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Improving oxygen conditions in periodically stagnant basins using sea-based measures - Illustrated by hypothetical applications to the By Fjord, Sweden

Anders Stigebrandt *, Ambjörn Andersson

Dept of Marine Sciences, University of Gothenburg, Gothenburg, Sweden

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ABSTRACT

To improve the water quality of a habitat or to stop eutrophication driven by internal loading of phosphorus from anoxic bottoms, the deepwater in inshore and offshore sea basins may be oxygenated using sea-based measures. The minimum oxygen concentration DO_{min} in periodically stagnant basins is controlled by three factors, namely (i) the rate of oxygen depletion dDO/dt. (ii) The residence time Te of the stagnant water. (iii) The oxygen concentration DO_{start} in the basin water at the beginning of a stagnation period. A theoretical framework is presented, suitable for evaluation of sea-based measures to improve the oxygen conditions in periodically stagnant basins. Five different sea-based measures to improve the oxygen conditions are recognized and discussed. The application of sea-based measures might be particularly attractive for habitat improvements in basins with poor oxygen conditions despite land-based measures are fully implemented. The sea-based measures are illustrated by hypothetical applications to the By Fjord on the west coast of Sweden, a salt-stratified fjord with periodically stagnant anoxic basin water confined behind the shallow Sunninge Strait in the mouth. An interesting result of one of the hypothetical applications is that dredging of the Sunninge Strait in 1958 and 1976 reduced tidal currents by a factor of 4. This reduced the tidal power supply to vertical mixing in the basin water, which led to prolonged residence time Te, from 2-3 years to 3–5 years, and deteriorated oxygen conditions in the basin water.

1. Introduction

The oxygen conditions of a water volume are determined by the rates of supply and consumption of oxygen. Supply of oxygen to periodically stagnant stratified basin waters enclosed by topographic barriers (sills), is usually provided mainly by inflowing "juvenile" water that is dense enough to replace the residing basin water (e.g. Aure and Stigebrandt, 1989). This description is valid for salt-stratified marine basins including, for instance, the major basins of the open Baltic proper. The basin water is stagnant during the period between two consecutive events of water exchange and the length Te of this period is denoted the residence time. The functioning of basins seasonally stratified by heat is usually much simpler since they are ventilated by vertical convection, driven locally by cooling at the sea surface.

Areas with hypoxic and anoxic conditions in the water are expanding globally (Diaz and Rosenberg, 2008). For instance, in modern time anoxic bottoms started to develop in the Baltic proper at the end of the 1950s and since the end of the 1990s anoxic bottoms occupy an area of about 45 000 km^2 (e.g., Hansson et al., 2019), which is greater than the area of Denmark. The rate of oxygen consumption in the basin water of the Gullmar Fjord, at the Swedish Skagerrak Coast, has increased by about 50% since the 1950s which explains the increased frequency of seasonal low oxygen concentrations in the stagnant basin water (Erlandsson et al., 2006).

The oxygen conditions are crucial for the water quality and the suitability of a water body as habitat for higher forms of life and accordingly for the diversity of organisms (e.g., Buhl-Mortensen et al., 2009). High rate of oxygen consumption and/or sluggish oxygen supply may cause hypoxia that may reduce the volume of good deepwater habitats and the diversity of organisms. Consequently, where applicable, the volume and the quality of a good habitat might be expanded by an increased rate of oxygen supply. Anoxia may have negative effects of biogeochemical nature, for instance diffusion of phosphorus (P) to the water column from storages in bottom sediments when these are

* Corresponding author.
E-mail address: anders.stigebrandt@marine.gu.se (A. Stigebrandt).

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covered by anoxic water (e.g., Mortimer, 1941; Emeiss et al., 2000; Gustafsson and Stigebrandt, 2007; Viktorsson et al., 2013; Stigebrandt et al., 2014: Hall et al., 2017; Sommer et al., 2017). It has been shown that the ongoing eutrophication of the Baltic Sea has been boosted and perpetuated by a major internal phosphorus source located to anoxic bottoms (Stigebrandt and Andersson, 2020). For the Baltic Sea, deepwater oxygenation has been identified as an efficient measure to establish an oxidized top layer on the sediment that by its content of iron oxides may adsorb phosphate ions and, in this way, constitute an efficient P filter discontinuing internal P loading from bottoms earlier covered by anoxic water (Stigebrandt et al., 2014; Stigebrandt and Andersson, 2020). This is supported by observations showing that the release of P from anoxic bottoms in the Baltic Sea decreased drastically when the bottom water was oxygenated by a major inflow of oxic water from the Kattegat (Almroth – Rosell et al., 2015). A rapid decrease of sediment phosphate fluxes when anoxic bottoms in eutrophic estuaries were oxygenated was reported by Harris et al. (2015). An additional example of discontinued P supply to the water column when earlier anoxic sediments in the By Fjord were artificially oxygenated is described in Section 4 below.

Sea-based measures of oxygenation can be tested by performing experiments in permanently stratified smaller basins. In the Baltic Sea, most coastal basins have seasonal temperature (heat) stratification. This is because perennial stratification by sea salt requires that the sill is deep enough to enable water of higher salinity, i.e., from the halocline, to enter the basin. The By Fjord on the Swedish West Coast is one of few salinity-stratified coastal basins in Sweden that are almost permanently anoxic. A pilot oxygenation experiment called BOX (Baltic Oxygenation Pilot Experiment) was carried out 2010–2012 in this fjord (Stigebrandt et al., 2015). The oxygenation measure applied was suggested by Stigebrandt and Gustafsson (2007) for application to the Baltic Sea. It implies that cold, oxygen saturated so-called winter water, located above the permanent halocline, is injected by pumping into the saltier and denser deepwater. The pumped water drives a concentrated and rising buoyant plume that entrains ambient deepwater and is interleaved in the pycnocline. Basin water is thus withdrawn by entrainment into the buoyant plume, which causes a compensating downwelling in the whole basin carrying oxygen downwards from the depth of interleaving to the depth of the outlet of the pump. However, unlike the Baltic Sea, the By Fjord has no storage of winter water. Instead, buoyant surface water of reduced salinity was injected into the deepwater by pumping.

Air/oxygen gas have been used to aerate/oxygenate even rather large freshwater reservoirs and lakes to improve the water quality and habitats for fish (Beutel and Horne, 1999) or e.g., to reduce mercury bioaccumulation (Beutel et al., 2014). A review of systems for hypolimnetic aeration and oxygenation is given by Singleton and Little (2006). Different methods to alleviate bottom layer hypoxia using induced downwelling on shallow stratified shelves are described by Koweek et al. (2020) and Xiao et al. (2018).

In the present paper, an equation for the minimum oxygen concentration DO_{min} in periodically stagnant basin water is presented. The equation describes how different factors influence DO_{min} and it is used to identify sea-based measures. Five different sea-based measures are described. However, which measure that should be chosen in a specific case depends on local conditions that determine costs and effects of different measures.

Having almost permanently anoxic deepwater of modest volume, the By Fjord is suitable for tests of different oxygenation measures. The fjord has been regularly monitored during several decades, hydrographical data can be found at SMHI (2022), and it has already hosted an oxygenation experiment (Stigebrandt et al., 2015). This should increase the value of the fjord as a test basin for deepwater oxygenation. In the present paper, five different sea-based measures to oxygenate deepwater are applied hypothetically to the By Fjord.

2. Theory

Oxygen is consumed continuously in the basin water, either due to aerobic decomposition of organic matter or due to oxidation of hydrogen sulfide and ammonia produced by anaerobic decomposition of organic matter. Here we consider periodically stagnant basins where the residence time of the basin water equals *Te*. The minimum concentration of dissolved oxygen DO_{min} in the basin water occurs at the end of stagnation periods. In section 2.1 we derive a general equation for DO_{min} that among others depends on the residence time *Te* of the basin water, which is determined by physical processes. In section 2.2 we show how *Te* can be estimated theoretically.

2.1. Derivation of an equation for DO_{min}

The time scale for oxygen depletion *TO* is the time it takes to reduce the concentration of dissolved oxygen *DO* in the basin water by a certain amount ΔO.

$$TO = -\Delta O \Big/ \left(\frac{dDO}{dt}\right) \tag{1}$$

Here dDO/dt is the mean rate of depletion of dissolved oxygen as observed by the change of the storage of oxygen in the basin water. dDO/dt can also be called the apparent oxygen consumption. Please note that the factual rate of oxygen consumption in the basin water may be greater than the rate of depletion because some of the oxygen consumed is not taken from the storage of *DO* in the basin water but is delivered by vertical diffusion into the basin water.

To evaluate possible effects of fish farming in net pens on the water quality in fjords, about 30 salt-stratified fjord basins in the county of Møre and Romsdal in Norway, hereafter called the MR-fjords, were investigated (Aure and Stigebrandt, 1989, 1990; Stigebrandt and Aure, 1989). In the basin water of the MR-fjords, diffusive oxygen fluxes contributed about 20% and depletion of the oxygen storage contributed about 80% to the total (factual) oxygen consumption (Aure and Stigebrandt, 1989). In the Gullmar Fjord, the diffusive contribution to the total oxygen consumption is about 10% (Erlandsson et al., 2006).

In the present paper, the magnitude of oxygen depletion ΔO in periodically stagnant basins is defined as follows,

$$\Delta O = (DO_{start} - DO_{min}) \tag{2}$$

Here DO_{start} and DO_{min} are the oxygen concentrations at the start and at the end, respectively, of a stagnation period. For this definition of ΔO, the time scale *TO* of oxygen depletion equals the duration *Te* of the stagnation, thus $TO = Te$.

It has been assumed that the mean rate of oxygen depletion dDO/dt in stagnant basin waters is proportional to the supply of particulate organic matter (POM) and inversely proportional to the mean thickness H_b of the enclosed basin water, defined by $H_b = V_b/A_t$, where V_b is the volume of the basin water and A_t the horizontal area of the fjord at sill level (Aure and Stigebrandt, 1989), thus

$$\frac{dDO}{dt} = -\frac{\mu \cdot FC_{app}}{H_b} \tag{3}$$

Here FC_{app} is the supply of carbon (gC/m^2/day) contained in POM, that is oxidized using dissolved oxygen *DO* stored in the basin water, i.e. the apparent oxygen consumption, and μ is the oxygen/carbon ratio for a complete oxidation of organic matter. If the organic matter is composed according to the Redfield molar ratio, i.e. C:N:P = 106:16:1, the ratio μ equals 3.5 (g O_2 per g C) (e.g. Aure and Stigebrandt, 1989) which includes the oxygen needed to oxidize ammonium, set free by the decomposition of organic matter, to nitrate. If Equation (3) is multiplied by the volume of the basin water *Vb*, one finds that the daily oxygen depletion in the basin water $V_b \bullet dDO/dt$ equals $A_t \bullet \mu \bullet FC_{app}$ (g O2 day^{-1}).

