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Tracer Measurement of Mixing in the Deep Water of a Small, Stratified Sill Fjord

by

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The exchange of the basin water, i.e. below sill depth, in fjords is commonly envisaged as a series of inflows of heavy water over the sill with shorter or longer periods of stagnation in between. During the stagnation periods vertical mixing is the dominating process of exchange but this mixing may be very weak, especially in cases with strong vertical density gradients at or below sill depth. Thus many fjord basins in Scandinavia exhibit anoxic conditions since the rate of oxygen transport to the basin water is lower than the oxygen consumption. This paper will describe some measurements of vertical mixing in a small fjord with a strong halocline right below sill depth. The stratification is maintained by the conditions outside the fjord rather than by local fresh water supply.

Several physical processes may contribute to the vertical mixing in the basin water. Breaking internal waves may create local turbulence either at the boundaries or in the interior of the fluid. Velocity shear from the wind driven or estuarine circulation or the tidal current may cause turbulence that penetrates into the basin. No general model is available to calculate the mixing from external forcing although certain aspects may be derived from energy arguments. Thus the flux Richardson number, which is the ratio of potential energy gain to the turbulent energy production, seems to attain a constant value which is reported to be in the range 0.05-0.15. This may be expressed as:

$$Rf = \frac{K_z N^2}{\epsilon_o} = \text{const.} \qquad (1)$$

where K_z is the vertical diffusion coefficient, $N^2 = \frac{g}{\rho}\frac{\partial\rho}{\partial z}$ is the stability of the water column and ϵ_o the turbulent energy production. The distribution of ϵ_o is not known and hence an empirical correlation of the type $K_z = f(N^2)$ should be sought.

1. Description of experimental basin

The present measurements were made in the fjord Byfjorden at the west coast of Sweden as a part of a larger study including hydrological, oceanographic, chemical and biological investigations. The fjord is approximately 4 by 1.5 km and has a maximum depth of 50 m. Outside the mouth there is a fjord system surrounding the islands of Orust and Tjörn which are adjacent to the Skagerak. The sill at 11 m depth is situated at the narrow entrance which is dredged to 80 m width at the bottom increasing to 145 m at the surface.

