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Mitigation of oxygen decline in fjords by freshwater injection

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ABSTRACT

The exchange of water masses between deep fjords and the open ocean is commonly constrained by a topographical barrier called the sill. While fjord water above the sill depth communicates relatively freely with the open ocean, water below the sill depth is caught inside the fjord basin. This basin water may remain stagnant in deep fjords for many successive years. During these periods, the biological consumption of dissolved oxygen is larger than the supply of new oxygen, and the fjord basin might experience hypoxia and even anoxia. Such deoxygenation is natural but can be amplified by warming and human activities involving supplies of organic matter and other nutrients. Here, we use a general circulation model to explore how deoxygenation can be mitigated by injecting fresh water into the fjord basin. The freshwater injection causes density reduction of the basin water with subsequent water exchange and oxygenation. Our results suggest that the basin water of Masfjorden, a 480 m deep fjord with a basin volume of 4×10^9 m^3, can avoid deoxygenation with a continuous freshwater injection of 0.05 m^3 s^{-1}. We conclude that freshwater injection might be an efficient tool to mitigate the deoxygenation of fjord basins.

1. Introduction

Many coastal areas, including bays and fjords, have become increasingly depleted in dissolved oxygen (DO) over the last 50 years (Breitburg et al., 2018; Pitcher et al., 2021). Such DO declines have been caused by increased loadings of mineral nutrients and organic matter originating from, e.g., sewage, agriculture, and fish farming, but are also associated with warming resulting in decreased oxygen solubility and increased respiration (Breitburg et al., 2018). Fjords were carved out by glaciers and filled with seawater around 17 000 years ago (Syvitski et al., 1989) and are often blocked by a sill located at the mouth of the fjord. The sill is a topographical barrier that isolates the deepest part of the fjord, the basin water, from direct communication with outside waters (Figs. 1 and 2). The basin water is situated deeper than the sill depth and tends to become stagnant for many years (Aksnes et al., 2019; Darelius, 2020). The water masses of the brackish sea surface layer and the intermediate layer, which are situated above the sill depth, communicate with coastal and oceanic water rich in DO. The continuous exchange of waters above sill depth is facilitated by estuarine circulation, tides, and advection in the intermediate layer (Aksnes et al., 1989; Stigebrandt, 2012). The basin water is more saline and denser than the intermediate water above. Density stratification results in weak vertical mixing and low oxygen transport into the fjord basin. Renewals of the basin water and its DO content are episodic and happen when the intermediate water advected into the fjord is denser than the basin water. Such renewals can be partial or complete, depending on the duration and density of these high-density inflow events. While fjords with deep sills can experience frequent renewals of the basin water, the residence time of fjords with shallow sills may be several years (Aure and Stigebrandt, 1989). In periods with insufficient water renewal of the fjord basin, the biological consumption (respiration) might become larger than the supply of DO to the fjord basin and cause hypoxia and even anoxia in some locations. Deoxygenation also involves reduced light penetration and increased darkening of the fjord basin with consequences for the mesopelagic biodiversity (Aksnes et al., 2009; Solås et al, in preparation). Deoxygenation is natural in many fjords but might be amplified by human activities involving increased supplies of nutrients and organic matter. Global warming can also contribute to deoxygenation (Aksnes et al., 2019). Changes in the duration of the stagnant periods, for example, brought along by the decreasing density trend on the Norwegian shelf (Darelius, 2020), will directly influence the oxygenation of the fjord waters. Fjord deoxygenation has socio-economic implications

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because it reduces the holding capacity for fish farming (Aure and Stigebrandt, 1990; Stigebrandt et al., 2004), an important industry in Norway. On the other hand, fish farming itself might contribute to deoxygenation (Aksnes et al., 2019; Aure and Stigebrandt, 1990).

Fjord basins can be oxygenated by pumping buoyant sea surface water into the basin at depth, and pilot studies have been performed in the relatively small By Fjord in western Sweden (Forth et al., 2015; Stigebrandt and Liljebladh, 2010; Stigebrandt et al., 2015). Johannessen et al. (2010) describe how freshwater injection served as “artificial respiration” of the naturally anoxic basin of Nordåsvannet, a five km^2-sized fjord in Bergen, western Norway. In 1969, the anoxia extended from 12 m depth to the bottom (90 m). The same year, Bergen municipality started to release freshwater (i.e., sewage outlet at that time) at 40 m depth which led to permanent oxygenation of the water column above this depth. Pumping of buoyant sea surface water has been suggested to improve oxygen conditions for larger basins such as the Bornholm Sea and the Baltic Proper (Stigebrandt and Gustafsson, 2007; Stigebrandt and Kalén, 2013). Stigebrandt and Andersson (2022) summarize and categorize five sea-based measures to improve the oxygen conditions in stagnant basins. In the present study, we investigate how Masfjorden (Fig. 2), a fjord with a sea surface area of 28.5 km^2, a sill depth of 70 m, and a maximal depth of 494 m, can be oxygenated by supplying buoyant water down to a desired depth (categorized as measure D in Stigebrandt and Andersson, 2022). Two previous studies (Aksnes et al., 2019; Darelius, 2020) suggest that an observed multi-decadal decline of DO in the basin water of Masfjorden is caused by reduced renewal frequency of the basin water. The reduction likely relates to a negative trend in the annual maximum density of shelf water being the source water for the renewal of fjord basins (Darelius, 2020).