The total vertical flux *FC* into the basin water equals $FC_{app} + FC_{diff}$, where FC_{diff} is the fraction of *FC* that is oxygenated by the diffusive

oxygen flux. As discussed above, the diffusive contribution to the oxygen budget in the basin water is usually rather small. For simplicity, we therefore make the following approximation $FC \approx FC_{app}$.

Equation (3) shows that for a given value of FC, thin stagnant layers have a higher rate of oxygen depletion than thicker layers. From an analysis of the oxygen consumption in the MR-fjords, Aure and Stigebrandt (1989) concluded that the vertical flux FC by settling POM decreases with increasing depth. They explained this to be an effect of pelagic mineralization of sinking POM that is generated in the euphotic zone. A formula describing this effect is implemented in the water quality model Fjordmiljø (Fjordenv) see Aure and Stigebrandt (1990) or Stigebrandt (2001).

With $TO = Te$ and using Equations (1)–(3), the following equation for the oxygen concentration DO_{min} at the end of a stagnation period may be obtained.

$$DO_{min} = DO_{start} - T_e \cdot A_t \cdot \mu \cdot FC / V_b \tag{4}$$

According to Eq. (4), DO_{min} is influenced by three factors, viz. *(i)* the rate of oxygen depletion, which is described by the flux of carbon FC into the basin water, by settling particulate organic matter POM. *(ii)* The residence time Te of the basin water. *(iii)* The oxygen concentration DO_{start} in the basin water in the beginning of a stagnation period.

DO_{start} will be less than DO_{in}, which is the initial oxygen concentration of inflowing, juvenile, basin water when leaving the neighbour basin. This is because the juvenile basin water with oxygen concentration DO_{in} during inflow entrains residing basin water with oxygen concentration DO_{min}, e.g., Liungman et al. (2001); Arneborg et al. (2004a). The oxygen concentration in the neighbour basin may vary both vertically and seasonally which makes DO_{in} sensitive to deepening of the entrance strait by dredging.

A general equation for the minimum of dissolved oxygen concentration DO_{min} in a periodically stagnant basin should also include the effect of artificial supply of dissolved oxygen to the basin water. This effect is inserted in Equation (4) and we obtain

$$DO_{min} = DO_{start} - T_e \cdot (A_t \cdot \mu \cdot FC - DOSUP) / V_b \tag{5}$$

Here $DOSUP$ (kg day^{-1}) is the rate of artificial supply of dissolved oxygen to the basin water.

From Equation (5) follows that bad oxygen conditions in periodically stagnant basin waters, here quantified by the minimum concentration DO_{min}, can be improved in several ways. The conventional way to improve the oxygen conditions in the basin water is to reduce FC by reducing the supply of organic matter to the basin water, using different land-based measures to remove plant nutrients and oxygen consuming matter from municipal and industrial wastewater and by various measures in farming practice. The focus of the present paper is on sea-based measures to improve the oxygen conditions in stagnant basins. The application of sea-based measures might be particularly interesting for periodically stagnant basins that have poor oxygen conditions despite land-based measures are fully implemented. Sea-based measures might also be considered to compensate for increased oxygen consumption due to e.g., fish farming in open cages or other human activities or to improve the habitat in basins with naturally poor oxygen conditions.

2.2. Physics – estimation of the residence time Te

The residence time Te of the basin water, i.e., the water below the sill depth, is a major factor for the minimum oxygen concentration DO_{min} (Equation (5)). Here we describe the physical processes controlling Te and how Te can be estimated theoretically.

Aure and Stigebrandt (1990) suggested that all basin water in salt-stratified basins can be expected to be exchanged during the elapse of the time Te defined by

$$T_e = \frac{R_e}{\frac{d\rho}{dt}} \tag{6}$$

Here Re (kg m^{-3} yr^{-1}) is an empirically determined average density reduction that must take place in the basin water before exchange of basin water can be expected and $d\rho/dt$ is the mean rate of density reduction in the basin water due to diapycnal, or vertical, mixing. The value of Re depends on $d\rho/dt$ and on the spectral distribution of the temporal variability of the density of the water at the sill level outside the basin. In basins with very low rates of density reduction, due to small energy supply to turbulent mixing processes and/or large thickness H_b of the basin water, Re may be controlled by the sub-annual variability of the density field at the sill level outside the fjord, see Stigebrandt (2012).

The mean rate of density reduction $d\rho/dt$ due to diapycnal mixing in the basin water of the MR-fjords was studied during stagnant conditions i.e., in periods lacking exchange of basin water. Aure and Stigebrandt (1990) found that $d\rho/dt$ is proportional to the specific rate of work against the buoyancy forces W [Watt/m^2], carried out by turbulent vertical mixing, and inversely proportional to the square of the mean thickness H_b of the basin water, thus

$$\frac{d\rho}{dt} = -\frac{CW}{gH_b^2} \tag{7}$$

Here $C \approx 2.0 \pm 0.6$ is an empirical non-dimensional coefficient and g the acceleration of gravity.

Tidal currents in the mouth of fjords are important energy sources for turbulence and mixing in the basin water. Stigebrandt and Aure (1989) differentiated between wave fjords, where the tidal current in the mouth generates internal tides in the adjacent basins, and jet fjords, where the tidal current in the mouth generates jet currents in the adjacent basins. The borderline between wave fjords and jet fjords is defined by the velocity c_i of long internal waves in the adjacent fjord basin. Accordingly, a basin is a jet basin if the amplitude of the tidal current in the mouth of the fjord is greater than c_i, otherwise it is a wave basin. The phase velocity c_i of long internal waves in a two-layer stratification is given by the following expression

$$c_i = \sqrt{g \frac{\Delta\rho}{\rho_0} \frac{H_t H_b}{H_t + H_b}} \tag{8}$$

Here $\Delta\rho$ is the density difference between the two layers, H_b the mean thickness of the lower layer, H_t the sill depth and the thickness of the upper layer. The group velocity of long internal waves equals the phase velocity c_i.

The diapycnal mixing in the basin waters of the MR-fjords was investigated by Stigebrandt and Aure (1989). They showed that the specific work against the buoyancy forces W [Watt m^{-2}] can be partitioned as follows,

$$W = W_0 + \frac{Rf \cdot E}{A_t} \tag{9}$$

Here W_0 is the background work likely driven by the local wind, E [Watt] is the power supply to the turbulence in the basin water by the tide in the mouth and Rf is the efficiency of turbulence with respect to work against the buoyancy forces by diapycnal mixing. As shown below, Rf and E are different for wave fjords, where $Rf = Rf_w$ and $E = E_w$, and jet fjords, where $Rf = Rf_j$ and $E = E_j$.

For two-layer stratification, the mean energy transfer E_w from the surface tide to sill-generated internal tides in an adjacent basin can be estimated using the following prognostic formula, derived from basic principles by Stigebrandt (1976).

$$E_w = \frac{\rho_0}{2} \omega^2 a^2 \frac{A_f^2}{A_m} \frac{H_b}{H_t + H_b} c_i \tag{10}$$

Here ρ_0 is a reference density, ω the tidal angular frequency, a the surface tidal amplitude in the fjord, A_f the horizontal surface area of the fjord, A_m the vertical cross-sectional area of the sill section, and c_i the group velocity of the internal wave given by Equation (8).

Based on a laboratory experiment, Stigebrandt (1976) argued that

the energy carried by the internal waves dissipates essentially in the basin water and that the fraction Rf_w of the energy E_w is used for work against the buoyancy forces. By applying the theory on the Oslo Fjord, he estimated that Rf_w equals 0.05. Later, Stigebrandt and Aure (1989) estimated $Rf_w = 0.056$ for the set of wave fjords among the MR-fjords.

The rate of energy transfer E_j to tidal jets is given by the following formula (Stigebrandt and Aure, 1989)

$$E_j \approx 0.42\left(\frac{1}{4}\right)\rho_0\omega^3 a^3 A_f^3 A_m^{-2} \tag{11}$$

Based on results for the MR-fjords, the efficiency factor Rf_j with respect to diapycnal mixing in the basin water is only 0.01 for jet fjords according to Stigebrandt and Aure (1989). They explained that this is because tidal jets dissipate essentially in the upper layer, above the sill depth, of the fjord. In Knight Inlet and Loch Linnhe, two highly energetic fjords, Klymak and Gregg (2004) and Allen and Simpson (1998) found that reflection of the tidal wave complicates the picture, see also Arneborg and Liljebladh (2009) for observations and a discussion of mechanisms facilitating dissipation and diapycnal mixing in fjord basins.

The background work W_0 against the buoyancy forces in the MR-fjords, for which A_f typically equals 10 km^2, is about 0.02 mWm^{-2} (Stigebrandt and Aure, 1989). Due to effects of the topography of the surrounding land, it is likely that the wind is stronger in larger than in smaller basins. In the much larger and tide-less Baltic proper, where A_f is of the order of 10^5 km^2, W_0 is about 0.10 mW m^{-2}. From these extremes, Stigebrandt (2001) suggested the following parameterization of W_0,

$$W_0 = B\cdot 10^{\left(0.2\cdot \log A_f - 2\right)} \tag{12}$$

Here $B = 1$ mW m^{-2} and Af is expressed in km^2. Equation (12) should be applicable to areas with similar wind climate as in the MR-fjords and if $Af < 10^6$ km^2.

The density of the basin water may also change if buoyant water, for instance surface water of lower density or freshwater, is mixed into the basin water by pumping. The rate of density reduction $d\rho/dt$ achieved by mixing buoyant water into the basin water is given by Equation (16) in section 5.5 below.

A formula for the specific work against the buoyancy forces W that brings about water exchange in salt-stratified basins, can be obtained by combining Equations (6) and (7).

$$W = \frac{Re\cdot g\cdot H_b^2}{C\cdot Te} \tag{13}$$

This equation may be used diagnostically to estimate the specific power W used for diapycnal mixing in the basin water if Te and Re have been estimated from time series of observations of density (salt and temperature) in the basin water. To the best of the present authors knowledge, formulas for diagnostic estimates of W have not earlier been presented in the literature.