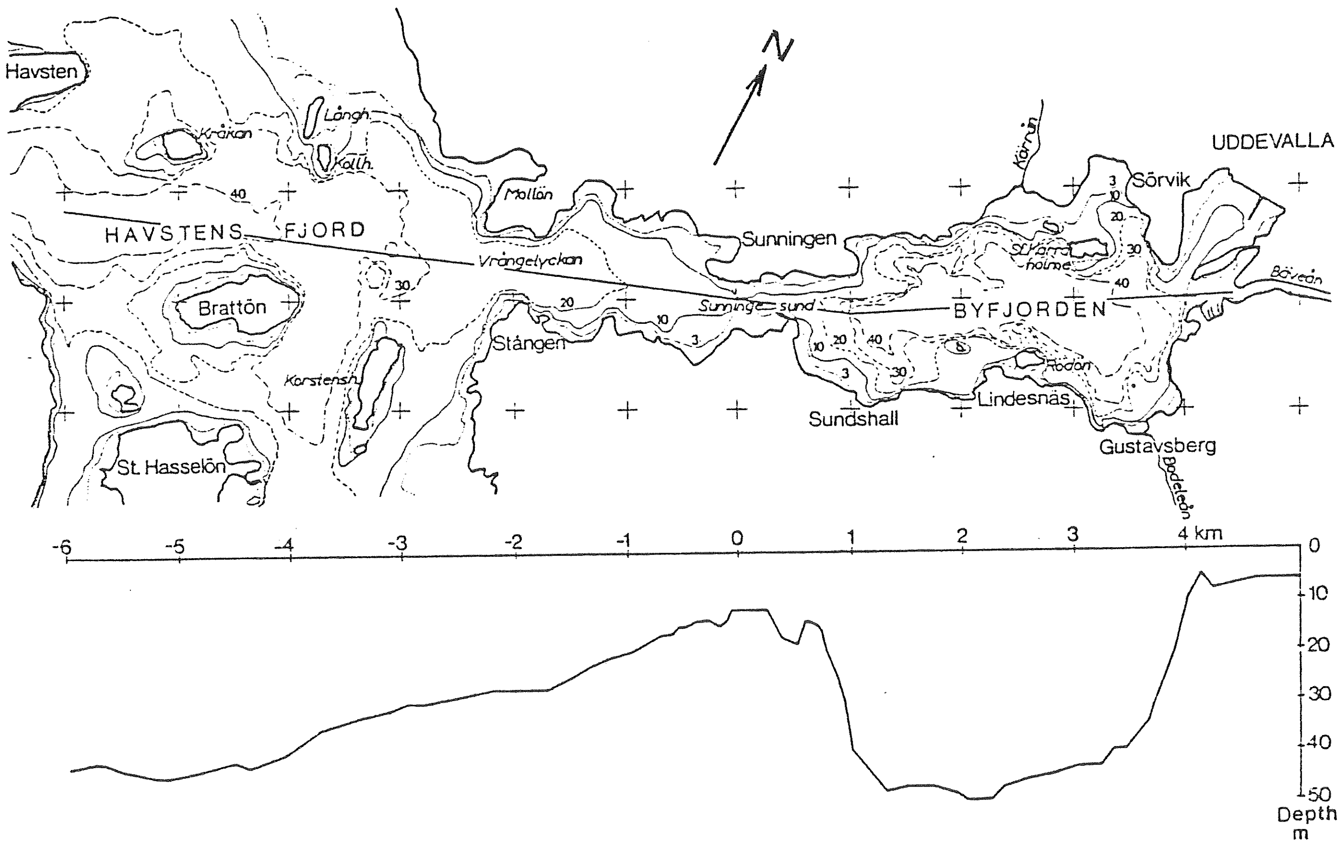

Fig. 1. Plan and elevation of the Byfjorden.

The tide is predominantly semidiurnal with a mean amplitud of approximately 15 cm. Metereologically induced variations of the water level are much larger with a difference between MHW and MLW of 1.87 m. The fresh water supply is low in the summer, $<1\ m^3/s$, rising to typically 5-10 m^3/s during autumn and spring.

2. Density stratification

The water column is strongly stratified with a halocline usually below the sill depth. This stratification is maintained by the Baltic current carrying brackish water from the Baltic up along the Swedish coast. The depth of this brackish layer varies between 10 and 20 m making possible inflows of denser water over the sill a few times per year. Large inflows reaching the bottom of the fjord are, however, rare and they have recurrence times of several years. Smaller inflows are trapped in the halocline at their density level and help to maintain the stratification. The salinity (or temperature) has proved to be less suited as tracer to evaluate the vertical mixing since these small inflows are difficult to identify and account for.

Local fresh water supply gives rise to a secondary halocline at 2-4 m depth during high flow periods. In the summer there is little or no trace of this supply and the estuarine circulation is off-set by tidal and wind mixing and currents. Typical salinity and temperature profiles for summer and winter conditions are shown in Fig.2.

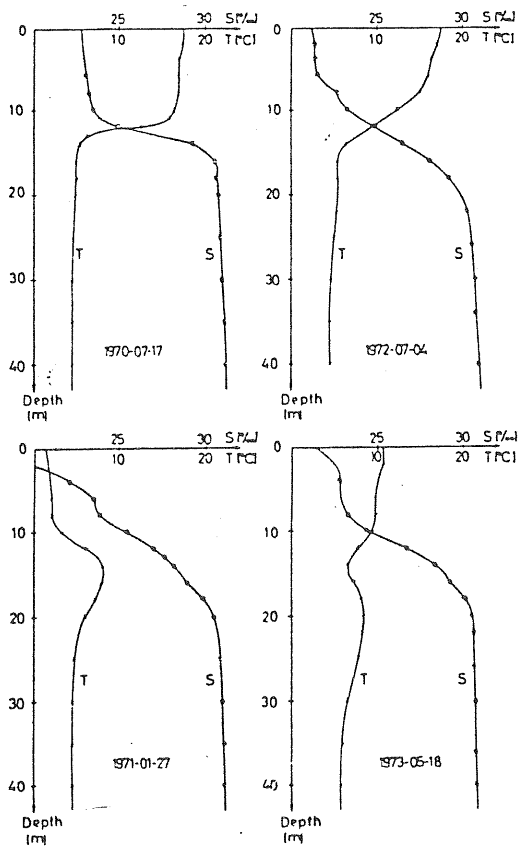

Fig.2. Some typical salinity and temperature profiles in the Byfjorden at different times of year.

