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Hydrodynamic implications in and around a caged fin-fish farm and its implications on the dispersal of farm debris

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ABSTRACT

One of the key factors in determining the accumulation of sediment and soluble nutrients within a lease is water movement. Water masses entering and leaving the farm determine the finfish ecosystem interaction. Understanding the hydrodynamic interaction with the farm is therefore key to understanding the potential ecological effects of individual farms. In addition, finfish farms are now being proposed in exposed offshore environments and have caused concern regarding their potential down stream impacts on currents and wave climate. Seven current meters, oxygen probes and CTD were deployed to examine the hydrodynamic interactions inside and outside a 270 m long Salmon farm in Newfoundland, Canada. Current meter results indicate that the fin-fish farm cages have a clear shadowing effect on the currents. Currents up stream were found to be considerably faster than those recorded downstream during the sampling period. Current speeds inside the farm were also found to be considerably slower than those found outside of the farm especially during high flow events. In-situ observations of currents were found to be similar to those predicted by previous CFD and hydrodynamic modelling studies. Modeling was also undertaken to calculate the energy lost as currents enter and leave a series of fish cages. In comparison to the observed flow the model compares relatively well. Flow recorded downstream of the farm was observed to be in the range predicted by the model as was the flow recorded inside and outside the cages. Current speed downstream of the farm is clearly affected by farm orientation which has important implications for the dispersal of farm debris. Average oxygen saturation within the cages over the 5 day sampling period was 80.2 % ± SD 5.7 %, compared to nearly 100 %, 20 m and 50 m from the farm site. Orientation of the farm may play some part in determining the location and amount of oxygen depletion within the farm. The farm also acts to push water from deeper in the water column up into the cages which has implications for farms situated in heavily stratified environments.

1. Introduction

Finfish aquaculture in near shore coastal areas has been growing world-wide in recent years, however global industry growth is slowing (FAO, 2020) from 10 % to less than 5% per year. Atlantic Salmon (*Salmo salar*) culture produced 2.4 million tonnes in 2018 accounting for 4.5 % of global finfish production, with an increasing demand (Asche et al., 2018). While there is increasing demand for salmonid products there is a current limitation in salmon industry growth due to the availability of consented water space / biomass in near shore areas. This increased demand for salmon products has led to increased farming intensity and the push for expansion into off-coast and offshore environments (Holmer, 2010; Kapetsky et al., 2013; Asche et al., 2018). With expanded production there is increasing interest and concern regarding the resulting potential environmental impact on coastal marine environments (Ottinger et al., 2016; Gentry et al., 2017; Davies et al., 2019)

Canada accounts for approximately 6% of salmonid culture globally and exceeds 1.5 billion dollars (Ca) in farm gate and supply sector value (Statistics Canada, 2018). This represents 25 % of the total value of harvested aquatic resources in Canada. Over 90 % of salmon and steelhead trout (137,000 tonnes) is grown using a floating cage system (gravity cages) located in sheltered near-shore environments. The Canadian finfish industry is predominately based in British Columbia, New Brunswick, Nova Scotia, and along Newfoundland's southern coastline.

Finfish farming in Canada has been the focus of several studies examining the effect of farm debris (faeces and uneaten food) on the sur-

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rounding seabed sediment, benthic community structure, benthic organic enrichment, and nutrient changes (*e.g.* Hargrave et al., 1993, 1997; Pohle et al., 1994, 2001; Wildish et al., 1999; Day et al., 2015; Cranford et al., 2017 & Verhoeven et al., 2018). Internationally, studies have also had similar emphasis (*e.g.* Hall et al., 1990; Mazzola et al., 1999; Holmer, 1999; Holmer and Kristensen, 1994, 1996; Holmer et al., 2001; Sara et al., 2004; Cook et al., 2006; Magill et al., 2006; Keeley et al., 2013 & 2018). Initially, numerical models predicting the distribution and effect of fish farm discharges (*e.g.* Gowen et al., 1989) were developed predicting carbon and waste deposition (sediment accumulation) rates from finfish farms. These simple models relied on current meter records and the waste production of the site but did not include the physical and biological parameters needed to predict the final fate of organic material. Other studies (*e.g.* Ross et al., 1993a & 1993b; Gowen et al., 1994; Silvert and Sowles, 1996; Nath et al., 2000; Cromey et al., 2002a; Keeley et al., 2013) have since improved the initial numerical models by adding biological and physical parameters and/or attempting to manage fish farm impacts.

Anders et al. (2004) modeled the holding capacity of sites for fish farming expressed in terms of maximum fish production per month. The holding capacity is estimated with regard to limiting adverse effects on the benthic fauna beneath the cages and water quality inside and outside the cages. Cromey et al., 2002a, 2002b) using DEPOMOD and newDEPOMOD (SEPA, 2017) combined a series of particle tracking, re-suspension, benthic and grid generation modules to calculate the distribution and effect of farm discharges. While the "particle tracking" module does have turbulence, settling velocity, and linear current components it does not resolve the detailed current field in and around the farm cages.

Resolving current fields in and around cages is not only important for resolving particulate waste dispersion to the seabed but is also important for adequately modeling the release of nutrients into the water column and the consumption of dissolved oxygen. It is also important for understanding the impacts downstream as farming gets moved into open ocean and exposed sites fronting dynamic shoreline systems. Potential impacts to shorelines are of concern of other coastal resource users such as surfers (reduced wave height) and local governments (coastal erosion and farm rubbish).