The theory above concerns salt-stratified basins that in some cases might be stagnant for years. In heat stratified basins, like freshwater lakes in temperate climate zones and many coastal basins in the Baltic Sea, the length Te of periods of hypolimnion/deepwater stagnation is a fraction of a year and determined essentially by the heating/cooling cycle at the sea surface. Consequently, in heat stratified basins Te should be only weakly dependent on the power W spent to diapycnal mixing in the hypolimnion during the stagnation period.

3. Sea-based measures to improve the oxygen conditions in stagnant basins

Sea-based measures may be used to improve the oxygen conditions manifested by an increase of DO_{min} in periodically stagnant basin water. Five different sea-based measures, named A, B, C, D, E, respectively, are described below.

A) To reduce the supply of nutrients to the surface layer by relocation of outlets containing plant nutrients from the surface layer to the basin water. This should reduce the primary production and thereby the supply of organic matter to the basin water, which should diminish the rate of oxygen depletion dDO/dt provided the basin water is located beneath the sunlit photic zone so that nutrients from the outlet do not contribute to primary production of organic matter in the basin water. However, outlets from e.g., sewage treatment plants may also contain dissolved oxygen as well as oxygen consuming substances, quantified by their inherent biological and chemical oxygen demand BOD and COD, respectively. This may change the rate of oxygen consumption and thereby the rate of oxygen depletion dDO/dt in the basin water.

B) To supply dissolved oxygen to the basin water at the rate $DOSUP$. This should reduce the rate of oxygen depletion dDO/dt in the basin water.

C) To increase the power supply to turbulence and diapycnal mixing in the basin water of salt-stratified basins. This will increase the work against the buoyancy forces W and the rate of density reduction $d\rho/dt$, c.f. Equation (7), and thereby shorten the residence time Te, c.f. Equation (6), and thus increase the rate of flushing of the basin water.

D) To inject and mix buoyant water, for instance surface water or freshwater, into the basin water. This will increase the rate of density reduction $d\rho/dt$, c.f. Equation (16) in Section 5.5, and the frequency of flushing of the basin water and thus shorten the residence time Te, c.f. Equation (6). The supplied buoyant water may contain dissolved oxygen and thereby also contribute to $DOSUP$ (Measure B).

E) To change the topography of the entrance strait. Dredging, usually undertaken to improve conditions for navigation, may change the vertical cross-sectional area and the depth of the strait. For a marine water body, dredging may change the amplitude of tidal currents in the strait and thereby change the tidal power supply to turbulence in the basin water (Equations (10) and (11)) and the residence time Te (Equations (6) and (9)). In addition, an increased sill depth may change the properties of juvenile basin water, for instance S_{in} and DO_{in} and thereby DO_{start}. Dredging of the entrance strait may thus influence DO_{min} in several ways. The theory for this measure may be applied backwards to estimate historic oxygen conditions in the basin water occurring before the entrance sill was dredged.

3.1. Comments

Measures C and D will increase the frequency of exchange (flushing) of the basin water and thereby shorten Te. If DO_{in} has a seasonal variation and the season of exchange of basin water changes, the value of DO_{in} and thereby the value of DO_{start} might change. A negative side effect of increased flushing might thus occur if the applied measure triggers water exchange to take place during a season with low oxygen concentration DO_{in} outside the fjord.

A large fraction of the diapycnal mixing in the deepwater of natural basins takes place in a boundary layer at the seabed (boundary mixing) driven by breaking internal waves (e.g., Stigebrandt, 1976; Stigebrandt 1979; Ledwell and Hickey, 1995; Goudsmit et al. (1997); Holtermann et al., 2012). Spatial variability of diapycnal mixing in fjords has been verified by microstructure mixing estimates, e.g., Arneborg et al. (2004a); Arneborg and Liljebladh (2009). Mixing in the boundary layer at the seabed creates horizontal density gradients driving alternating baroclinic currents between the boundary layer and the interior of the water body (intrusions). The circulation in the basin water driven by boundary mixing may thus be arranged in several relatively thin cells on top of each other. It is expected that an increased power supply to

internal waves in the basin water would reinforce mixing in the boundary layer at the seabed and thereby the adherent intrusions caused by horizontal density gradients sustained by the boundary layer mixing.

Modus operandi for the vertical circulation in the basin water caused by Measure C, described above, differs from that caused by Measure D. In Measure D, a deep outlet of buoyant water forms a rising entraining buoyant plume that is interleaved in the pycnocline. The withdrawal of basin water due to entrainment into the plume, causes compensatory downwelling between the depths of outlet and interleaving as depicted in Fig. 5. The plume-driven circulation thus occurs in one thick cell. The plume-driven downwelling, with a speed of about 1 m day^{-1}, is quite evident in the hydrographic observations obtained during the BOX experiment in the By Fjord, see Figure 3 in Stigebrandt et al. (2015). See also the model paper by Stigebrandt and Kalén (2013).

Measure C, increased mixing in the basin water may be performed in many ways, for instance using rotating rods. The mixing is then local, and the mixed water will by intrusions, driven by horizontal pressure gradients sustained by the artificial mixing, be transported away from the mixing area and in this way change the density in the basin water.

Aure and Stigebrandt (1990) developed the model Fjordmiljø, also known as FjordEnv, that computes the minimum oxygen concentration DO_{min} in the basin water and its response to changes of the rate of supply of organic matter due to, for instance, fish farming in net pens, and to changes of the residence time *Te* due to topographical changes of the entrance strait. The model and some later improvements are described in Stigebrandt (2001).

Successful applications of Measures A to E should lead to an increase of DO_{min} and thereby also to an increased DO_{start}, as discussed beneath Equation (4). However, the spin-up time of this effect, that is due to mixing of juvenile and resident basin water during exchange of basin water, is probably 2 to 3 times longer than the residence time *Te*, c.f. Section 5.6.

4. The By Fjord

In this paper, sea-based measures to improve the oxygen conditions in periodically stagnant basin waters are demonstrated by hypothetical application to the periodically stagnant basin water of the salt-stratified By Fjord, the innermost basin in the fjord system between the Swedish mainland and the Orust Island (Fig. 1). The tide is essentially semi-diurnal with a mean amplitude of about 0.15 m. Sunninge Strait, or

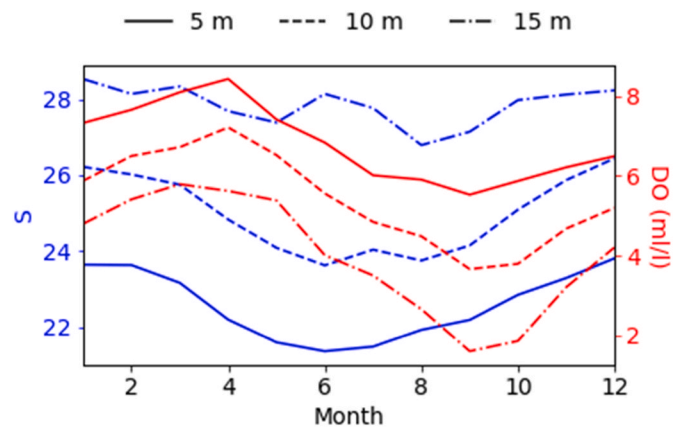

Fig. 2. Seasonal variations shown by monthly means of salinity *S* and dissolved oxygen *DO* at 5, 10 and 15 m depth, respectively, in the Havsten Fjord in the period 1990–2019. Data from SMHI (2022).

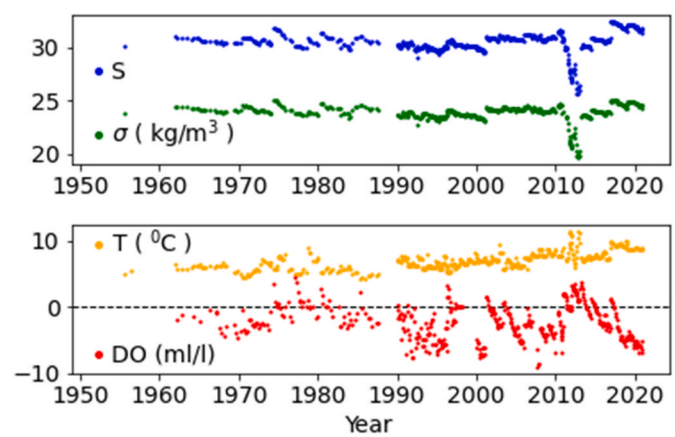

Fig. 3a. Volume weighted mean values of salinity (*S*), temperature (*T*), density σ, and dissolved oxygen (*DO*) in the basin water beneath 17.5 m depth for the period 1950–2021. In anoxic water, hydrogen sulphide is shown as negative *DO* i.e., 1 $H_2S = -2DO$ (by moles).

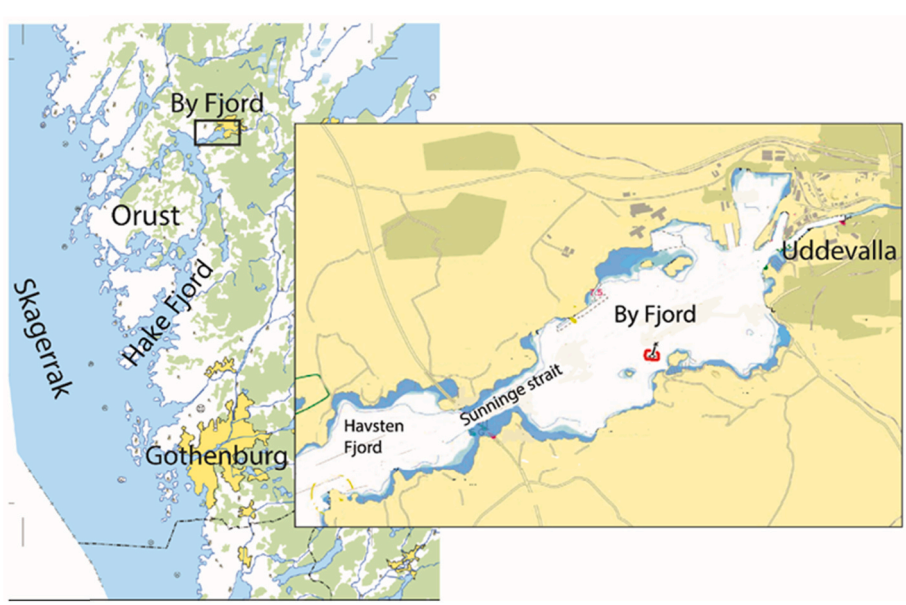

Fig. 1. Map of the area. The red circle shows the location of the pontoon equipped with pumps during the oxygenation experiment BOX in the period 2010–2012.