Here, we apply measure D in Stigebrandt and Andersson (2022). But rather than pumping water from the sea surface to depth, we assume a freshwater source that is situated sufficiently high above the sea level allowing freshwater to flow (through a pipe) to the desired depth (Fig. 1). In Masfjorden (Fig. 2), like in most other Norwegian fjords, this measure is facilitated by steep hillsides and abundant freshwater sources. In addition to small rivers, the freshwater supply to Masfjorden includes the outlet of a hydroelectrical powerplant at the head of the fjord. The freshwater supply sets up an estuarine circulation in the uppermost meters of the fjord but does not affect the circulation in the fjord basin (Aksnes et al., 1989).

We use a general circulation model to simulate the effect of freshwater injection through a pipe at depth on the DO content of the fjord basin. The expectation is that the freshwater injection will lead to density reduction of the basin water at a time scale that allows increased water renewal and a permanent increase in the DO content of the basin water.

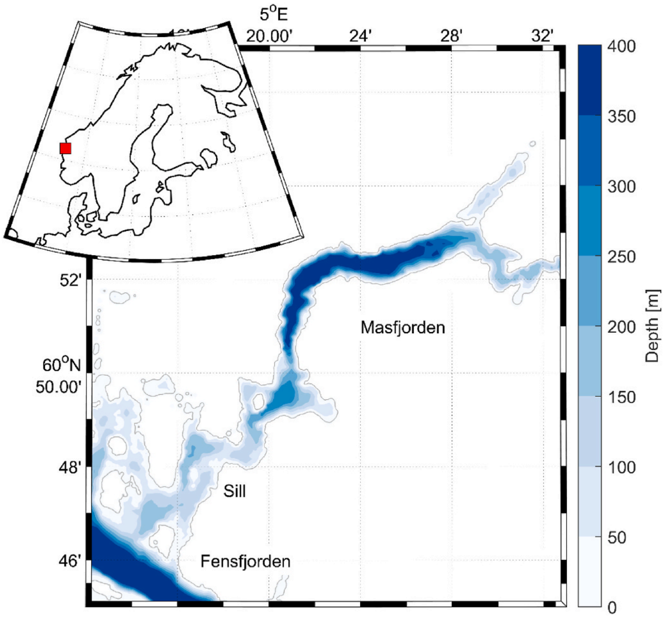

Fig. 2. Map showing the bathymetry of Masfjorden. The fjord has a maximum depth of 495 m and a sill depth of 70 m. A red square in the inset shows its location. The bathymetry data were collected from the online data source, http://www.norgedigitalt.no, established by the Norwegian Mapping Authority, the Hydrographic service. The original resolution is about 50 m on an irregular grid. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Methods

To investigate the effect of freshwater injection on the DO in the fjord basin, we run a numerical circulation model (section 2.1) with and