The stability, N^2, is strongest in the halocline with mean values at 10-16 m in the range $30 \cdot 10^{-4} - 90 \cdot 10^{-4}\ s^{-2}$. In the deepest part, 30-50 m, the corresponding values are $0.2 \cdot 10^{-4} - 0.8 \cdot 10^{-4}\ s^{-2}$.

3. Tracer experiment

As part of the Byfjorden study, (Göransson and Svensson,1975), a large scale tracer experiment was designed with the double aim to simulate a proposed sewage outfall below the halocline and to study the inflows of deep water over the sill and the vertical mixing after the simulation phase was terminated. As tracer was used Rhodamine B, which was mixed with surface water and continously pumped out at 25 m depth through two horizontal nozzles, Fig. 3. The pumping was carried out during the period July 23 to November 1, 1970, with intermissions for in all 22 days. The pumping capacity was 205 l/s and the total amount of Rhodamine injected was 127.1 l trade solution.

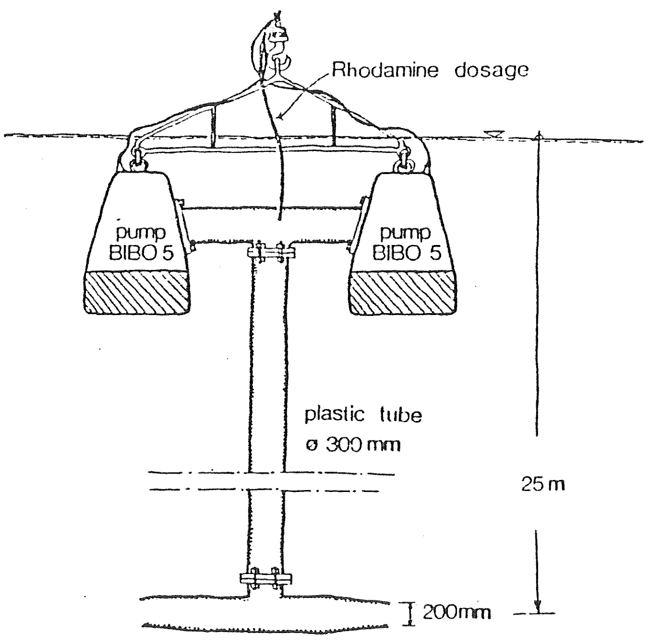

Fig.3 Pump arrangement for tracer test in the basin water.

The distribution of tracer and density during the pumping has been described by Göransson (1977) and used to verify a model for sewage discharge into the deep water of confined basins.

The vertical distribution of tracer at different times after the pumping had stopped is shown in Fig.4. The profiles are from a point in the central part of the fjord, which is representative for the whole fjord since differences in concentration in the horizontal were small.