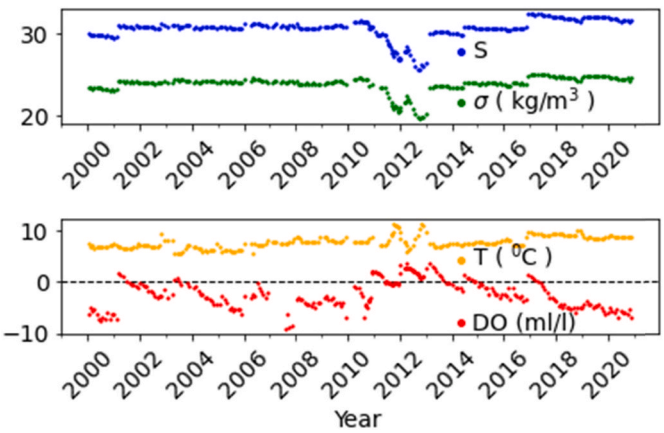

Fig. 3b. As for Fig. 3a except for the shorter period 2000–2021.

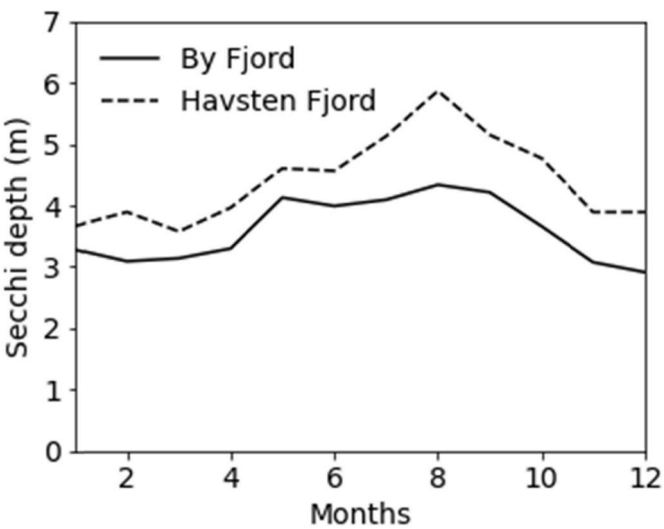

Fig. 4. Monthly mean Secchi depth in the By Fjord and the Havsten Fjord for the period 1990–2019. Data from SMHI (2022).

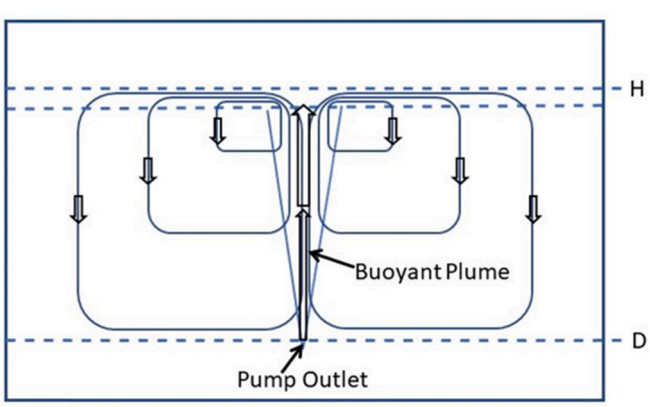

Fig. 5. Sketch of the circulation cell in the basin water driven by entrainment into a plume of buoyant water from a submerged outlet at depth *D*. The entraining buoyant plume is interleaved at about the depth *H*. Here it maintains a horizontal density gradient that spreads the interleaved plume water horizontally at about this depth. The entrainment of ambient water into the rising plume creates a compensating downwelling in the basin water, c.f. Figure 3 in Stigebrandt et al. (2015).

Sunningen, connects the By Fjord to the Havsten Fjord. This strait has been dredged several times to meet increasing navigational demands by ship traffic to the harbour of Uddevalla and to the shipyard Uddevallavarvet AB (1946–1986). A certificate, signed by two marine pilots in 1738, states that it is possible to pass Sunningen with 12 feet draught during easterly winds and 13–14 feet draught during westerly winds. A report from the customs authority dated 1827 tells that the depth of the narrow navigable channel in Sunningen is 15 feet, see Kristiansson (1953). Since 1996, the dredged depth of Sunningen equals 13.5 m. Data on the depth conditions in the strait were extracted by Göransson and Stigebrandt (1998) from sea charts based on depth soundings in 1850–61, 1928 and 1953 and from information provided by Uddevalla Harbour. The evolution of the sill depth (greatest depth) and the width of the strait at different depths during six epochs are presented in Table 1. The horizontal area of the fjord basin equals 6.15 km^2 and the largest depth is about 50 m. The horizontal area of the fjord basin at selected depths, and the fjord volume below these depths, are given in Table 2.

The water in the By Fjord is vertically stratified by sea salt and can be divided in three types; the basin water ($S > 28$) located beneath the sill level (13.5 m), the intermediary water ($28 < S < 20$), above the basin water, and surface water having reduced salinity due to local freshwater runoff (e.g., Göransson and Svensson, 1975). Three rivers, the Bäve River, the Kärra River, and the Bodele River, fall into the By Fjord. The mean flows are 4.59, 0.46 and 0.30 m^3s^{-1}, respectively. In the period 2012–2014 the rivers brought 6 tonnes P yr^{-1} and 130 tonnes N yr^{-1} to the fjord (Ruist et al., 2017). The outlet from the sewage treatment plant, Skansverket, brings annually 1,7 tonnes of P and 50 tonnes of N to the mouth of the Bäve River (Table 3). About 17 tonnes of the nitrogen are in reduced form (ammonium).

The main connection between the Havsten Fjord and the Skagerrak goes through the wide Hake Fjord (Fig. 1). For a description of the fjord system, see Hansson et al. (2013). The Kattegat, south of the Skagerrak, is strongly stratified by sea salt, mainly due to the huge outflow of brackish water ($S \sim 7$) from the Baltic Sea (e.g., Läpperanta and Myrberg, 2009). This is mixed by local winds with the rather saline ($S \sim 33$) deepwater in the Belt Sea and Kattegat. The often about 15 m deep Baltic Current, emanating from the surface layer of the Kattegat, flows along the eastern rim of the Skagerrak and its salinity is usually in the interval $20 < S < 30$ (e.g. Svansson, 1975; Gustafsson and Stigebrandt, 1996). The vertical stratification at the Swedish Skagerrak coast varies perpetually due to variations of thickness and salinity of the Baltic Current when leaving the Kattegat and horizontal advection and vertical mixing performed by local winds over the Skagerrak (Gustafsson and Stigebrandt, 1996). The ever-changing vertical density distribution at the coast creates alternating horizontal pressure gradients between the coastal area and the adjacent fjords, leading to vivid baroclinic water exchange such that the stratification above the sill levels of the fjords tends to adjust to the vertical stratification at the coast (Klinck et al., 1981; Stigebrandt, 1990; Aure et al., 1997; Arneborg, 2004). This kind

Table 1
The smallest width (m) at selected depth levels in Sunninge Strait during six epochs.

Depth (m)	Epoch					
	1738-	1860-	1928	1958-	1976-	1996-
0	365	365	365	365	365	365
3	80	80	80	130	230	230
5	0					
6		60	60	110	215	215
7		0				
8			20			
9			0			
11				80	190	190
12					185	185
13.5						100

Table 2
The horizontal fjord area at, and the fjord volume below, selected depths in the By Fjord. (After Göransson and Stigebrandt, 1998).

Depth (m)	Area (km^2)	Volume below ($m^3 \bullet 10^6$)
0	6.15	137.7
5	5.08	109.8
10	4.16	86.6
12	3.85	78.6
13.5	3.69	73.0
14	3.64	71.1
16	3.41	64.1
17.5	3.25	59.1
18	3.20	57.5
20	2.98	51.3
25	2.60	37.4
30	2.28	25.2
35	1.91	14.5
40	1.46	6.4
45	0.3	1.4
50	0.02	0

Table 3
The outlet from Skansverket in 2020 (Jannie Lundell & Linda Nilsson, personal Communication).

	Amount		Comment
P	1.7	tonnes yr^{-1}	
N	50	tonnes yr^{-1}	17 tonnes yr^{-1} are in the form of ammonium
Water	0.220	$m^3 s^{-1}$	Annual average
DO	≈5	g m^{-3}	Uncertain, only few observations
BOD	20	tonnes yr^{-1}	
COD	198	tonnes yr^{-1}	

of water exchange, called intermediary water exchange, is the dominating mode of water exchange in the fjord system (Hansson et al., 2013). The residence time of water above the sill depth in the By Fjord is about 1 week (Göransson and Stigebrandt, 1998).

The density of the coastal water varies on a wide range of timescales as explained above. In periods with lasting north-easterly winds over the Skagerrak, occurring in particular in late winter and early spring, wind-driven Ekman currents transport surface water to the Norwegian coast from where the baroclinic Norwegian Coastal Current transports the surface water to the North Sea (Aure and Sætre, 1981; Gustafsson and Stigebrandt, 1996). The loss of surface water of lower density (salinity) by export leads to up-welling and peaking density along the Swedish Skagerrak coast, which may lead to inflow of quite dense water that may exchange the basin water in the fjords. However, the deeper basin water in the By Fjord has a residence time of 3–5 years due to the combined effect of very low rate of density reduction $d\rho/dt$ and large sub-annual variability of the density field at the coast, see Stigebrandt (2012). Continuous hydrographical observations by anchored instruments in the By Fjord show that a complete exchange of basin water takes about one week (Stigebrandt et al., 2015), see also the model study by Liungman et al. (2001).

Exchange of basin water in the By Fjord by inflow of juvenile basin water occurs when the density of the water in the Havsten Fjord just above the maximum depth of the Sunninge Strait, is greater than the density of the basin water. In this fjord system, density variations are mainly due to salinity variations. The monthly mean salinity S and dissolved oxygen concentration DO at 5, 10 and 15 m depth in the Havsten Fjord have been computed from observations. There are large seasonal variations of both salinity and dissolved oxygen, with maximum in winter and minimum in summer (Fig. 2). It is therefore likely that water exchange occurs in winter when the density is high because the salinity is high and the temperature is low (not shown). This is fortunate because the oxygen concentration DO is then at, or close to, its maximum value. Obviously, one should avoid triggering water exchange in the months July to November (Fig. 2).

