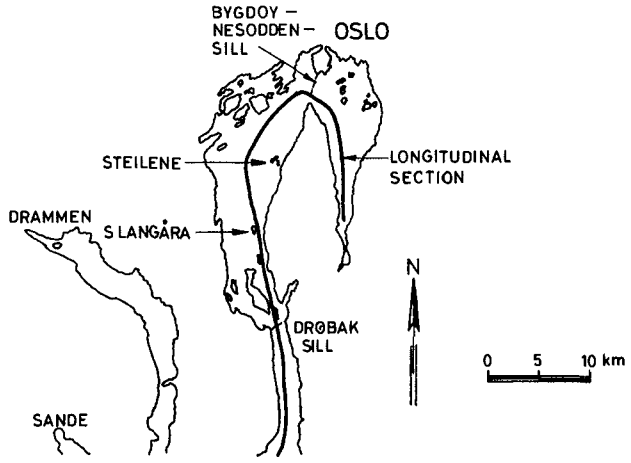

FIG 1 THE OSLOFJORD, PLAN AND SECTION

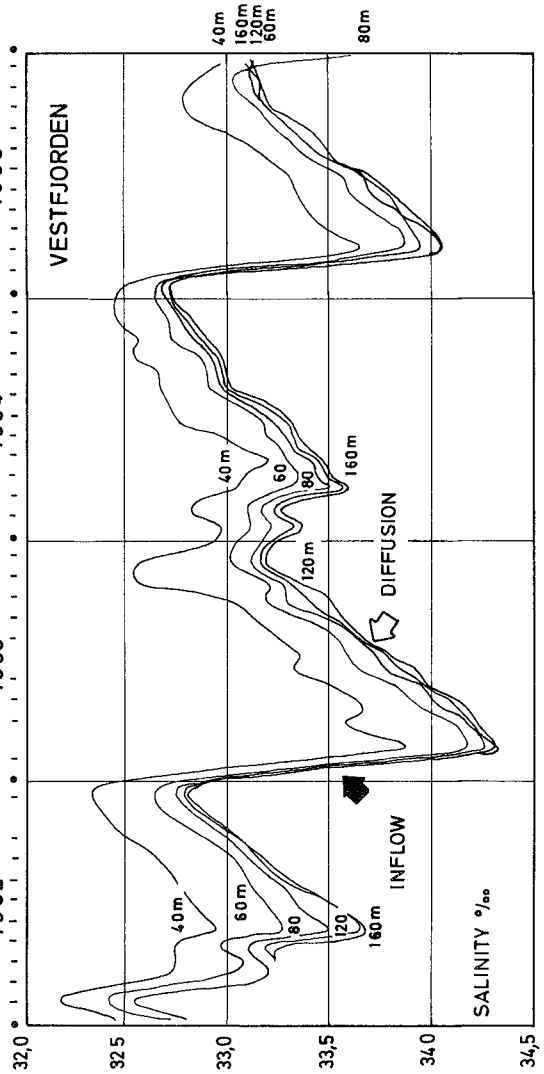

FIG 2 OBSERVED ISOHALINES, OSLOFJORD

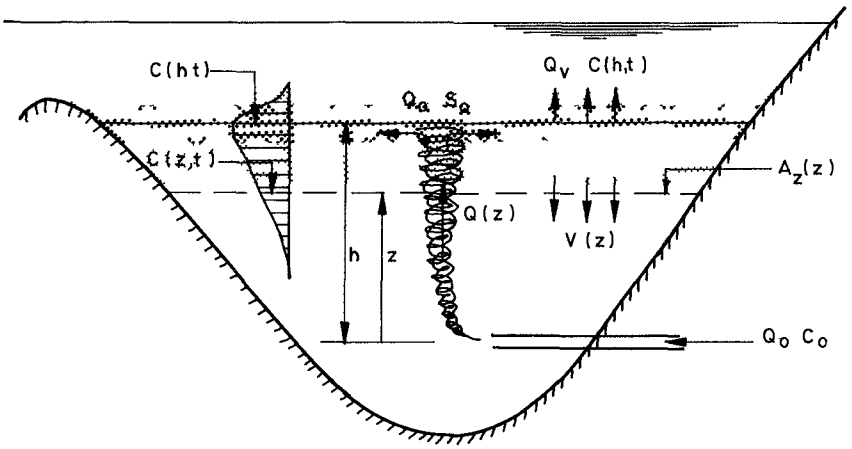

FIG 3 SCHEMATIC OF A SECTION THROUGH THE FJORD

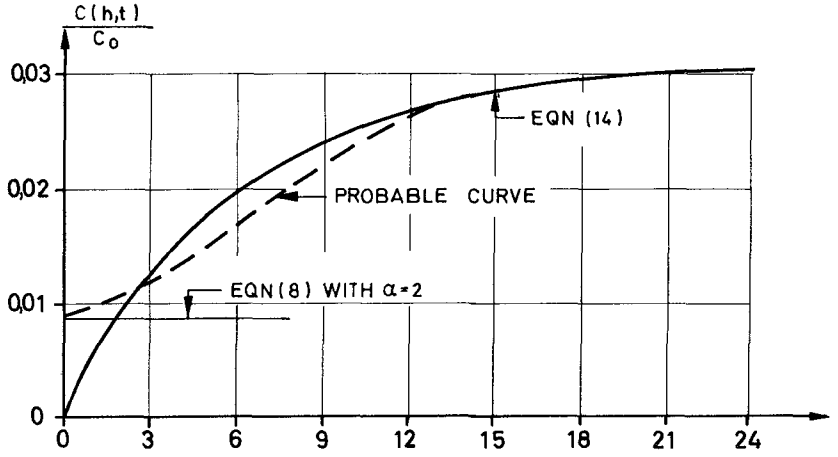

FIG 4 TIME HISTORY OF CLOUD CONCENTRATION AT TRAPPING LEVEL (OSLOFJORD)