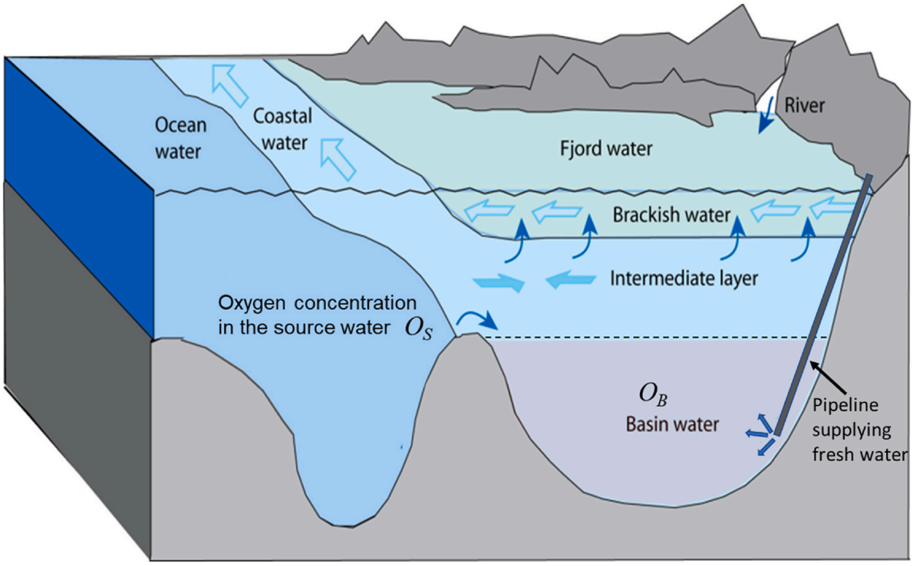

Fig. 1. Sketch of a fjord. Fjords have a three-layered structure with a thin layer of brackish water at the top, an intermediate layer between the brackish water and the sill depth, and the basin water below the sill depth (not drawn to scale). The oxygen content of the basin water (O_B) is periodically renewed with oxygen-rich water (O_S) advected into the fjord (see text). To the left, we have indicated a pipeline injecting freshwater into the basin water (Modified after Aksnes et al., 2019).

without constant freshwater injection at 480 m depth in Masfjorden. The model is run from January 1, 2012, to October 15, 2021. The vertical turbulent diffusivity and the respiration rate of the model have been adjusted to fit the observed decline in basin water density and DO during a period (2012–2016) without basin water renewals (section 2.2). We have used simple analytical models to estimate the freshwater injection rate to use in the simulation experiment (section 2.3) and the energy requirement associated with this injection (section 2.4). Bi-weekly observations of hydrography from Sognesjøen are used as boundary conditions for the simulations, and simulations are compared with observations from Masfjorden (section 2.5).

2.1. Numerical circulation model

We apply a hydrostatic version of the Bergen Ocean Model (Berntsen et al., 2016). Horizontally, the grid size is 600 m, and we use 100 terrain following σ-layers with a finer vertical resolution near the sea surface. We use a formula from Lynch et al. (1995) to enable adequate resolution of the brackish surface layer. The vertical grid resolution close to the surface is approximately 1 and 0.014 m in the deep basin and over the sill respectively. Horizontally, the grid is too coarse to represent detailed flow variations within the fjord. In the present study, however, we focus on the water exchange between Masfjorden and the open ocean. This exchange is primarily driven by density differences. We have ensured that the volume of the simulated Masfjorden agrees with the measured volume of Masfjorden and that the model sill depth corresponds to the real sill depth (70 m). The horizontal kinematic viscosity is set to 450 m^2 s^{-1} to reduce artificial mixing, and the horizontal diffusivity is set to zero. We apply the Mellor-Yamada 2 ½ level scheme (Mellor and Yamada, 1982) to compute vertical viscosity and diffusivity. When using this scheme, minimum values of viscosity and diffusivity can be specified, and these values are adjusted to obtain dilution of the Masfjorden basin water in agreement with the observations in a stagnant period (see section 2.2).

In the simulation with an injection of freshwater at 480 m depth, we aim to mimic the mixing and entrainment that will occur in nature with submerged outlets in a stratified fjord. A sketch of the circulation of a freshwater outlet is given by Stigebrandt and Andersson (2022, their fig. 5). Mixing and dilution in a submerged system is also described in Fischer et al. (1979). The dilution factor can be substantially increased if the freshwater is released through a set of diffusers so that the freshwater mixture will find a level of equal density at a depth well below the sill depth. In the model, the water is released with a flux of 0.05 m^3 s^{-1} in a grid cell of 600 × 600 × 8.64 m^3. With this low freshwater flux relative to the size of the grid cell, the dilution factor will be large, mimicking a situation with many small diffusers. If the mixed body of fluid in this grid cell becomes less dense than the water above, the vertical viscosity and diffusivity of the Mellor-Yamada 2 1/2 level scheme will grow to the order of 0.1–1 m^2 s^{-1} and rapidly mix the water at depth.

We have added a state variable to the model representing DO. The local DO concentration is affected by turbulent mixing, advection, and a constant biological sink term reflecting the respiration of heterotrophic organisms (Aksnes et al., 2019). The residence time of the water in the brackish and intermediate layer is relatively short, and the boundary conditions outside the fjord hence determine the oxygen concentration here (see section 2.5).

Biweekly observations at Sognesjøen hydrographical station (4° 50.4′E 61° 01.4′N, see section 2.5) have been interpolated linearly in time to give boundary conditions for the simulations. On inflow into the fjord (above the sill depth of 70 m), the water is assumed to be rich in oxygen, i.e., 6 mL L^{-1}. The model forcing includes tides and constant local freshwater runoff (155 m^3 s^{-1}) at the head of the fjord. Simulations are initialized with measurements of salinity, temperature, and DO obtained from the deepest location of Masfjorden in late 2011 (Fig. 3). The simulations are run from January 1, 2012, to November 1, 2021.