In regard to wave height, several studies have investigated the wave dampening effects of floating structures (Dong et al., 2008), as well as floating cages (Zhao et al., 2007; Lee et al. 2008; Zhao et al., 2019), cage arrays (Bi et al., 2015, 2017), and the combined effects of net panelling and biofouling (Bi et al., 2020a). The overall effect of floating cages on wave height is to dampen waves with the effects dependent on factors such as degree of biofouling, wave period, number of cages, incident angles *etc.*

The current literature has described the use of numerical techniques and/or miniature physical models dedicated to modelling the forces and geometry changes of finfish net structures exposed to waves and currents (Fredriksson et al., 1999a & Fredriksson et al., 1999b, 2000; Lader et al., 2001; Lader and Enerhaug, 2005; Bi and Xu, 2018; Bui et al., 2020). Those studies focused on cage design, performance and reliability of the structure, and not necessarily ecological or farm-specific hydrodynamic interactions.

Many of the cage design studies do indicate that locally (within the space of a cage set) current speeds can be reduced by more than 80 % of their initial velocity inside the cages, and that this reduction is a function of net solidity/porosity and cage arrangement (Noymer et al., 1998; Madin et al., 2010; Plew, 2011;Gansel et al., 2012a, 2012b, 2012C; Klebert et al., 2013; Bi et al., 2015; Bi and Xu, 2018; Bi et al., 2020b). In addition to net solidity/porosity and cage arrangement, the angle of the nets relative to the flow of water can significantly increase drag around cages. Laboratory experiments and numerical simulations conducted on net panels and cage sets (Hosseini et al., 2011; Kumazawa et al., 2012; Bi et al., 2013; Zhou et al., 2015; Tang et al., 2017; Bi and Xu, 2018) have shown that drag increases around net panels with increasing attack angle, with velocity reductions of greater than 15 % reported in Bi et al. (2013).

Flow reductions due to varying attack angles are also compounded by the presence of multiple cages in close proximity (*i.e.* within a set of cages on a lease; Bi et al., 2017; Bi and Xu, 2018). There are some *in situ* studies which have focused on small cage arrangements with few of the studies examining full commercial farm sized hydrodynamic interactions (Johansson et al., 2007; Gansel et al., 2014; Winthereig-Rasmussen et al., 2016; Solstorm et al., 2018; Klebert and Su, 2020). Several of these authors have suggested that further *in situ* hydrodynamic observations are required to further our understanding of numerical modelling requirements.

There is now a critical need to investigate the hydrodynamic influence of full-scale operational farms with *in situ* observations. Such case studies will aid to serve as verification tools for modelling exercises used to predict growing conditions of the fish on the farm, the fate of farm discharges, and the downstream and inter-cage hydrodynamic effects of the farm.

The present study presents observations of hydrodynamic effects of finfish farms, including modification to currents, stratification, and dissolved oxygen as water masses flow in and subsequently out of a salmon farm in southern Newfoundland, Canada. It also describes these observations using numerical terms. These observations have significant implications for modelling farm waste dispersal and prediction of potential benthic and water column impacts from finfish farms. Additionally, this study will aid in understanding the likely downstream impacts of future large scale off coast and open ocean farms.

2. Methods

2.1. Study area

One of the largest potential areas for aquaculture development in Newfoundland is Fortune Bay (Fig. 1). Fortune Bay, a basin intermediate in scale between typical fjords and ocean basins, is 137 km long and 40 km wide with a mean depth of 120 m and a maximum of 526 m (Hay and De Young, 1989). The bay has three sills ranging in depth from 100 to 125 m. There are two independent sources of deep water in Fortune Bay, the relatively warm and saline Modified Slope Water (MSW, 4 °C and a salinity of 34.5 ppt) derived from the continental shelf region (McLellan, 1957) and the colder Labrador Current (LC, -0.5 to –1.0 °C and salinity of 33.5 ppt). The general trend is MSW to enter the western side of the bay while the LC enters from the south resulting in a layered system (markedly different salinity and temperatures), (De Young and Hay, 1987). Within the bay, deep water exchange occurs bi-annually, under the influence of winter and spring winds and the LC (Richard and Haedrich, 1991). There are also reports of currents >3 knots occurring in parts of the bay once or twice per year, usually in the fall, which may involve a rigorous exchange of water (pers.com Jonathan Moir). Freshwater input from the Salmon and Bay Du Nord Rivers provides much of the estimated 50 m^3/s of freshwater input to the western side of the bay.