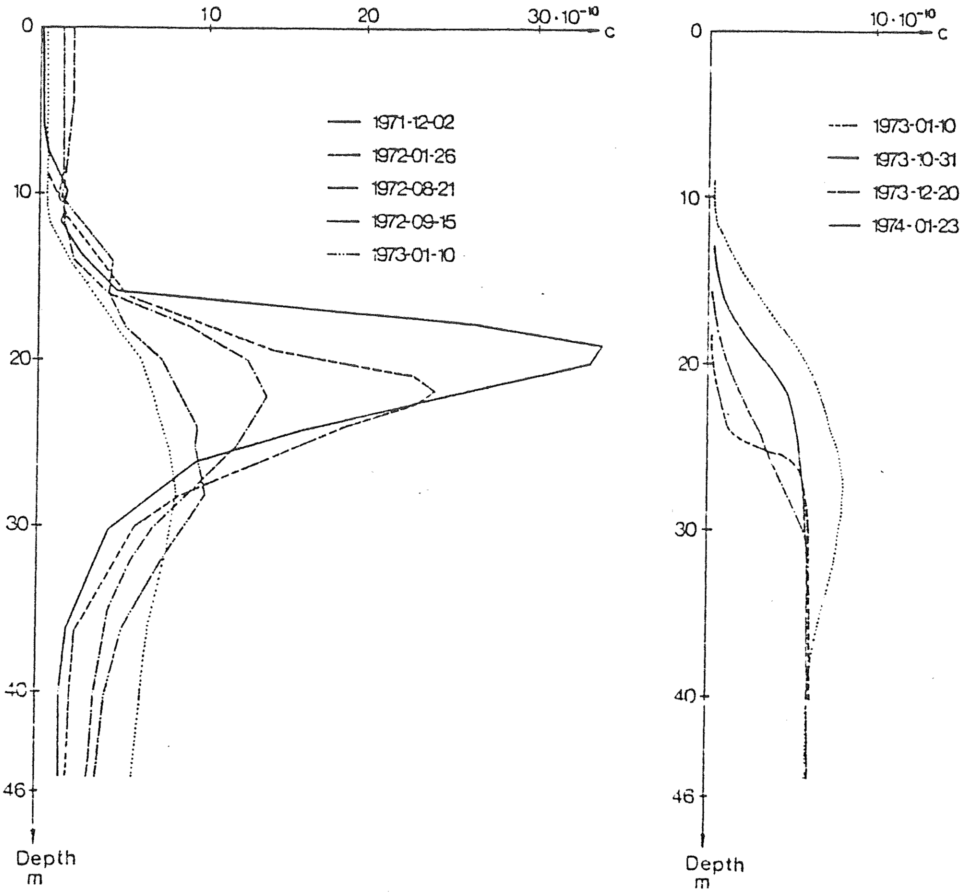

Fig. 4 Vertical distribution of tracer at different times after the pumping had stopped.

The tracer profiles reveal significant inflows of water reaching the lower part of the halocline in January and August-September 1972 and in December 1973. In the calm periods between inflows the development of the concentration profile is characteristic for vertical diffusion.

4. Stability of the tracer

The fluorescence of Rhodamine B is known to decay in light and to adsorb on particles in the water (Feuerstein & Selleck 1963, Smart & Laidlow 1977) and the use of Rhodamine B for quantitative work in turbid waters is questionable. In the Byfjorden, however, the concentration of suspended solids is too low to significantly affect the fluorescence and the light intensity in the deep water is practically zero, which precludes photochemical decay. The influence of the anoxic conditions has not been found in the literature.

An analysis of the decay of the tracer was made for the calm period Jan 26-Aug 21 1972 assuming that no tracer material was transported through the level of maximum concentration at 22 m depth. The change of total mass of tracer below that level should thus be due to degradation or adsorption on sedimentating particles. The measured amount of tracer below 22 m depth is shown in Fig.5. The straight line in the diagram corresponds to an exponential decay, $C = C_o \cdot \exp(-1.64 \cdot 10^{-8}\, t)$, where t is the time in sec. This decay formulation has been used in the calculation of diffusion coefficients.

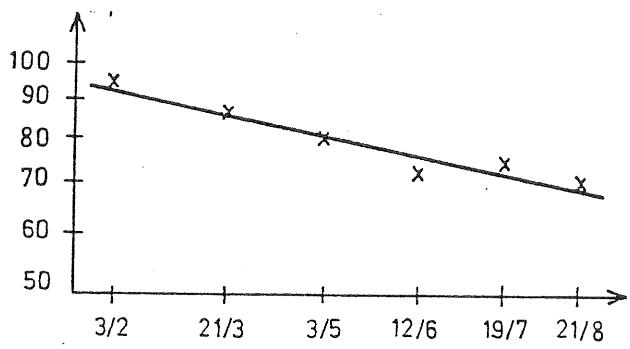

Fig.5 Total measured amount of tracer below 22 m depth in Jan. to Sept. 1972.

5. Evaluation of diffusion coefficients.

The vertical mixing is described as a one-dimensional diffusion process with variable diffusion coefficients, K_z, and cross-sectional area, A. The concentration of tracer thus follows the equation

$$\frac{\partial c}{\partial t} = \frac{1}{A}\frac{\partial}{\partial z}\left(K_z A \frac{\partial c}{\partial z}\right) - kc \qquad (2)$$

where k is the decay coefficient. Eq (2) may be integrated from the bottom, z_b, of the basin to evaluate the diffusion coefficients

$$K_z = \frac{1}{A\frac{\partial c}{\partial z}} \cdot \left[\frac{\partial}{\partial t}\int_{z_b}^{z} Acdz - k\int_{z_b}^{z} Acdz\right] \qquad (3)$$

This procedure yields, however, low accuracy where the gradients are small, especially near the level of maximum concentration and has been supplemented by a numerical solution of Eq(2) starting from measured concentration profiles in the beginning of calm periods. Small adjustment of the diffusion coefficients may then be made to fit the data. Results from the computations for two time periods and the used sets of K_z are shown in Fig.6.