An extensive investigation of the environmental status of the By Fjord was undertaken in the beginning of the 1970s. The primary production was found to be twice as high as in fjords nearby and in Kattegat (Söderström, 1976). The distribution of carbon in the surface sediments indicate that the fjords around the Orust Island are eutrophicated (Olausson, 1975b). By comparison with an investigation from 1929 to 1930 by Gislén, it was found that the maximum depth of stationary algae had been halved in the Havsten Fjord in 1973 (Table 1 in Rex, 1976).

There is no information about the nutrient supply to the By Fjord during the 1700s and 1800s. According to Olausson (1975a), the population in Uddevalla was about 4000 in year 1800, 8400 in year 1900 and 16 000 in year 1940. Present time population is about 56 000. Before about year 1900, manure from animals and people was likely the main fertilizer for farming and there were probably only small losses to streams and rivers. In the period 2012–2014, the supply of P by freshwater runoff was about 6.0 tonnes yr^{-1}, of which about 5.0 tonnes yr^{-1} came with the Bäve River (Ruist et al., 2017). In the beginning of the 1970s the outlet of P from Bäve River was about 8 tonnes yr^{-1} (Göransson and Stigebrandt, 1998) so it seems that the P supply by runoff is declining. The outlet of P from municipal sewage increased due to the use of water toilets and an increasing population and in the beginning of the 1970s it was about 18 tonnes yr^{-1}. In 1980 it had been reduced to 11 tonnes yr^{-1} and in 1996 the outlet of P had been reduced further to 1.2 tonnes yr^{-1} (Göransson and Stigebrandt, 1998). Thereafter it has increased to 1.7 tonnes yr^{-1} (Table 3) due to an increased number of households connected to the sewage treatment plant.

The basin water in the By Fjord is anoxic most of the time due to extensive anaerobic decomposition of organic matter and long residence time Te. Large amounts of poisonous hydrogen sulphide and ammonia accumulate together with phosphate in the basin water. Consequently, the bottoms in the basin water lack higher forms of life. During the pilot oxygenation project BOX, in the period 2010–2012, the basin water was oxygenated using Measure D. Surface water was pumped (about 2 m^3s^{-1}) to 35 m depth where it was ejected in horizontal jets that mixed with the ambient basin water and formed a rising and entraining buoyant plume, which created a compensating downwelling in the basin water with the speed of about 1 m day^{-1}, see Fig. 3 in Stigebrandt et al. (2015). Within about one year, a top layer of the bottom sediment in the basin water had been oxygenated, leading to discontinued leakage of phosphorus from the sediment and to colonization of the earlier azoic bottoms. During the oxygenation experiment, the accumulated amount of phosphate in the basin water was much less than before the experiment due to more frequent water exchange and discontinued leakage from the bottom sediments when these became oxidized. The discontinued P supply from the bottom sediment is quite evident for the long period of oxic conditions in the basin water starting early in 2013, see Fig. 4c in Stigebrandt et al. (2015). Repeated exposure of caged mussels and passive samplers (SPMDs and DGTs) during the oxygenation did not show any increase in the leakage of measured organic pollutants or toxic metals from the bottom sediment. Ecological and biogeochemical changes in the fjord during the BOX experiment are described in Stigebrandt et al. (2015); De Brabandere et al. (2015); Forth et al. (2015). About four years after the end of the experiment, conditions had reversed and approached those prevailing before the experiment (see Fig. 3b). A Swedish national screening survey of biological effects in polluted areas in 2017–2018 found in the By Fjord only minor effects of pollution on fish health and no effects on Nassarius snails (Förlin et al., 2019).

Starting as a private initiative, five reefs were placed on the seabed in water depths 5–8 m in the southwestern corner of the By Fjord in 2015 to give shelter for lobster and cod from seals and cormorants. From observations by filming, it was found that the reefs became populated by cod. After three years, the reefs were populated by up to 60 cm long cods. The interest for the project grew and there are now 69 reefs in the fjord, financed by authorities (the Swedish Agency for Marine and Water Management) and companies and private persons. Information about

the project and several films can be found at Torskundret i Byfjorden - Fjordtorsk i Bohuslän. The project has raised interest in improving the water quality of the basin water by oxygenation. This should transform the basin water, including a bottom area of about 3 km^2, to a good habitat for cod and other animals. Oxygenation of the basin water will also discontinue the leakage of phosphorus P from anoxic bottoms (Stigebrandt et al., 2015), which will reduce the P loading and improve the water quality of the fjord system outside the By Fjord.

5. Application of sea-based measures A, B, C, D and E to the By Fjord

For application of the various sea-based measures to a specified basin, it is necessary to know the residence time *Te* of the stagnant basin water and the mean rate of oxygen depletion dDO/dt, due to supply *FC* of carbon contained in particulate organic matter POM to the basin water. In Chapter 5.1 below, the (diagnostic) values of these and other key variables in the By Fjord are estimated from observations. Hypothetical applications of the sea-based Measures A to E to the By Fjord are described in Chapters 5.2 to 5.6, respectively.

5.1. Diagnostic analysis of the basin water

Different sea-based measures may be applied to stagnant basins to improve the oxygen conditions, measured by the minimum concentration of dissolved oxygen DO_{min} as described in Chapter 3. To compute the change of DO_{min} if a certain measure is applied, the initial residence time *Te* and the specific flux FC of carbon, contained in settling POM, must be known, see Equation (5). Time series of hydrographic observations obtained in the basin water are needed to estimate *Te* and *FC*. The hypsographic function of the By Fjord (Table 2) is used to estimate volume weighted values of density ρ and dissolved oxygen *DO* from repeated observed vertical profiles of ρ(z,t) and *DO*(z,t), where z is depth and t observational time. Hydrographical data were obtained from SMHI (2022). *Te* may be estimated from the evolution of ρ, and *FC* may be estimated from the rate of oxygen depletion dDO/dt (see Equation (3)). For reliable estimates of changes, the requirement that the water has not been exchanged between two consecutive observations must be fulfilled. Volume weighted values of density ρ and dissolved oxygen *DO* are determined for the volume below 17.5 m. This depth for the upper boundary of the basin water is chosen because the water in a few metres thick layer just below the sill depth, 13.5 m, is less stagnant. Fig. 3a

shows the evolution of the volume-weighted salinity *S*, temperature *T*, dissolved oxygen concentration *DO* and density, expressed as $\sigma = \rho - 1000$ (kg m^{-3}), in the basin water below 17.5 m.

The oxygen depletion in the basin water below 17.5 m can be estimated to close to 2 tonnes day^{-1} for the stagnation period starting early in 2013 with $DO_{start} \approx 6.2$ g m^{-3} (Fig. 3b). For a plot with higher resolution, seeFigure 4a in Stigebrandt et al. (2015). However, the volume below 17.5 m equals 81% of the volume V_b of the basin water below the sill depth 13.5 m (c.f. Table 2). This means that the oxygen depletion in the basin water, $V_b \bullet dDO/dt$ can be estimated to about 2.5 tonnes day^{-1}. Assuming long-term balance between supply and consumption of organic matter in the basin water, this oxygen depletion requires that the supply of carbon, $FC \bullet A_t$, to the basin water equals $2.5/\mu = 0.71$ tonnes day^{-1}. Here μ (=3.5 tonnes O_2 per 1 tonnes C) is the amount of oxygen needed to oxidize organic matter of so-called Redfield composition, defined beneath Equation (3), and A_t is the horizontal area of the fjord basin at the sill level. With $A_t = 3.69$ km^2 (Table 2) the specific carbon flux *FC* into the basin water of the By Fjord is estimated to about 0.19 tonnes km^{-2} day^{-1} or 5.7 g m^{-2} $month^{-1}$. This is close to an estimate based on observed oxygen depletion during an earlier period by Stigebrandt and Liljebladh (2011). From the evolution of the density (σ) for the period 1961–2010, i.e., before the pumping experiment influenced *Te*, we estimate that *Te* varies between 3 and 5 years (Fig. 3a).

Conclusion. In the By Fjord, the residence time *Te* of the basin water in the period 1961–2010 is 3–5 years. The oxygen depletion $V_b \bullet dDO/dt$ is about 2.5 tonnes $O_2 day^{-1}$ and the corresponding vertical flux of carbon *FC* contained in settling organic matter is 0.71 tonnes day^{-1}.

5.2. Measure A

This measure is to relocate the outlet from the municipal sewage treatment plant, Skansverket, from the mouth of the Bäve River (Fig. 1) to the basin water beneath the photic zone. This might reduce the primary production and thereby *FC* and the rate of oxygen depletion dDO/dt in the basin water. In the By Fjord, the photic zone reaches about 2 times deeper than the Secchi depth (Söderström, 1976). The monthly mean Secchi depth in the By Fjord for the period 1990–2020 is about 4 m or less (Fig. 4). The photic zone should thus on average reach down to about 8 m depth. Accordingly, if the outlet is interleaved in the basin water, i.e. below the sill depth (13.5 m), the accompanying nutrients would be located well below the photic zone. Provided the nutrients in the basin water do not contribute to primary production in the fjord during exchange of basin water, which usually occurs in winter, nutrients contained in the outlet from Skansverket should not contribute to primary production in the fjord.

The annual outlet of plant nutrients from Skansverket to the mouth of the Bäve River is 1.7 tonnes P and 50 tonnes N (Table 3), of which 17 tonnes of N are in the form of ammonium. The NP-ratio in the outlet water is thus 29:1 by weight, which is much above the Redfield ratio 7.2:1, showing that phosphorus is the limiting plant nutrient. The length of the production season is assumed to be about 0.7 year. To estimate how this nutrient supply influences the oxygen consumption in the basin water, it is assumed all phosphorus from the outlet is used for primary biological production in the fjord that is exported to the basin water with sinking particulate organic matter POM. Assuming standard (Redfield) composition of organic matter (i.e. C:P = 41:1 by weight), 0.7•1.7 tonnes of P would lead to the production of organic matter containing 0.7•1.7•41 = 48.8 tonnes C. To oxidize this would require 3.5•48.8 ≈ 171 tonnes O_2 yr^{-1} or 470 kg O_2 day^{-1}. This might be an overestimate because some of the organic matter produced by the nutrients from Skansverket should settle on bottoms above the sill depth in the fjord and some should be exported through the Sunninge Strait to the Havsten Fjord, depending on the sinking speed of POM and the residence time of water above the sill depth, see Stigebrandt (2001) and Erlandsson (2006).