The farm site chosen for this study was located 300 m west of the Cinq Islands Formation 6 km south of the settlement of Pools Cove (Fig. 1). The water depth at the farm site ranged from 28–40 m and the farm was comprised of nine circular cages each with a diameter of 38.5 m. Cage nets are comprised of 50 mm mesh with a mesh thickness of 3 mm, with a depth of 20 m, on a bearing of approximately 30 °N (Fig. 2). Cages were stabilized using flotation in the form of 50 cm thick piping and were anchored to the seabed using 1-ton concrete blocks. At the time of the study, the farm had an annual biomass of ap-

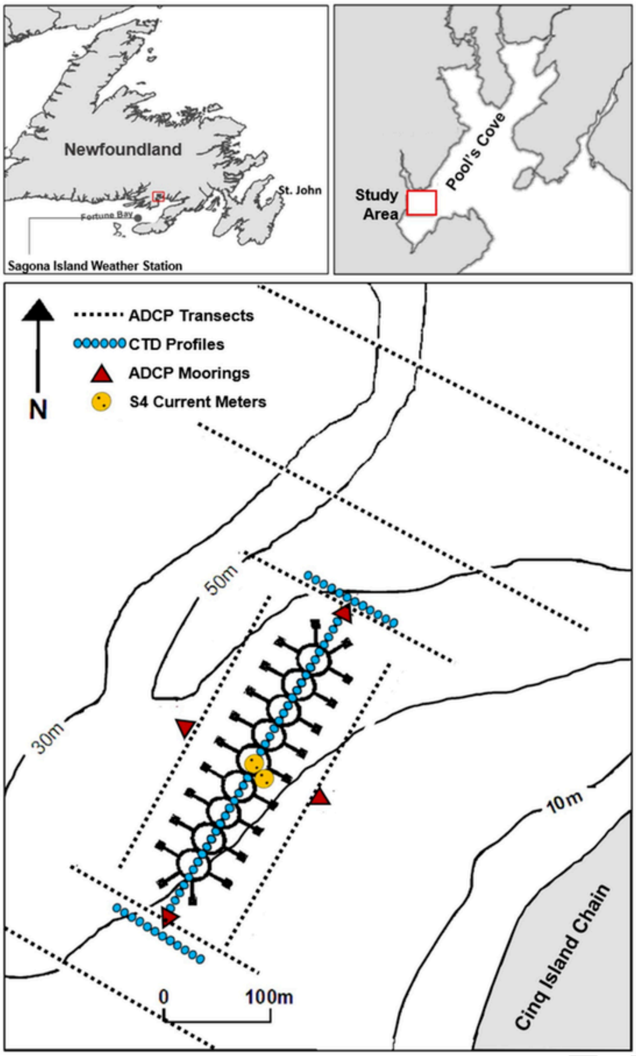

Fig. 1. Location of study site, in Pool's Cove, Newfoundland, Canada with equipment deployment location and bathymetry.

proximately 3000 tons with an approximate stocking density of 15 kg m^{-3}.

2.2. Currents

Four RDI 600khz (workhorse sentinel) Acoustic Doppler Current Profilers (ADCP) were moored on the seabed 50 m from the farm cages at the southern, northern, eastern and western ends of the farm from September 29th to October 5th 2004 (Fig. 1). The ADCP were programmed to record current speed and direction in 3 dimensions at 20 s intervals with an average recorded every 20 min. Currents were sampled every meter to the sea-surface. Boat mounted ADCP measurements were made using an RDI 600khz (Workhorse Sentinel) run from a 12v boat battery and bolted onto the side of the boat on the 2nd, 3rd and 4th of October 2004. Transects were made across the southern and northern ends of the farms 50, 100, and approximately 500 m from the edge of the cages to establish flow conditions around the farm. Additional transects were also made along both sides of the farm approximately 50 m from the edge of the cages (Fig. 1).

Three S4 current meters (Inter Ocean Systems) were deployed to compare currents inside, outside, and beneath a farm cage on September 29th, 2004. The first current meter was suspended inside the middle cage (cage 5) of the farm by attaching a rope across the cage and tying the current meter to the middle of this line on a 10 m cable (Fig. 2a). The second current meter was suspended from an anchor line at 10 m-water depth approximately 2 m from the cage edge. The final current meter was bottom moored on the seabed beneath the cage (cage 5) at a depth of 35 m.

Current measurements were also taken using two Marsh-McBirney Electro Magnetic Flo-mate current meters (Model 2000 portable flow-meter). Current measurements were made inside, outside and between each of the nine farm cages several times per day from the 30th of September to the 5th of October 2004 (Fig. 2b). Current measurements were taken at 1, 5, and 7 m water depths with the sensor left for a period of 30 s at each depth to stabilize, after which a reading was recorded.

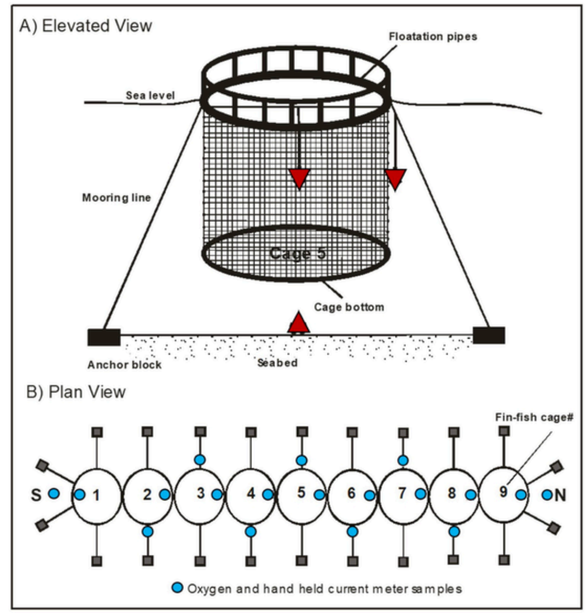

Fig. 2. A) Elevated View of the 5th cage showing cage mooring along with the location of S4 current meters (Red Triangles) deployed inside and outside the cage. B) Plan View of the entire farm showing cage mooring and location of handheld oxygen and current meter measurements (Blue Circles).