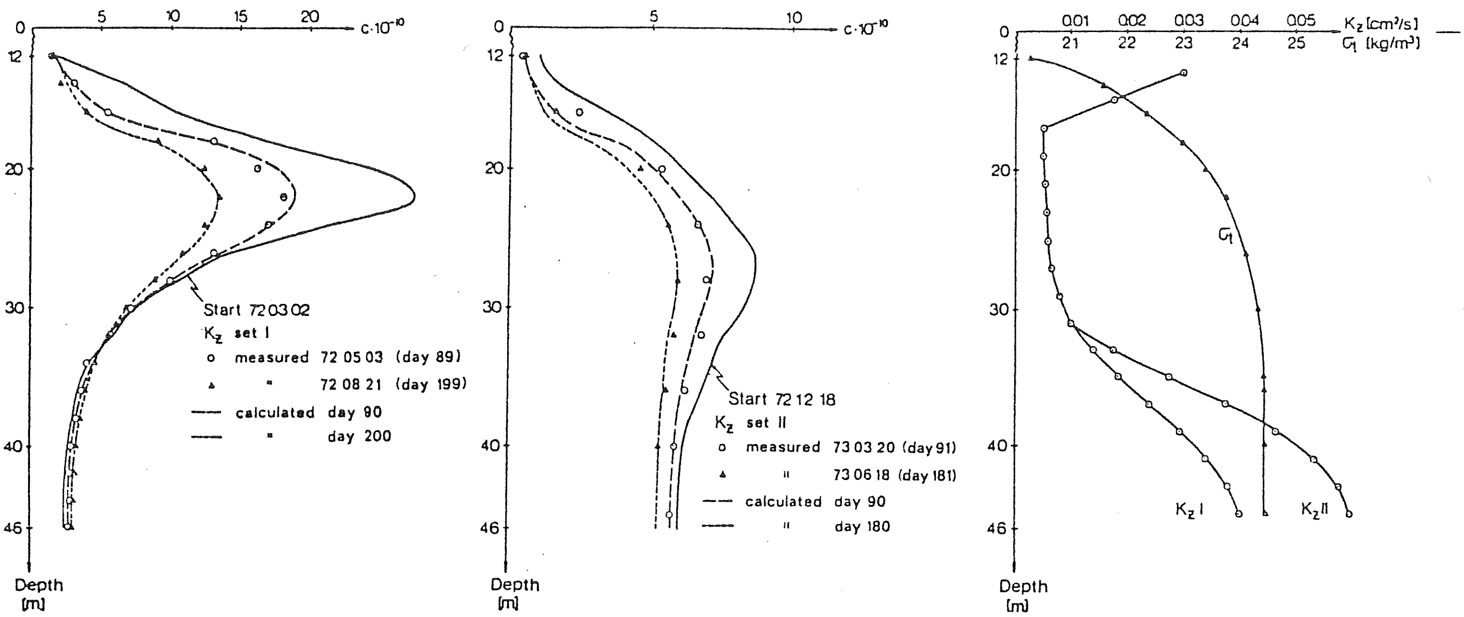

Fig. 6 a) and b) Measured and calculated tracer profiles during two periods with no large inflows.
c) The diffusion coefficients used for the calculations and the mean density profile during the first period.

The diffusion coefficients are negatively correlated to the vertical density gradient but for the values at 13 and 15 m depth, in the sharpest part of the halocline. This is, however, most likely the result of small inflows into this depth interval due to internal waves in the halocline of the water area outside the Byfjorden. The diffusion coefficients of Fig.6 would, if applied to the salinity profile, lead to a lowering of the halocline which has not been observed.

The lowest values of the diffusion coefficient, 0.005 $cm^2\ s^{-1}$, are found in the halocline and there is a continuous increase toward the bottom where approximately 10 times that value is found. The accuracy of the measured coefficients is best in the upper part of the profile where it has been estimated to $\pm$ 0.0015 $cm^2\ s^{-1}$ and decreases toward the bottom.

6. Analysis

The resulting diffusion coefficients from the tracer experiment are plotted against N^2 in Fig.7 together with some determinations based on salinity measurements during periods when the advective inflows have been unlikely due to low halocline in the water outside the fjord.