The outlet from Skansverket also contains dissolved oxygen *DO* and reduced matter that will be oxidized with an estimated oxygen demand BOD + COD ≈550 kg day^{-1} (Table 3). As long as the outlet is located to the mouth of the Bäve River, the reduced matter should be oxidized above the sill depth and thus not lead to oxygen consumption in the basin water. However, if the outlet is relocated to the basin water, the oxygen required to oxidize the reduced matter, i.e. 550 kg O_2 day^{-1}, will be taken from the basin water and thus lead to an increased oxygen consumption. However, this may partly be compensated by dissolved oxygen contained in the outlet. The mean outlet of water is 0.220 m^3 s^{-1} and its concentration of dissolved oxygen is about 5 g m^{-3} (Table 3). This should give a supply of oxygen to the basin water of about 95 kg day^{-1}. We may thus conclude that the outlet should increase the rate of oxygen consumption in the basin water by about 550–95 = 450 kg day^{-1}. This is about equal to the expected reduction of the rate of oxygen consumption in the basin water of 470 kg day^{-1}, as estimated above, if the nutrients carried by the outlet are interleaved beneath the photic zone in the basin water. Interleaving of the outlet from Skansverket below the photic zone in the basin water would thus likely not reduce the rate of oxygen consumption in the basin water. The freshwater contained in the outlet would, however, lead to increased rate of density reduction $d\rho/dt$ in the basin water (Measure D) and this effect is estimated in Section 5.5 below. There may be hygienic advantages to relocate outlets from the surface layer to the basin water, but this aspect is beyond the theme of the present paper.

Conclusion - Relocation of the outlet from Skansverket from the surface layer to the basin water beneath the photic zone should likely not lead to changed oxygen consumption in the basin water. However, it might lead to reduced residence time *Te* of the basin water, see Measure D below.

5.3. Measure B

This measure is to supply dissolved oxygen to the basin water at the rate *DOSUP* with the purpose to reduce the rate of oxygen depletion dDO/dt in the basin water and thereby increase DO_{min}. From Equation (5) follows that if, for instance, *DOSUP* equals the rate of oxygen consumption $A_t \bullet \mu \bullet FC$, the oxygen concentration will stay close to DO_{start}, the concentration just after an event of water exchange. In Chapter 5.1 above the oxygen depletion rate in the basin water of the By Fjord was estimated to about 2.5 tonnes O_2 day^{-1}. An important question to answer is how large the oxygen supply *DOSUP* must be to maintain the oxygen concentration above a certain specified minimum value DO_{min}. The following example demonstrates that the required oxygen supply *DOSUP* depends on the residence time *Te*.

At the end of an event of basin water renewal, the oxygen concentration in the basin water equals DO_{start}. The "oxygen reserve" *DOres* in the basin water just after an event of water exchange is $DOres = V_b \bullet (DO_{start} - DO_{min})$. If, for instance, $DO_{start} = 7$ g m^{-3} and $DO_{min} = 2$ g m^{-3} and $V_b = 73 \bullet 10^6$ m^3 (Table 2) then $DOres = 365$ tonnes. If oxygen is continuously withdrawn (by consumption) from the oxygen reserve *DOres* during the whole residence time *Te*, then *DOres/Te* (tonnes/day) is the highest allowed rate of withdrawal of *DO* during the stagnation period. If $Te = 5$ years (1826 days) the highest allowed rate of withdrawal of *DO* from the reserve equals 0.20 tonnes day^{-1}. However, if $Te = 1$ year (365 days) the withdrawal from the reserve can be 1 tonne day^{-1}, which is 40% of the current rate of oxygen depletion in the basin water of the By Fjord. An installation for basin water oxygenation should thus deliver 2.3 tonnes day^{-1} or 840 tonnes year^{-1} if the residence time of the basin water is 5 years. However, if the residence time is 1 year, the installation is required to deliver 1.5 tonnes day^{-1} or 550 tonnes year^{-1}. This example shows that if a stagnant basin is going to be oxygenated, one might consider combining measures supplying oxygen and measures reducing the residence time *Te*.

Because oxygen may be added without large disturbances of the vertical temperature (density) stratification, Method B has been applied to several inland lakes and freshwater reservoirs. To compute the transfer of oxygen from bubbles to the recipient one may use a single bubble model combined with a plume model (Wüest et al., 1992) and a hydrodynamic model of the recipient.

For efficient dispersal of oxygen in the basin water, one may take advantage of the natural dispersive circulation induced by boundary mixing, briefly discussed in Section 3, and locate the outlet from the oxygenation device in the turbulent bottom boundary layer. One should be aware that the natural boundary mixing may drive several rather thin circulation cells on top of each other which implies that oxygen should be supplied to several depths in order to efficiently oxygenate all parts of the basin water. To avoid gas bubble disease in deep systems like fjords basins, it seems important to secure that the oxygen concentration does not exceed the saturation concentration at sea level which calls for an oxygen concentration control program when applying Method B.

What would it cost? The present price of oxygen in large quantities seems to be about 5 SEK kg^{-1} (Linde gas AB - 2021) + transportation costs and costs for an oxygen tank at the shore and an oxygenation device in the basin water. To buy 840 tonnes of oxygen would cost about 4.2 MSEK. It is tentatively assumed that the annual costs of transports and of the oxygenation device and its infrastructure is 1.8 MSEK. The cost to oxygenate the By Fjord using oxygen gas would then be about 6 MSEK yr^{-1}. This cost may be reduced by 1.5 MSEK yr^{-1} if the residence time *Te* is reduced to 1 year which can be achieved if Measure C or Measure D is applied simultaneously.

In future, oxygen might be available as a cheap by-product (side-stream) from large-scale industrial production of "green" hydrogen gas produced by electrolysis of water using renewable energy. This should increase the interest to use Measure B.

Conclusion. The tentatively estimated cost of using 2300 kg oxygen day^{-1} in an oxygenation system for the By Fjord is about 16 400 SEK day^{-1}. If *Te* is reduced to 1 year, using Measure C or D simultaneously, the estimated cost will be reduced to about 12 400 SEK day^{-1} plus the cost of applying Measure C or D.

5.4. Measure C

This measure is to shorten the residence time *Te* and thus increase DO_{min} *by* increasing the power supply to turbulence and vertical (diapycnal) mixing in the basin water, which will increase the rate of density reduction $d\rho/dt$.

The actual power *W* spent on diapycnal mixing processes in the basin water of the By Fjord may be estimated in two different ways, using either the diagnostic Equation (13) or the prognostic Equations (9), (10) and (12). For the application of Equation (13) we use the following numbers, $Re = -1$ kg m^{-3} yr^{-1}, $g = 9.81$ m s^{-2}, $H_b = 19.8$ m, $C = 2 \pm 0.6$, $Te = 3$ years ($= 94.5 \bullet 10^6$ s). We then obtain $15.6 < W < 29$ μWatt m^{-2}. For insertion in the prognostic equations, we also need $A_t = 3.69$ km^2, $A_f = 6.15$ km^2, $A_m = 2900$ m^2, $Rf = 0.056$, $\omega = 2\pi/T$, $T = 12$ h, $a = 0{,}15$ m, $H_t = 13.5$ m. Inserting numbers in Equation (12) gives the background (wind-driven) work $W_0 = 14$ μWatt m^{-2} and inserting numbers in Equation (10) gives the total tidal supply $E_w \sim 1440$ Watt so that the specific tidal supply in the basin water equals $Rf \bullet E_w/A_t = 19$ μWatt m^{-2}. From Equation (9) we then get $W = 33$ μWatt m^{-2}. This is slightly above the expected range obtained from the diagnostic Equation (13).

If $Re = -1$ kg m^{-3} yr^{-1} holds also for shorter residence times, using Equation (13) one may conclude that $Te = 1$ year may be achieved by increasing *W* by a factor of 3, i.e. to about 100 μWatt m^{-2}. However, to attain $Te = 1$ with certainty for the By Fjord, one should adopt a higher value of *Re*, for instance 4 kg m^{-3} as found empirically during the BOX oxygenation experiment (c.f. Fig. 3b). This will increase the required *W* to about 400 μWatt m^{-2}. The power supplied to the turbulence in the basin water should then be $W \bullet A_t/Rf \approx 26$ kWatt provided the efficiency of the mixing process *Rf* equals 0.056.

A wind-driven device, for instance, might be used for vertical mixing in the basin water. It is expected that the wind is strong enough to drive the device about 40% of time. The nominal effect of the wind-driven device should accordingly be about 65 kW. However, this is probably too much because increased mixing in the basin water will not only reduce *Te* but it will also increase the diffusive oxygen transport into the basin water which will reduce the rate of oxygen depletion. However, the magnitude of that effect is not estimated in the present paper. Finally, we have not found in the literature any documented case of an implementation of Measure C. To learn more about this method, a pilot experiment should be undertaken.

Conclusion. This measure may reduce *Te* but it may probably not achieve $DO_{min} > 2$ g m^{-3} in the basin water of the By Fjord. The needed oxygen supply to the basin water with $Te = 1$ year is about 1.5 tonnes day^{-1} if $DO_{start} = 7$ g m^{-3} (Section 5.3). The required oxygen must be supplied by either Measure B or Measure D although an unknown part of the required oxygen supply may come with an increased diffusive flux due to the intensified vertical mixing in the basin water. This measure requires further analysis before being ready for implementation.

5.5. Measure D

This measure is to inject and mix buoyant water, either freshwater or surface water of reduced density, into the basin water. This will increase the rate of density reduction $d\rho/dt$ in the basin water and thereby shorten the residence time *Te*. The supplied buoyant water will also

bring dissolved oxygen to the basin water and thus contribute to *DOSUP*. The long term means of salinity, temperature and dissolved oxygen at some selected depths in the By Fjord are given in Table 4.