2.2. Calibration of turbulent diffusivity and respiration rate

The vertical turbulent diffusivity and a constant biological sink term for oxygen (representing respiration) were adjusted so that the simulated density and DO reflect the observations obtained in the period from early 2012 to late 2016 at 350 m depth in Masfjorden (Fig. 4). In

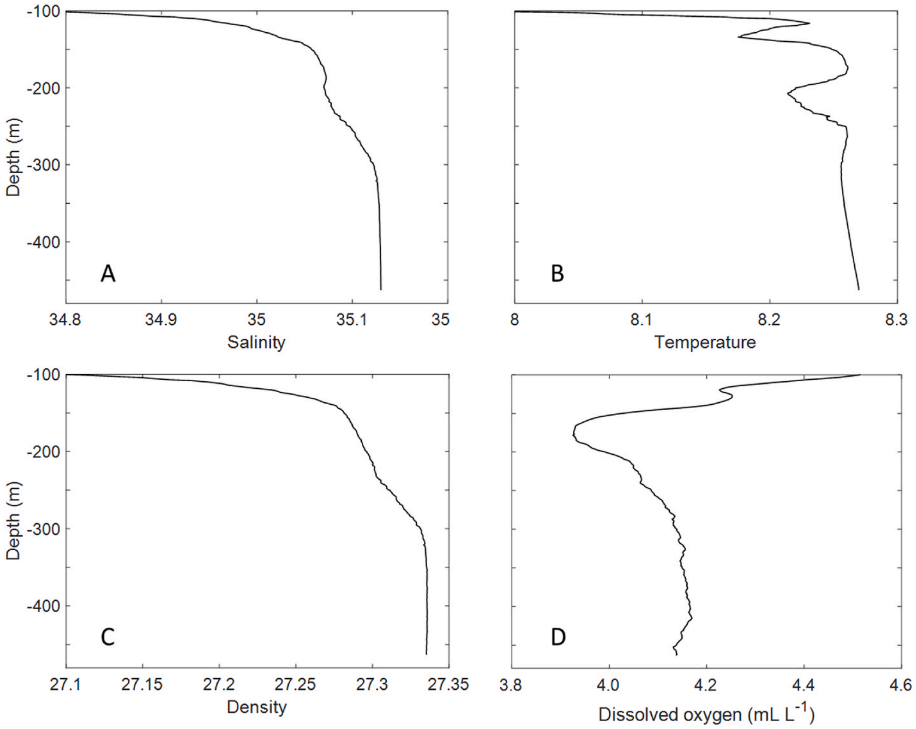

Fig. 3. Observations of salinity (A), temperature (B), density (C), and dissolved oxygen (D) in the basin water of Masfjorden on October 13, 2011. These observations are used to initialize the simulation model.

this period, the observed water density and DO decline monotonically, i.e., presumably without intrusions of high-density water into the fjord basin. The observed decline rates are approximately 0.01 kg m^{-3} yr^{-1} (Figs. 4a) and 0.5 mL L^{-1} yr^{-1} (Fig. 4b), respectively, for density and DO. During previous stagnation periods, Darelius (2020) observed a reduction in the basin density of 0.015 kg m^{-3} yr^{-1}.

2.3. Analytical expression for approximating the freshwater injection rate

At the freshwater outlet in the fjord basin, we assume a jet regime that is followed by a buoyant plume regime where freshwater mixes with the ambient basin water. When the buoyant plume reaches neutral buoyancy, it spreads horizontally in the basin, as discussed in Stigebrandt and Liljebladh (2010, their fig. 6). We use a simplified analytical expression to approximate the freshwater injection rate (Q_F) to use in the numerical simulations.

Let V be the volume of the fjord basin (i.e., the volume below the sill depth), ρ_A the density of the water above the sill depth, and $\rho_A + \Delta\rho$ the average density of the basin water before the freshwater injection. The objective is to inject freshwater with a density ρ_0 into the basin so that the density of the basin water after a period, T, approaches ρ_A. Then, the basin water will be susceptible to a deepwater renewal and the associated oxygenation. In terms of mass, this objective corresponds to the situation where the total mass of the basin is reduced from $(\rho_A + \Delta\rho)V$ to $\rho_A V$, i.e., the total mass is reduced with the amount $\Delta\rho V$. We assume that, within the period T, the injected freshwater is conserved within the basin. The total amount of freshwater, V_F, that is required to reduce the mass of the basin with an amount corresponding to $\Delta\rho V$ must obey

$$\Delta\rho V = (\rho_A - \rho_0)V_F \tag{1}$$

Since $V_F = Q_F T$, insertion and rearrangement provide

$$Q_F T = \frac{\Delta\rho}{(\rho_A - \rho_0)} V \tag{2}$$

When applying equation (2), V and ρ_0 are known, and $\Delta\rho$ and ρ_A can be estimated from measurements. We can hence solve for the product of Q_F and T. The time scale of natural water renewals of fjord basins depends on the fluctuations of the density field outside the sill, as discussed, for instance, in Darelius (2020) and Stigebrandt and Andersson (2022). The simple Eq. (2) may still be applied to estimate Q_F for a given T. With numbers relevant for Masfjorden ($V = 4 \times 10^9$ m^3, $\Delta\rho = 0.01$ kg m^{-3}) and a desired $T = 1$ year, the required freshwater flux is, according to Eq. 2, 0.05 m^3 s^{-1}, the flux used in the numerical experiment.