2.3. Oxygen measurements

Dissolved oxygen (expressed as percent saturation) and temperature measurements were recorded using an YSI 55 oxygen probe. Measurements were made inside and outside each of the nine farm cages, three times per day at 3 -h intervals from the 30th of September to the 5th of October 2004 (Fig. 2b). The oxygen probe was lowered to a depth of 5 m and left to equilibrate for two minutes before being recorded. Within each sampling period three repetitive measurements were recorded with additional measurements taken outside the northern and southern most cages at 1, 20, and 50 m distance twice per day.

2.4. CTD

Temperature, conductivity, dissolved oxygen (expressed as percent saturation), and fluorescence profiles (Fig. 2b) were taken at the farm site on the 2nd and 4th of October 2004 using a XR-420-CDT (Richard Brancker Research Ltd). Additional dissolved oxygen (expressed as percent saturation), salinity, and temperature measurements were taken using a YSI 3800 multi-parameter Sonde.

3. Results and discussion

3.1. Oxygen

Dissolved oxygen concentrations were observed to be lower inside the nine farm cages sampled compared to observations 20 m and 50 m outside the farm site. Average oxygen saturation within the cages over the 5 day sampling period was 80.2 %± SD 5.7 %, compared to nearly 100 %, 20 m and 50 m from the farm site. Oxygen saturation within cages was found to decrease during the study period with average values decreasing from 87.4 %± SD 5.1 % on September 30th to 72 %± SD 4.7 % on October 4th. Oxygen depletion was also observed to be the greatest in the centre of the farm (Fig. 3a–c). We assumed the reduction in oxygen saturation within cages is due to depletion by the fish and the observed decrease over time is linked to a 30 % increase in daily feed fed to the fish over the study period. A similar sample series from the same farm, in June 2004 (data from Hartstein et al., 2004), also showed lower oxygen levels inside the farm (Fig. 3d). In this case the southern end (predominantly upstream) of the farm had percent oxygen saturation >85 % (Fig. 4). In contrast the northern end of the farm (predominantly downstream) had lower measurements ranging from 64.8 %± SD 2.5–78%± SD 2.1. Measurements taken outside the farm, in June 2004, at 20 and 50 m indicated oxygen saturation of close to 100 %.

As inferred from physical models (*e.g.* Gansel et al., 2012b) and CFD (*e.g.* Bi et al., 2017; Bui et al., 2020; Rickard, 2020), the orientation of this cage arrangement plays some part in determining flow under and around the cages and thus the amount of oxygen depletion within the farm. A previous study, Hartstein et al. (2004) found that farms oriented parallel to the current will likely maximize DO depletion at the downstream end. Oxygen depleted water is recycled through each of the nine cages and the current velocity (which controls the supply of new oxygen) decreases due to energy loss through the farm. In this present study, currents ran near perpendicular to the farm (see below) and oxygen saturation was found to be lower at all cages in comparison to outside the farm but with no obvious bias to one end. The centre of the farm did show greater reduction in oxygen saturation than the outer most cages.

Observations from Hartstein et al. (2004) and this study indicate DO saturations below 75 % within cages at this farm. Several studies examining the effects of oxygen depletion on adult salmon have indicated that when DO concentrations are kept below 75 % saturation, the fish demonstrated lack of appetite, reduced growth and feed utilization (Forsberg and Bergheim, 1996; Crompton et al., 2003). In Newfoundland, it is common to farm with a set of cages oriented into a single row or two rows, often one cage width apart. Similar cage arrangements can be observed in around Canada, Norway, and in Australia and in some cases doubles rows of cages (*i.e.* 2 × 8) are moored together with no gaps between at all (*i.e.* in parts of New Zealand and Australia). Based on our observations we would expect greater reductions in oxygen due to the latter cage configuration. We suspect the latter cage arrangements to have poorer feed performance (lower oxygen means less efficient feed use) due to the lower levels of oxygen that we observed in the cages during this study. Changes in stocking density would also play an important part in oxygen concentrations in various cage arrangements.

CTD sampling corroborated the results from the YSI sondes with relatively high levels of oxygen (%sat) outside the farm compared to samples collected inside the farm where dissolved oxygen decreased as low as 65 % saturation (Fig. 4). Again, DO saturation values were found on average to be lower inside the cages towards the end of the study period.

3.2. CTD

Two transects of temperature, salinity, and oxygen, extending through the farm, shows some change in water column structure (Fig. 4). On the 2nd of October temperature decreased with depth across the entire transect from approximately 9.4 °C at the surface to 4.3 °C at 30 m water depth. Salinity increased with depth from 31.6ppt at the surface to 32.8ppt at 30 m depth. CTD data collected on the 4th of October indicates that within the cages there is a decrease in temperature