Here we estimate the density reduction if the flow Q of buoyant water of salinity S_1 is mixed into the basin water of salinity S_2. In systems where the vertical stratification is mainly due to salinity gradients one may for simplicity use the following equation of state for brackish water, thus

$$\rho = \rho_0(1+\beta S) \tag{14}$$

Here ρ_0 is the density of freshwater and β the salt contraction factor which equals $0.8 \bullet 10^{-4}$ (S^{-1}). From Eq. (14) follows

$$\frac{d\rho}{dt} = \rho_0 \beta \frac{dS}{dt} \tag{15}$$

Following Stigebrandt and Liljebladh (2011), the salinity S_2 of the basin water of volume V_b will change as follows if a pumped flow Q (m^3s^{-1}) of surface water of salinity S_1 is mixed into the basin water.

$$\frac{dS_2}{dt} = -\frac{Q}{V_b}(S_2 - S_1) \tag{16}$$

Using Eq. (15), the density ρ of the basin water will change as follows,

$$\frac{d\rho}{dt} = -\rho_0 \beta \frac{Q}{V_b}(S_2 - S_1) \tag{17}$$

If, for instance, the salinity S_2 of the basin water equals 30, the freshwater ($S_1 = 0$) from the sewage treatment plant Skansverket ($Q = 0.22\ m^3\ s^{-1}$) would give a density reduction of 2.27 kg yr^{-1} if mixed into the basin water. If surface water (0 m) is used S_1 equals 19.59 (Table 4). Then Q should be 0.64 $m^3\ s^{-1}$ to attain the same rate of density reduction as if using the freshwater from Skansverket. To obtain a rate of density reduction of 4.0 kg $m^{-3}\ yr^{-1}$ requires that $Q = 0.39\ m^3\ s^{-1}$ if freshwater is used and $Q = 1.13\ m^3s^{-1}$ if surface water (0 m) is used.

Measure D supplies buoyant water but also accompanying dissolved oxygen. Supplying buoyant water to the basin water will increase the rate of density reduction $d\rho/dt$ and shorten *Te*. During the oxygenation project BOX 2010–2012, surface water (2 m^3s^{-1}) was mixed into the basin water which reduced *Te* to about 1 year (Fig. 3b). In Section 5.2 above it was shown that if *Te* equals 1 year, the oxygen supply to the basin water of the By Fjord required to keep DO_{min} above 2 g m^{-3} equals 1.5 tonnes day^{-1} if $DO_{start} = 7$ g m^{-3}. With the mean oxygen concentration of the buoyant water at the sea surface (0 m) equal to 10.33 g m^{-3} (Table 4), the buoyant water may bring 1.5 tonnes oxygen (daily mean) to the basin water if $Q = 1.7\ m^3\ s^{-1}$. With this flow rate, the rate of density reduction $d\rho/dt$ equals 6 kg $m^{-3}\ yr^{-1}$. This may be a too high rate of density reduction because it implies an increased risk of inflow of juvenile basin water during autumn when the oxygen conditions may be poor in the Havsten Fjord (Fig. 2). However, by lowering the intake depth of the pump, a less buoyant, saltier, water may be pumped. For a pump intake at 5 m depth $DO = 9.34$ g m^{-3} (Table 4). To bring 1.5 tonnes of oxygen per day (daily mean) to the basin water the pumped flow should in this case be $Q = 1.86\ m^3s^{-1}$. With $S_1 = 22.17$ (Table 4), this would reduce the density of the basin water by about 5 kg $m^{-3}\ yr^{-1}$. This example shows that for a specified oxygen need, it is to some extent possible to regulate the rate of density reduction in the basin water by changing the intake depth of the pumped water. Accordingly, using freshwater, e.g. from the Bäve River, to satisfy the oxygen needs would give an unwantedly high rate of density reduction with heightened risk of exchange of basin water during the autumn.

Table 4
Long term averages of salinity *S*, temperature *T*, and dissolved oxygen *DO* at three depths in the By Fjord as estimated using the Shark data base (SMHI, 2022).

Depth (m)	S (g kg^{-1})	T (°C)	DO (g m^{-3})
0	19.59	10.55	10.33
5	22.17	10.90	9.34
10	24.50	10.36	7.00

The power P needed to pump $Q\ m^3s^{-1}$ of buoyant water of density ρ_1 into the basin water, can be estimated from Equation (18), from Stigebrandt and Liljebladh (2011). In this equation, ρ_m is the mean density of the water column in the fjord between the levels of intake and outlet, U_p the speed in the pipe, U_0 the speed at the outlet nozzle and h is the pipe length. The friction factor λ depends on properties of the wall of the pipe. *Eff* is the efficiency of the pump. The first term on the right-hand side is the power needed to accelerate the water through the nozzles, the second term the power needed to overcome wall friction in the tube and the third term an estimate of the power needed to overcome the hydrostatic pressure due to the higher density of the water column down to the outlet.

$$P = Q\rho_1 \left[\frac{U_0^2}{2} + \lambda \frac{U_p^2}{2} + \frac{g}{\rho_0}(\rho_m - \rho_1)h \right] \Big/ Eff \tag{18}$$

Using $Q = 2\ m^3s^{-1}$, $\rho_0 = 10^3$ kg m^{-3} $U_0 = 2$ m s^{-1}, $g = 10$ m s^{-2}, $(\rho_m - \rho_1)/\rho_0 \approx 6.5$ kg m^{-3} (estimated using data from Table 6), $h = 35$ m and with the pump setup in the BOX project, where *Eff* was about 0.6 and $\lambda \ll 1$, Equation (18) gives $P \approx 14$ kW. If the mean price of 1 kWh equals 0.5 SEK, the annual cost of electric power will be about 60 000 SEK. To this cost must be added energy taxes and costs of the pumping system. During the oxygenation experiment in the By Fjord, these costs together amounted to about 400 000 SEK yr^{-1}. A rough estimate of the total cost to oxygenate the By Fjord by pumping and mixing surface water into the basin water is thus about 460 000 SEK yr^{-1} or 1300 SEK day^{-1}. During the BOX project, the pump station was installed on an anchored pontoon in deep water. Based on experience from this arrangement, one should consider locating a permanent pump station to the shore, not too far from the deepest part of the basin.

It is recommended that the effects on density and *DO* in the basin water of this measure are simulated mathematically before implementation, as done by Stigebrandt and Liljebladh (2011) for the By Fjord. If not, unwelcome inflows of juvenile basin water from neighbouring basins with seasonally low oxygen concentration DO_{in} may appear as annoying surprises.

Conclusion: The total daily cost to provide the basin water of the By Fjord with 1500 kg of oxygen, by pumping and mixing surface water into the basin water, is about 1300 SEK. At the present, this is less than 10% of the estimated cost using oxygen gas (Measure B).

5.6. Measure E

This measure concerns the long-term response of the oxygen conditions in stagnant basin water to changes of the topography of the mouth. Deepening of the mouth may change the properties of inflowing juvenile basin water, like S_{in} and DO_{in}, and thereby DO_{start}. From Fig. 2 we conclude that the oxygen concentration DO_{in} of inflowing juvenile basin water from the Havsten Fjord should decrease with increasing sill depth. Concentrations of DO_{in} during the epochs of different Sunninge Strait topographies are suggested in Table 5. Deepening of the mouth will also reduce the volume V_b of the basin water. Changes of the vertical cross-sectional area of the mouth will change the amplitude of tidal currents in the mouth and thereby the tidal energy contribution to turbulence and diapycnal mixing in the basin water of adjacent basins (Stigebrandt, 1976, 1979; Stigebrandt and Aure, 1989), which will change the rate of density reduction $d\rho/dt$ (Equation (7)), the residence time *Te* (Equation (6)) and DO_{min} (Equation (5)). Possible changes of the oxygen conditions in the basin water of the By Fjord that may have occurred due to topographical changes caused by dredging of the Sunninge Strait are analysed below.

Dredging has increased the sill depth in the Sunninge Strait by a

Table 5
Properties of the Sunninge Strait and the By Fjord during different epochs with different sill depth H_t (Table 1) and vertical cross-sectional area A_m of the Sunninge Strait. A_t is the horizontal area of the basin at sill depth (Table 2), H_b the estimated mean thickness of the basin water, S_{in} the estimated salinity and DO_{in} the estimated oxygen concentration of juvenile basin water from the Havsten Fjord. U_{tide} is the estimated tidal current amplitude. The estimated mean densities of the upper and lower layers are ρ_1 and ρ_2, c_i the speed of the internal wave in the By Fjord, W the specific work against the buoyancy forces and Te the residence time of the basin water.

Epoch	1738-	1860-	1928-	1958-	1976-	1996-
$\#i$	1	2	3	4	5	6
H_t (m)	5	7	9	11	12	13.5
A_m (m^2)	750	910	970	1580	2760	2900
A_t (km^2)	5.08	4.71	4.34	4.00	3.85	3.69
H_b (m)	21.6	21.3	21.0	20.6	20.4	19.8
S_{in} (ppt)	28	29	30	31	31.5	32
DO_{in} (g m^{-3})	11.2	10.4	9.8	9.4	9.2	9.0
U_{tide} (m s^{-1})	0.17	0.14	0.13	0.08	0.05	0.04
ρ_1 (kg m^{-3})	1016.61	1016.95	1017.48	1017.90	1018.06	1018.47
ρ_2 (kg m^{-3})	1021.1	1021.9	1022.7	1023.5	1023.9	1024.24
c_i (m s^{-1})	0.423	0.503	0.567	0.628	0.656	0.670
W (μWatt m^{-2})	59.4	58.5	61.5	46.6	33.6	33.2
Te(i)/Te (6)	0.67	0.66	0.61	0.77	1.05	1.00

Table 6
Mean density (kg m^{-3}) at different depths in the By Fjord (BF) and the Havsten Fjord (HF) for the period 1990–2009. Data from SMHI (2022).

Depth (m)	BF	HF
0	1015.39	1017.05
5	1017.82	1017.87
10	1019.80	1019.78
15	1022.75	1022.17
20	1024.19	1023.94
30	1024.57	1025.46
40	1024.55	1025.63

factor of about 3, from 4 to 5 m in the 1730s to 13.5 m in 1996 (Table 1). The vertical cross-sectional area A_m of the mouth has increased from about 750 to about 2900 m^2 (Table 5). The amplitude of the semidiurnal tidal current U_{tide} in the mouth, which is inversely proportional to the vertical cross-sectional area A_m of the mouth, has accordingly decreased by a factor of about 4 since the 1730s (Table 5). Furthermore, changing the sill depth will change the salinity S_{in} of juvenile basin water from the Havsten Fjord. From Fig. 6 we estimate that S_{in} was about 28 when the sill depth was about 5 m and that it has increased with the sill depth as suggested in Table 5, with S_{in} during the present epoch equal to about 32.