In the By fjord experiment (Stigebrandt et al., 2015; Stigebrandt and Andersson, 2022), the flux of sea surface water pumped into the fjord basin was 2 m^3 s^{-1}. From Eq. (2), we estimate the corresponding time scale of water renewal to be approximately 100 days. This appears to agree with fig. 3 in Stigebrandt et al. (2015), as substantial changes in density and dissolved oxygen are seen for this timescale.

2.4. Energy required for the freshwater injection

Energy is required to inject freshwater at a particular depth. One way to meet this energy requirement, at least where steep mountains and hills characterize the surroundings, is to use a freshwater source located at a certain height above sea level. Here, we calculate this height. An alternative use of the freshwater is to produce electricity, and we use the potential energy to indicate a running cost of the oxygenation measure.

The bottom pressure of the fjord, assuming a sea surface at level 0, is

$$P_1 = P_{atm} + g\int_{-H_M}^{0} \rho(z)dz \ . \tag{3}$$

The pressure at the pipe outlet is

$$P_0 = P_{atm} + g\rho_0 H_{intake} + g\int_{-H_M}^{0} \rho_0 dz \ . \tag{4}$$

For the freshwater to flow through the pipe, we must have $P_0 > P_1$. This gives the following inequality

$$H_{intake} > \int_{-H_M}^{0} \frac{\rho(z) - \rho_0}{\rho_0} dz \ . \tag{5}$$

Setting $H_M = 480$ m and using the observed density profile from Masfjorden, we find that H_{intake} must be larger than 13 m. This value only balances the pressure at depth, so H_{intake} must be increased to overcome friction. The power potential for hydroelectrical energy production can be expressed:

$$PP = g\, H_{intake}\rho_0 Q \ . \tag{6}$$

Setting $H_{intake} = 20$ m and $Q = 0.05$ m^3, we get a power potential (PP) of 10 kW, which is 4–5 orders of magnitude lower than the installed capacity of the Matre hydroelectrical power station in Masfjorden. This estimate is an upper bound for the "lost" hydroelectrical power production associated with the water injected at 480 m depth in the fjord basin.

2.5. Observations

Conductivity-Temperature-Depth (CTD) profiles from the deepest part of Masfjorden (5° 24.7′E 60° 52.3′N) are available on a quasi-annual basis from 1975 and onwards. Here we use profiles from 2011 to initialize the model (Fig. 3) and observations from 2012 to 2021 to compare with the simulated scenario without freshwater injection (Figs. 4 and 5). The CTD package includes an oxygen sensor that is factory calibrated, but the measurements obtained before 2019 were not compared to Winkler-titration. An oceanographic mooring was deployed from February 2021 to February 2022 at the sill of Masfjorden (70 m, 5° 17.88′E, 60° 48.23′N), covering a major renewal event in April 2021, described below. Unfortunately, the current meter mal-functioned and did not register any data, but we present density records from an RBR CTD deployed at 65 m depth.

The Institute of Marine Research in Bergen has measured salinity and temperature at Sognesjøen hydrograpical station (4° 50.4′E 61° 01.4′N, https://catalogue.odis.org/view/53), approximately 30 km northwest of Masfjorden, about every second week since 1935. We use temperature and salinity observations to characterize the environment outside Masfjorden. These observations are taken every second week and interpolated in time to give boundary conditions for the simulations (see section 2.1).

3. Results

3.1. Simulation without freshwater injection

The model is initialized with observations from 2011 (Fig. 3) and run from Jan. 1, 2012, to Oct. 15, 2021. After 2016, the DO observations indicate partial inflow events that halted the steady decline in oxygen prior to 2016 (Fig. 5C), and in 2021, there was a major inflow of dense (Fig. 5A) and oxygen-rich water that brought the oxygen values in the deep basin back to the 2012 level (Fig. 5C).

The moorings located at the sill in 2021 confirm the renewal event suggested by the CTD profiles (Fig. 6). In April, there are two periods where the density at the sill (the blue line in Fig. 6) exceeds the density of the deepest basin water (black broken line in Fig. 6). Observed densities at Sognesjøen (red stars in Fig. 6) also exceed the basin water density. However, the model simulation (Fig. 4B and D) does not capture this renewal, and the simulated density and oxygen continue to decline (Fig. 5B and D).