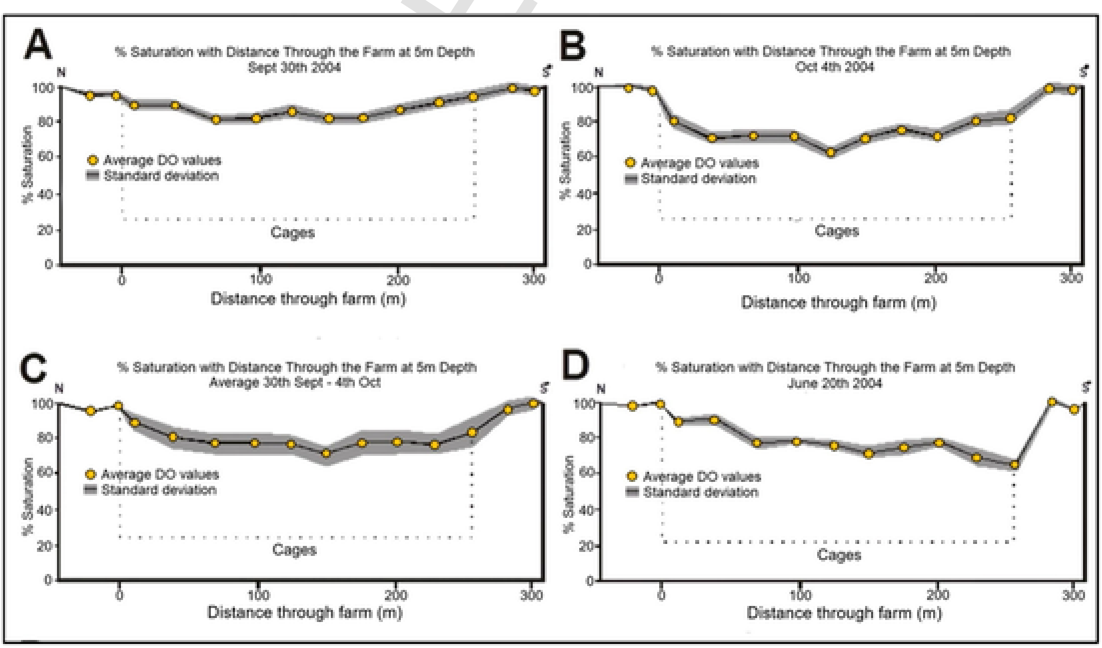

Fig. 3. Percent oxygen saturation with distance through the farm A) September 30th B) October 4th C) average profile from 30 September to the 4th of October D) profile from June. During the June data collection period the current direction was parallel to the farm with an average speed of approximately 4 cm/s at the upstream end compared to approximately 2.5 cm downstream two meters below the sea surface (Hartstein et al, 2004). In contrast the current direction during this September study was running perpendicular to the farm (see additional sections for current data). Plots were compiled from oxygen data collected from both the CTD and the YSI 55 oxygen probe.

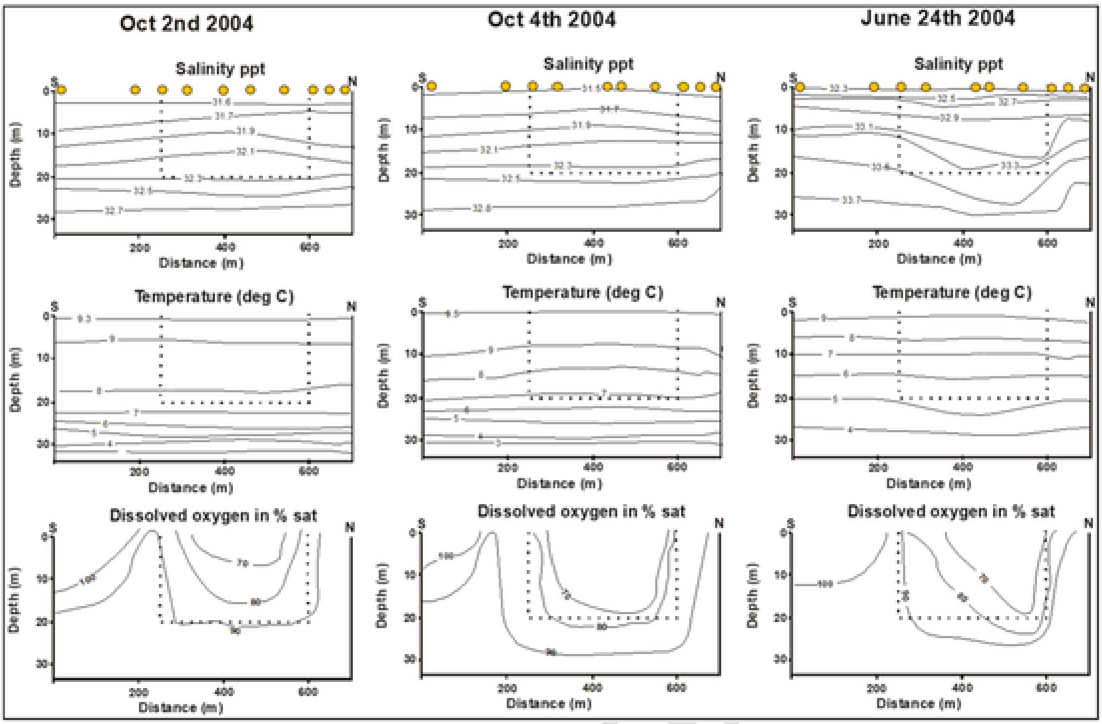

Fig. 4. Results of CTD casts showing salinity, temperature and dissolved oxygen in % saturation with depth and distance through farm. Transects start 200 m south of the farm and finish approximately 100 m north of the last cage. Dotted lines indicated farms cages.

compared to similar depths outside the cage (Fig. 4). Reasons for this temperature decrease are described in a later section. Salinity with depth was similar to that recorded on the 2nd of October.