When exchange of basin water occurs some of the residing basin water, with oxygen concentration DO_{min}, will be entrained and mixed into the inflowing juvenile basin water, with oxygen concentration DO_{in} (e.g. Liungman et al., 2001; Arneborg et al., 2004). The oxygen concentration DO_{start} in the basin water at the start of a period of stagnation will therefore be lower than DO_{in}. During the oxygenation experiment 2010–2012 in the By Fjord, injection of surface water into the basin water by pumping reduced Te from 3 to 5 year to about 1 year (Fig. 3b) whereby DO_{min} at the start of the inflows of juvenile basin water increased. This led to increasing values of DO_{start} and a maximum of about 6.2 g m^{-3} (≈4.4 L m^{-3}) was achieved early in 2013 after a series of annual water exchanges (Fig. 3b).

To estimate the effect of topographical changes of the mouth on the residence time Te of the basin water we use Equation (13) rewritten as follows,

$$Te = \frac{Re \cdot g . H_b^2}{C \cdot W} \tag{19}$$

Provided Re and C have the same values during all epochs, the residence time Te for epoch number i relative to the residence time for the present epoch ($i = 6$) equals

$$\frac{Te(i)}{Te(6)} = \frac{H_b^2(i)}{H_b^2(6)} \cdot \frac{W(6)}{W(i)} \tag{20}$$

The numerical values of the parameters needed to estimate Te are given in Table 6.

The density difference Δρ between the upper and lower layers, above and below the sill depth, is needed to estimate the internal wave speed c_i (Equation (8)) in the By Fjord. The mean densities at standard observational depths in the By and Havsten Fjords are given in Table 6. At the sea surface, the density is lower in By Fjord than in Havsten Fjord due to the freshwater supply to By Fjord. In the intermediary layer, between the surface layer and the sill depth, the densities are quite similar due to extensive water exchange. The density is higher in By Fjord at 15 and 20 m depth because the sill retains denser water. At 30 and 40 m depths the density is higher in Havsten Fjord. The mean density ρ_1 of the upper layer of the By Fjord, above the sill depth, for the different sill depths during the six epochs is estimated using Table 6. We estimate that when the sill depth increased from 5 to 13.5 m, ρ_1 increased from 1016.61 to 1018.47 (Table 5). At the present, the mean density ρ_2 of the lower layer equals 1024.24 (using Table 6) so that Δρ(6) ≈ 5.77 (kg m^{-3}). The

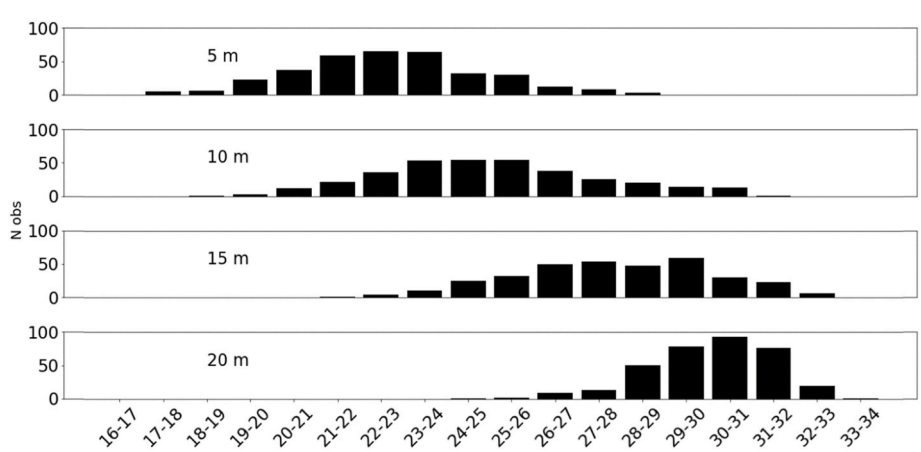

Fig. 6. The number N of salinity observations (vertical axis) in different salinity intervals (horizontal axis) at the standard observational depths 5, 10, 15 and 20 m in the Havsten Fjord in the period 1960–2020. Data from SMHI (2022).

salinity of the lower layer may have increased by 4 units (ppt) from Epoch #1 to Epoch #6, c.f. S_{in} in Table 5. Using Equation (14) we estimate that this should correspond to an increase of the density of the lower layer by about 3 kg m^{-3} from Epoch #1 to Epoch #6. The density difference $\Delta\rho = \rho_2 - \rho_1$ can then be estimated to about 4.5 kg m^{-3} during Epoch #1 and slightly increasing for $i = 2$ to 6 (Table 5). The computed values of $c_i(i)$, $W(i)$ and $Te(i)/Te(6)$ are given in Table 5 $c_i > U_{tide}$ for all epochs showing that the By Fjord is a wave fjord. Since $W_0 = 14$ μWatt m^{-2} (Section 5.4), it follows from Table 5 that $W–W_0 > W_0$ for all epochs showing that tides are more important than the local wind for the diapycnal mixing in the basin water.

According to our analysis, the residence times *Te* for epochs 1, 2 and 3 were about 65% of the present residence time. Since *Te* at the present is 3–5 years, *Te* should have been 2–3 years for epochs 1, 2 and 3. The dredging leading to epoch 3 slightly reduced the residence time because the energy supply *W* to mixing processes increased slightly since the effect of reduced tidal speed in the strait was slightly overcompensated by the effect of reduced volume V_b ($= A_t \bullet H_b$) to mix.

Olausson (1975a) believed that the oxygen situation in the By Fjord was much better 2000 years ago when the sill depth was estimated to be about 25 m. The deterioration was explained to be a consequence of the decreasing sill depth due to the ongoing postglacial land rise. However, this conclusion is not correct because the residence time *Te* should be inversely proportional to the rate of density reduction $d\rho/dt$ in the basin water (Equation (6)), which is proportional to the power supply to vertical mixing (Equation (7)) and most of the power supply emanates from tidal currents in the mouths of fjords (Stigebrandt and Aure, 1989). Thus, land rise has gradually increased the speed of tidal currents in the mouth and thereby reduced *Te* and improved the oxygen conditions in the basin water of the By Fjord.

We have not been able to find descriptions of the environmental state of the By Fjord for the period before regular hydrographical observations started in the 1950s (c.f. Fig. 3a). However, the maximum depth of benthic algae in the Havsten Fjord was halved from 1930 to the beginning of the 1970s, showing a reduction of the penetration depth of solar radiation (Rex, 1976). This was most probably due to increased primary production due to strongly increased outlet of P to the By Fjord (Söderström, 1976). The rate of oxygen consumption in the basin water of the Gullmar Fjord, just north of the Orust fjord system (Fig. 1), increased by about 50% from the 1950s to the beginning of the 2000s. The main reason for this is believed to be an increased production of particulate organic matter POM in the Skagerrak (Erlandsson et al., 2006). This regional effect of eutrophication may have contributed to an increased vertical flux of POM also in the By Fjord during the same period.

Based on the analysis above, it is suggested that DO_{min} in the basin water of the By Fjord was substantially higher before the 1930s than at the present because of the following three reasons. 1) DO_{in} was higher due to the shallower sill. 2) Due to stronger tidal mixing *Te* was shorter before the dredging in 1958, likely 2–3 years instead of 3–5 years as at the present. 3) The rate of oxygen depletion dDO/dt was certainly smaller because the population was much smaller than today (Section 4), and the use of water toilets and artificial fertilizers were still small. It is thus very likely that the oxygen conditions in the basin water in the By Fjord have deteriorated since about 1920 due to increasing supply of nutrients from municipal sewage and agriculture leading to increasing primary production. The dredging in 1958 likely increased the residence time *Te* of the basin water and the dredging in 1976 prolonged *Te* to the present 3–5 years, which further deteriorated the oxygen conditions in the basin water of the By Fjord.

Conclusion: The oxygen conditions in the By Fjord have likely degenerated due to dredging of the Sunninge Strait in 1958 and 1976. This led to reduced tidal energy supply to turbulence and diapycnal mixing in the basin water, which prolonged the residence time of the basin water from approximately 2-3 years before 1958 to 3–5 years after 1976. The large nutrient supply during the last century certainly increased the primary production and thereby the rate of oxygen depletion leading to large oxygen debts (large negative values of DO_{min}) at the end of stagnation periods.

6. Brief summary

We have presented a theoretical framework describing the mechanics of water exchange and oxygen supply and depletion in periodically stagnant basin water. Based on this, we present five different sea-based measures to improve the oxygen conditions and the corresponding habitat improvement in periodically stagnant deepwater. The measures should be applicable to many locations. Applications of the measures are demonstrated by hypothetical applications to the By Fjord, Sweden. Which measure, or combination of measures, that should be chosen in a specific case must be determined from an evaluation based on local conditions.

From our hypothetical applications to the By Fjord we found that Measure A, relocation of the outlet from the municipal sewage treatment plant Skansverket from the surface layer to the basin water, will not reduce the rate of oxygen depletion in the basin water. It will, however, increase the rate of density reduction $d\rho/dt$ and the frequency of water exchange and thereby reduce the residence time *Te*, but DO_{min} will still be negative (anoxic conditions). Measure B, supply of oxygen gas to the basin water, and Measure D, injection of well oxygenated surface water into the basin water by pumping, may keep the basin water of the By Fjord permanently oxygenated. To provide a good habitat in the basin water, DO_{min} should be 2 g m^{-3} or higher. At the present, the cost using Measure D is an order of magnitude less than the cost using Measure B, but this may change in future if the price of oxygen becomes much lower than today. Evaluation of Measure C, increased vertical mixing in the basin water, requires further analysis.

Interestingly, we conclude that the oxygen conditions in the basin water of the By Fjord before about 1930 most probably were considerably better than today. Thereafter, the oxygen conditions deteriorated. First, due to increasing supplies of nutrients from municipal sewage from a growing population and agriculture, which increased the primary production and the vertical flux of organic matter and the associated rate of oxygen depletion in the basin water. Later, dredging in 1958 and 1976 to meet increasing navigational demands by ship traffic to the harbour of Uddevalla and the shipyard Uddevallavarvet AB, increased the vertical cross-sectional area of the Sunninge Strait which led to much reduced speed of the tidal currents in the strait and therefore to reduced vertical mixing and reduced rate of density reduction in the basin water which led to prolonged residence time *Te*, from 2 to 3 years before 1958 to 3–5 years after 1976.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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