The model system is driven by boundary conditions based on linear

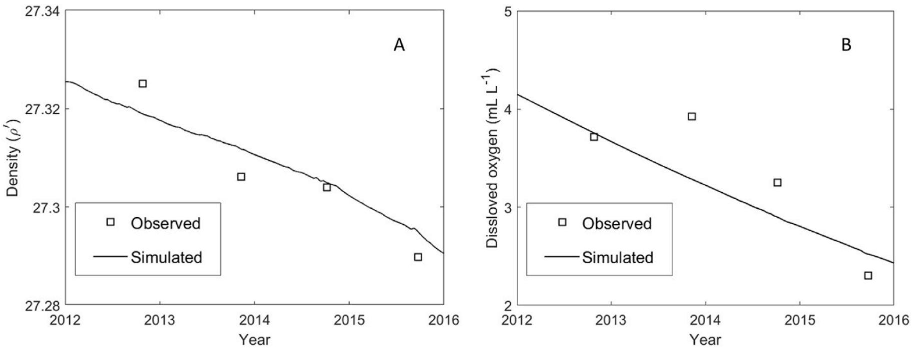

Fig. 4. Observed and simulated reduction in density (A) and DO (B) at 350 m depth in Masfjorden for the period used to calibrate the model's turbulent diffusivity and respiration rate.

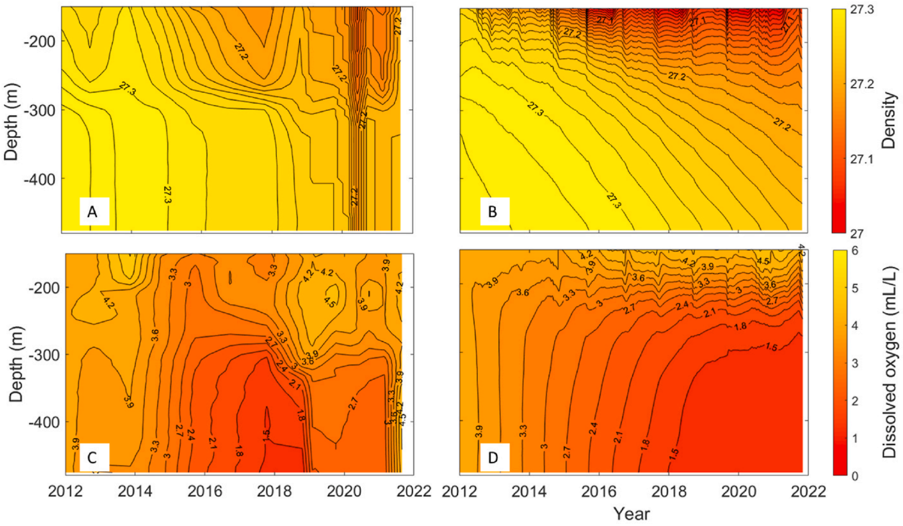

Fig. 5. Values of observed (A) and simulated (B) perturbation density, ρ' in kg m^{-3} (ρ' = ρ – 1000 kg m^{-3}) and observed (C) and simulated (D) DO in mL L^{-1} in Masfjorden.