3.3. Current meter data

We have three different types of current meter data to discuss. We made measurements at fixed depths using a handheld current meter, averaging for thirty seconds at each depth. On average the flow inside the cages was 22 %, 24 % and 28 % less than those measurements made directly outside the cage at 1 m, 5 m, and 7 m depth. Additional measurements made between the cages show that the flow there was 37 % higher than measurements made inside the cages and 10–15% higher than the flow observed outside the cages. Such flow speeds would indicate that water is being forced through the gaps (usually 1–2 m) between cages. Similar observations have been observed in CFD and physical modeling studies (Bi and Xu, 2018; Bui et al., 2020; Klebert and Su, 2020).

The data from the boat mounted ADCP was noisy due to the presence of cages, the nets themselves, and the many anchor lines surrounding the cages. We suspect that there was always one lobe of the four-beam ADCP signal that was being interfered with by the cages or cage structures. We did obtain some successful transects farther away from the cages on the 2nd, 3rd, and 5th of October. These transects indicated a near surface speed of approximately 4 cm/s on the 2nd and 3rd of October from the northeast and an average speed of more than 10 cm/s on the 5th of October with a decrease in speed observed with depth.

We also deployed S4 current meters at 10 m depth inside and outside (eastern side of cage Fig. 1) the 5th cage. The time series for these current meter data run from 29 September to 5 October (see Fig. 5). On average the currents are relatively weak, both inside and outside the cages, with speeds of less than 5 cm/s and little difference inside and outside the cages. Indeed there are times when the currents inside the cage (indicated by the red dots) are stronger than those outside.

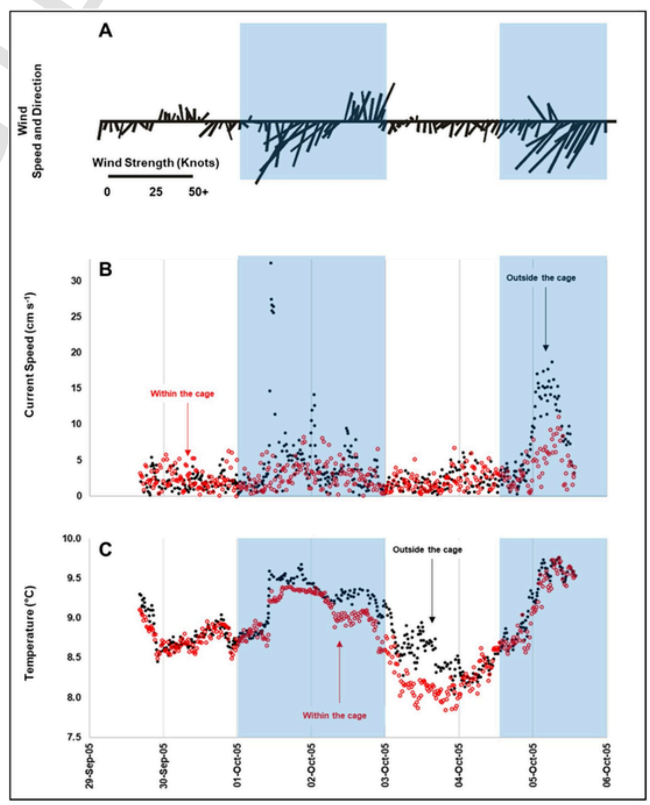

Fig. 5. Wind (A), current speed (B), and temperature (C) records from inside and outside the 5th cage (see Fig. 2 for current meter location). Wind records were taken from Sagona Island Weather Station (station ID 8,403,255) approximately 39 km SW from the site (see Fig. 1). Strong current periods highlighted in blue.

The difference plot (Fig. 6) shows this result most clearly. We noted that the nets had been recently cleaned and there was little or no biofouling.

There are three periods with strong currents, each associated with strong wind events, on 1st and 2nd of October, for just a few hours when the peak currents are 30 cm/s from 220–240° and 14 cm/s from 45° and on the 5th of October when there is an extended period when the currents reach 20 cm/s from 240°. During the first two periods the currents inside the cage barely change from background levels in spite of the large currents just outside the cages. The peak differences (Fig. 6) are only slightly smaller than the peak speeds (Fig. 5). During the third event, which lasts for many hours, the currents inside the cage do rise to about half the level of those observed outside the cage. The peak speeds observed outside the cage are almost 20 cm/s while those observed inside the cage are just over 10 cm/s. These observations corroborate in-cage flow reductions observed in physical models (Gansel et al., 2012a, 2012b, 2012c), CFD (Bi et al., 2017), and dye tracking studies (Gansel et al., 2014).

The data from the bottom mounted ADCP were free from the side-lobe interference that we observed from the boat mounted system. We were careful to deploy the ADCPs far enough from the farm to avoid acoustic interference with the underwater netting (see Figs. 1 and 7).