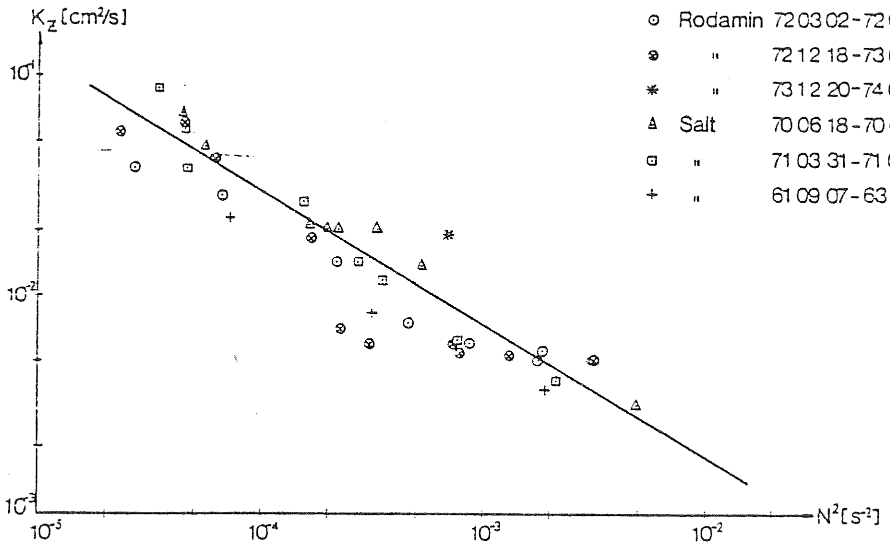

Fig. 7 Relation between vertical diffusion coefficients, K_z, and stability, $N^2 = \frac{g}{\rho}\frac{\partial\rho}{\partial z}$, in the deep water of the Byfjorden.

Considering that the measurements shown in Fig.7 are made on different tracers under different conditions of mean wind velocity and fresh water supply and cover both longer and shorter time periods, the general agreement is good. The relationship may be expressed as

$$K_z = 1.2 \cdot 10^{-4}\ (N^2)^{-0.6} \qquad (4)$$

A similar treatment of data for salt diffusion was made by Gade (1970) in the Oslo fjord. In that case the exponent of (N^2) had the value -0.8. By comparison with Eq.1 it appears as the product

$Rf \cdot \epsilon_o$ is proportional to $(N^2)^{0.4}$ in the Byfjorden and $(N^2)^{0.2}$ in the Oslo fjord. Alternatively $Rf \cdot \epsilon_o$ may be regarded as decreasing with depth as the stability continuously decreases from the halocline to the bottom of the fjord.

It has not been possible to correlate the measured diffusion coefficients to variations in wind velocity or the estuarine circulation and it is thus likely that the turbulence energy is supplied by internal waves generated by the tide as suggested by Stigebrand (1977). In his model the energy of the tidal induced internal waves is set equal to the total energy conversion in the deep water which is obtained by integrating Eq. 1 over the deep water volume. A direct comparison with the model in the Byfjorden case is, however, difficult due to the influence of advective water exchange in the upper part of the halocline.

REFERENCES:

Göransson, C-G. and Svensson, T. (1975) The Byfjord: Studies of water exchange and mixing processes. Statens Naturvårdsverk (Swedish Environmental Protection Board) PM No. 594, Stockholm, Sweden.

Cederwall, K., Göransson, C-G. and Svensson, T. (1975) Subsequent dispersion. Methods of measurement. In Gameson (ed.) "Discharge of Sewage from Sea Outfalls" Pergamon Press, London, pp 309-318.

Göransson, C-G. (1977) Mathematical model of sewage discharge into confined, stratified basins - especially fjords. Proc. 17th Congres of IAHR, Vol.3, paper B43, 1977.

Feuerstein, D.L. and Selleck, R.E.: Fluorescent tracers for dispersion measurements. J.Sanit.Eng.Div., ASCE, 89, SA4, pp 1-21, 1963.

Smart, P.L. and Laidlaw, I.M.S.: An evaluation of some fluorescent tracers for water tracing. Water Resources Research, 13, No.1, pp 15-33, Febr 1977.

Gade, H.G.: Hydrographic investigation in the Oslo fjord, a study of water circulation and exchange processes. Geophysical Inst., Univ. of Bergen, Norway, Rept.24, Sept. 1970.

Stigebrand, A.: Vertical diffusion driven by internal waves in a sill fjord. J.Phys.Oceanography, Vol.6, July 1976.