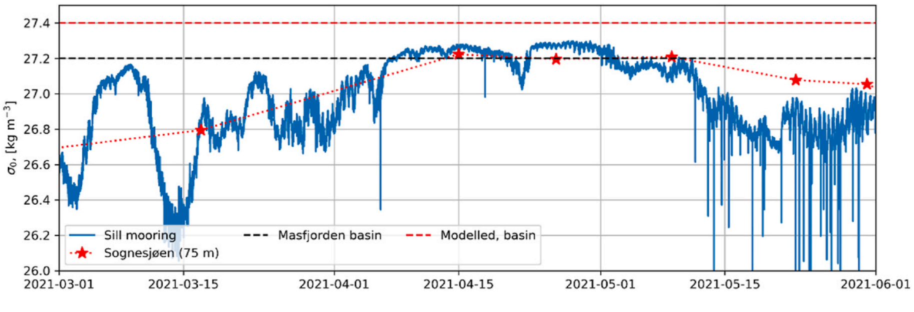

Fig. 6. Record of density ($\sigma_0 = \rho - 1000$ kg m^{-3}) at 65 m depth at the sill of Masfjorden, from March–May 2021 (blue line). The red stars indicate the density observed at Sognesjøen, 75 m depth; the dotted red line indicates the linear interpolation used as the boundary condition for the model simulations, and the dashed red line is the modelled bottom density in April 2021. The dashed black line is the observed bottom density of Masfjorden in February 2021. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interpolation between discrete observations at Sognesjøen (red, dotted line in Fig. 6). The density observed at Sognesjøen may deviate from the corresponding values at the Masfjorden sill. In particular, the density at Sognesjøen in April 2021 is lower than that observed at the Masfjorden sill (Fig. 6). In combination with a coarse numerical resolution of mixing processes, such discrepancies between the assumed and the true boundary condition will, over time, create a drift in the modelled water density of the basin (Fig. 5A and B). In April 2021, the simulated density at the bottom of Masfjorden is 27.24 kg m^{-3}. Because this value is higher than the observed boundary values at Sognesjøen (red stars in Fig. 6), water renewal is blocked in this period. Thus, the model system appears to overestimate the resistance to basin water renewals. Given the objective of the present study, we do not consider this critical, as it will lead to a conservative estimate of the efficiency of freshwater injection as a measure to increase the oxygenation of the basin water.

3.2. *Simulation with freshwater injection to the basin water*

The numerical experiment involving freshwater injection of 0.05 m^3 s^{-1} at 480 m depth causes a much more rapid density decrease (Fig. 7A) than for the observed and the simulated natural situation (Fig. 5A and B). The freshwater injection facilitates a more frequent inflow of oxygen-rich water into the fjord basin. After 2018, the DO concentration was above 4 mL L^{-1} in the fjord basin. A larger freshwater injection resulted

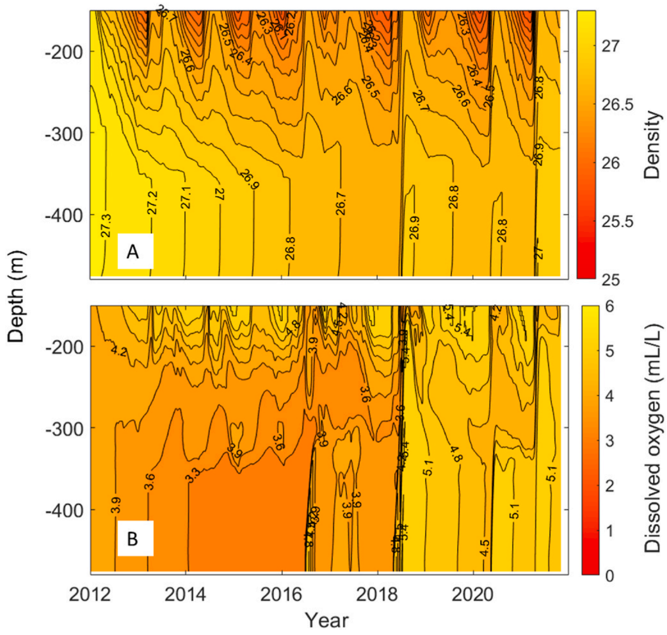

Fig. 7. Values of perturbation density ρ' in kg m^{-3} (A) and the DO concentration (B) in Masfjorden for the experiment with 0.05 m^3 s^{-1} freshwater released at 480 m depth in Masfjorden.

in a reduced timescale of dilution, e.g., ten times increase in the flux (to 0.5 m^3 s^{-1}) led to rapid oxygenation the first year (not shown).

4. Discussion

Our results suggest that fjords suffering from deoxygenation can be permanently oxygenated by injecting relatively small amounts of freshwater into the fjord basin. Similar approaches involving the pumping of sea surface water into anoxic and hypoxic water of the Baltic Sea have been suggested by Stigebrandt and Kalén (2013) and proved effective in a physical experiment in the By fjord at the Swedish west coast (Forth et al., 2015; Stigebrandt et al., 2015). In that experiment, sea surface water was pumped at a rate of around 2 m^3 s^{-1} into the anoxic fjord basin The renewal frequency increased by a factor of 10, resulting in long-term oxygenation. For Masfjorden, having a fjord basin (4×10^9 m^3) that is 1000 times larger than the By fjord, our results suggest that an injection rate of $\sim$0.05 m^3 s^{-1} is sufficient to keep a renewal frequency that ensures high DO of the fjord basin. Given the much larger basin of Masfjorden than of the By fjord, such a low injection rate might appear surprising. This is primarily due to i) the relatively small density difference between the upper (70 m) and the lower (495 m) boundaries of the fjord basin and ii) that we assume injection of freshwater rather than (saline) sea surface water. For locations other than Masfjorden, the required injection rate and associated energy expenditure can be approximated from topographical characteristics and the density gradient of the fjord basin according to Eqs. (1)–(6).