We present the mean currents at 10 m depth and the mean profiles for the last day, 5th October, when there was a strong current event (see Fig. 7). The mean flow is quite clearly from the Northeast to the Southwest with strong currents observed outside the cage at locations 1, 2 and 3. Much weaker currents were observed outside of the cage on its northwest side (downstream of the farm) at location 4 and inside the farm. The profile data also clearly show this with strong currents observed in the upper 10–15 m at locations 1 and 2 (upstream of the farm), with peak speeds of 12–15 and 10–13 cm/s respectively. At location 3, the southeast corner, the peak speeds are similar, 10–12 cm/s but the layer of strong flow is somewhat thinner. At location 4, on the northwest side of the farm, the peak speed is only 8 cm/s and there is very little flow below a rather thin surface layer. Quite clearly, the cages have had shadowing effect on the currents that extends at 100′s of meters from the farm.

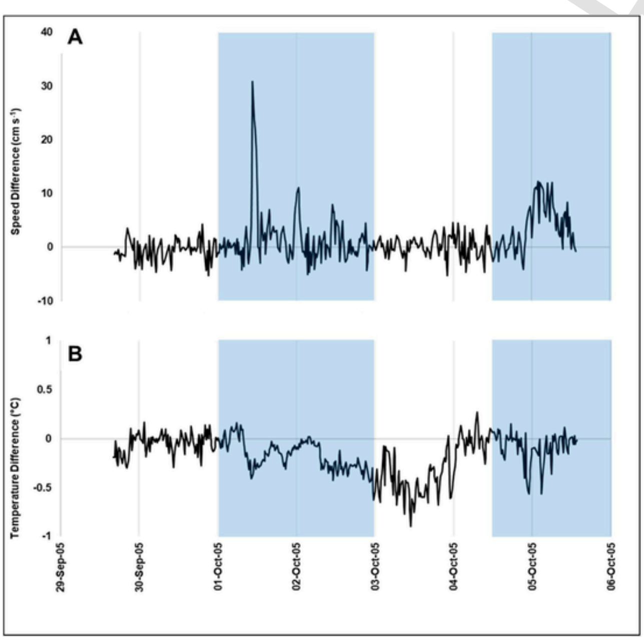

Fig. 6. Current speed (A), and temperature (B) difference plots from outside to inside the 5th cage. Positive direction indicates speed or temperature is greater outside the cage compared to inside the cage. Strong current periods highlighted in blue.

The S4 current meters also provided measurements of temperature, at 10 m depth inside and outside the 5th cage. For almost half the period the temperature differences inside and outside the cages are very small, less than a few tenths of a degree. For three days in the middle of the record, the temperature difference comes close to 1° C. During this period, the water outside the cage is consistently warmer than water inside the cage (Figs. 5 and 6). The presence of cooler water inside the cages most likely indicates the presence of cooler deeper water since there is fairly strong thermal stratification present during this period. A temperature difference at this depth, 10 m, corresponds to bringing cooler water from a depth of 13–16 m. It may also be that this temperature difference corresponds to changes in water temperature outside the cages, because of advection, that has not yet flushed into the cages. Whatever the cause, there are clearly substantial temperature differences from inside to outside of the cages.

This temperature difference could affect the heath of the fish in a number of ways depending on the season. During summer where sea surface temperatures are high, cooling of the surface waters may act to mitigate the adverse effects of summertime peaks in temperature. For instance, during the summer of 2003 one farm in southern Newfoundland lost over 150,000 fish due to the stress caused by extreme sea surface temperatures (pers.com D. Canines 2005). In contrast during colder periods a decrease in temperature may act to reduce food consumption and ultimately slow fish growth. These observations have implications for fish welfare in highly stratified water bodies with potentially sharp gradients of dissolved oxygen (*e.g.* Macquarie Harbour, Tasmania). Cage induced hydrodynamic forcings can immerse fish in deeper, poorly-oxygenated water (Hartstein et al., 2019; Maxey et al., 2020) for prolonged periods, resulting in lowered FCR and potential mass mortalities.

Finally, in regard to the current, oxygen, and temperature data an important point to note is that a fin-fish farm as an entity influences the flow features and for that reason one should not just consider the influence of one cage in isolation. A farm consists of numerous cages placed next to each other along a line. The impact of a farm (line of cages) on the hydrodynamics depends on the flow direction relative to the farm orientation. In this case the flow is perpendicular to the farm and the farm is 'relatively wide and short'. The flow separates in front of the farm and a lee zone is found behind the farm. As a result the velocity is the lowest in the center of the farm and should increase towards either end. The flushing time scale for a cage is the longest in the center of the farm and for that reason the lowest oxygen levels are found in the cages close to the center. In the case when the flow is parallel with the farm it is 'relatively narrow and long'. A boundary layer grows along the farm in the flow direction. And as a result in this case the velocity is the highest in the upstream cage and the lowest in the downstream cage *i.e.* the flushing time scale for a cage increases in the flow direction and for that reason the lowest oxygen concentrations are expected in the downstream cages (Hartstein et al., 2004). The advection of water from the upstream cages to the downstream cages may, in this case, further aggravate the poor conditions in the downstream cages. A number of studies (Winthereig-Rasmussen et al., 2016; Bi and Xu, 2018; Solstorm et al., 2018) have observed a wake similar to our observations and observe downstream impacts resulting in lower current flows and eddying several hundred meters from the nearest cage.