Our results show that the numerical model can reproduce the observed DO decline in the fjord basin during stagnant periods. To realistically simulate the natural inflow events, however, we conclude that boundary specifications, i.e., the biweekly observations at Sognesjøen are insufficient. We believe that future monitoring and studies of water exchanges and DO-dynamics of Norwegian fjords would benefit from continuous monitoring at the permanent hydrographic stations established in the 1930's by Jens Eggvin, a pioneer in operational oceanography (Sætre, 2007). Alternatively, boundary specifications can be obtained by the output from models such as the NORKYST-800 (https://ocean.met.no/models, Asplin et al. (2020)) covering the Norwegian coastline. We considered this in the preparation of the present study and found that the NORKYST-800 output provided general trends in temperature and salinity that agreed with the observations at Sognesjøen. The model output, however, could not account for the major basin water renewal in 2011 that facilitated the observed stagnation period the successive years in the Masfjorden basin (Fig. 5A and C).

Deoxygenation of coastal areas, including fjords, is a growing concern (Pitcher et al., 2021), and our results suggest that freshwater injection might be an affordable mitigation measure for fjord basins. The main concern related to the deoxygenation of these basins is reduced habitat for invertebrates and fish and increased habitat for certain opportunistic species being tolerant for low DO. Fjords with very shallow sills (shallower than 10 m) and basins (less than 100 m), often called polls, might be periodically or permanently anoxic in the water column and the bottom sediments. Anoxic water effectively eliminates the permanent residency of organisms requiring DO for respiration. However, anoxic water is unlikely in fjords like Masfjorden with a relatively deep sill. According to Aksnes et al. (2019), the average DO content of the Masfjorden basin fluctuated between 2 and 5 mL L^{-1} from 1976 to 2016. Superimposed on these fluctuations, they reported an overall decline in DO over the 41-year-long period. This multi-decadal decline was attributed mainly to reduced renewal frequency due to the concurrent warming of the oceanic source water, particularly after 1990 (Aksnes et al., 2019; Darelius, 2020). In recent years, fish farming waste might also have contributed to deoxygenation. Consequences on the biota of DO fluctuations not involving anoxia are challenging to assess and obviously less severe than for anoxia. However, a study of the deep soft-bottom macrofauna of four fjords in western Norway found significantly altered structure in the soft-bottom communities following the DO decline in the basin waters (Johansen et al., 2018). These changes were mainly due to the increased abundance of opportunistic polychaete species.

Above the bottom, it is primarily the mesopelagic zone that is subject to deoxygenation in deep fjord basins. Deoxygenation and associated water column darkening appear to reduce the habitat and growth of zooplanktivorous mesopelagic fishes (Sørnes and Aksnes, 2006), the dominant fish species in deep Norwegian fjords (Bagøien et al., 2001; Giske et al., 1990). Oxygenation of fjord basins will likely increase the productivity and diversity of the local fish community, but this remains to be verified. The statement could be tested in an experiment comparing the biota before and after oxygenation, similar to the experiment in the anoxic By fjord (Forth et al., 2015; Stigebrandt et al., 2015). Such a project must run over several years and will likely generate valuable knowledge on the effects of fjord deoxygenation and oxygenation on fjord ecosystems.

In addition to the environmental effects of deoxygenation and oxygenation, there are also socio-economic consequences. Sheltered Norwegian coastal water, which includes more than 1000 fjords, hosts a large fish farming industry where the economic value by far exceeds the value of the wild catch fisheries in the Barents Sea, Norwegian Sea, and the North Sea combined. However, a critical constraint on fish farming is the environmental holding capacity (Ervik et al., 1997; Hansen et al., 2001; Stigebrandt et al., 2004) which underlies regulations on where to locate fish farms. In fjords like Masfjorden, the ventilation rate and associated DO content of the basin water is crucial determinants for the holding capacity (Aure and Stigebrandt, 1989, 1990). Multi-decadal variations in the ventilation rate (Darelius, 2020) cause variations in the holding capacity with consequences for the farming industry (Johnsen and Loeng, in prep.). For example, in 2017, following several years without basin water renewals, the DO in Masfjorden declined below 1.5 mL L^{-1} below 450 m. This led to a recalculation of the holding capacity and withdrawal of the permit to produce fish in two salmon farms and reduced production in two other farms (Statsforvalteren, 2017). Freshwater injection into the fjord basin stabilizes the ventilation rate, thereby removing variations in the holding capacity and large fluctuations in DO. There are, however, arguments against such environmental engineering, e.g., that fjord basins being naturally anoxic or hypoxic should be protected rather than manipulated. Also, counteracting the environmental effects of fish farming and other human disturbances by another disturbance might imply a risk of increasing the total human impact. In addition to balancing advantages and disadvantages with oxygenation measures, considerations also involve values and perspectives related to human use of nature outside the scope of the present study.

Declarations of interest

None

CRediT authorship contribution statement

Dag L. Aksnes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Elin Darelius:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization. **Jarle Berntsen:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization.

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.

Data availability

Data will be made available on request.

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