3.4. Flow Reduction Model

The current meter data show that the salmon cages have a significant effect on the circulation. We did not fully map the changes in the water flow around the cages but we do see a reduction of current speeds both inside the cages, between 20–80%, and a similar reduction in the current speeds on the downstream side of the cages. However,

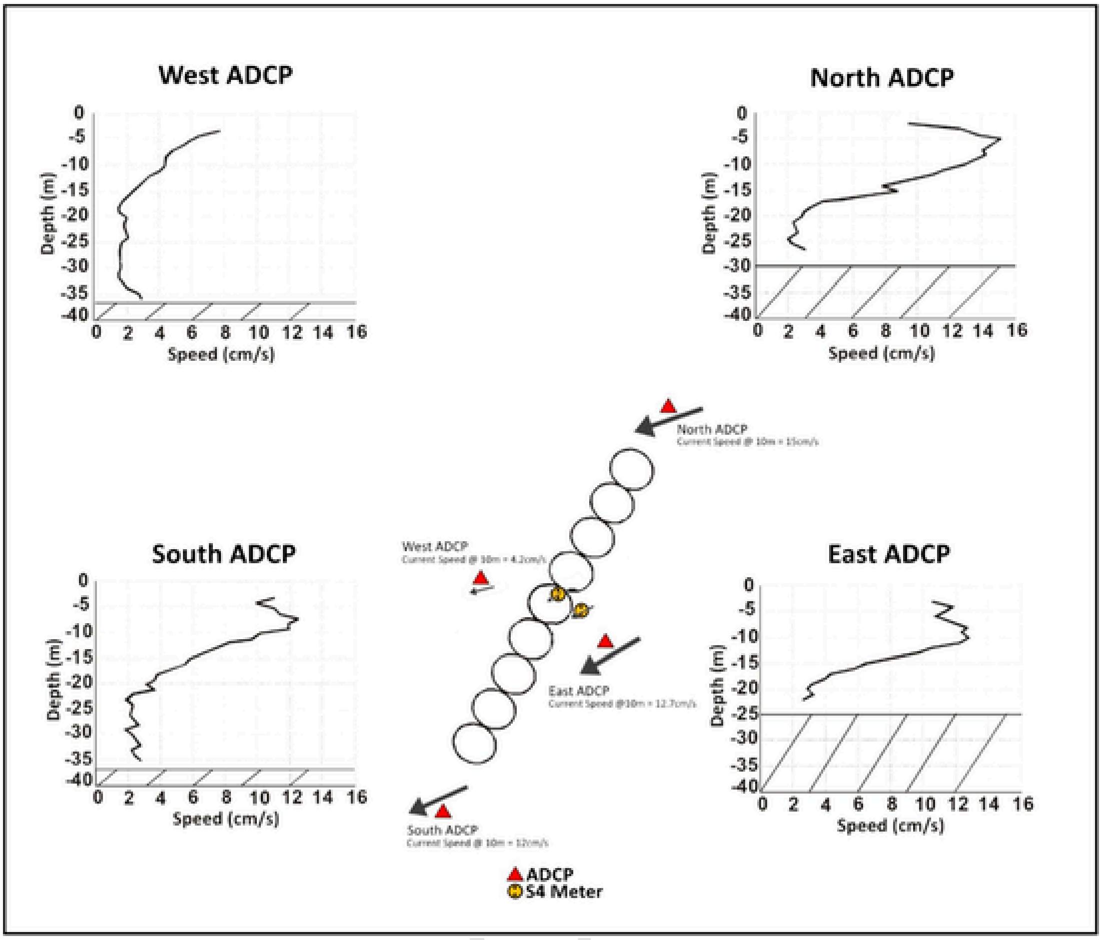

Fig. 7. Schematic indicating current speed and direction on the 5th of October 2004. Solid arrows indicate current speed and direction recorded at 10 m water depth by the ADCP current meters situated around the farm and two S4′s situated inside and outside the middle cage. The four graphs indicate the average current speed with depth at each ADCP for the 5th of October.

the cages are not solid objects, they are made of fish net, in this case with a mesh size of 50 mm which is subjected to biofouling subsequently increasing the surface area of the mesh resulting in potential drag and a further reduction in current. Several studies have examined the impacts of biofouling on drag and subsequent current flow reduction (Madin et al., 2009; Gansel et al., 2014, Lader2001; Bi and Xu, 2018; Xu and Qin 2020). All studies observed that biofouling increased drag which resulted in a reduction in current flow, an increase in hydrodynamic load, and in the case of Gansel et al. (2014) and Xu and Qin (2020) a reduction in oxygen and water quality within fish cages. Our own observations of finfish cages have also shown that the industry is well aware of the adverse impacts biofouling has current flow, fish health and water quality given the amount of effort placed into cleaning cages of biofouling organisms. While we did not specifically include biofouling impacts, the use of higher solidity per cage (Fig. 8) accounts for potential impacts of biofouling.

In addition, there were roughly 60,000 salmon in each cage, each salmon in this instance weighing about 5.0 kg. In this section, we present an analysis to determine the expected effect of the cages and then compare our analysis with observations. Such an approach should allow others to carry out similar analyses on other cage structures with different features and scales. We see this work as a validation step for existing numerical models (Lader et al., 2003; Lader and Enerhaug, 2005; Gansel et al., 2008) accounting for both the blocking characteristics of the cages and their porous structure as well.

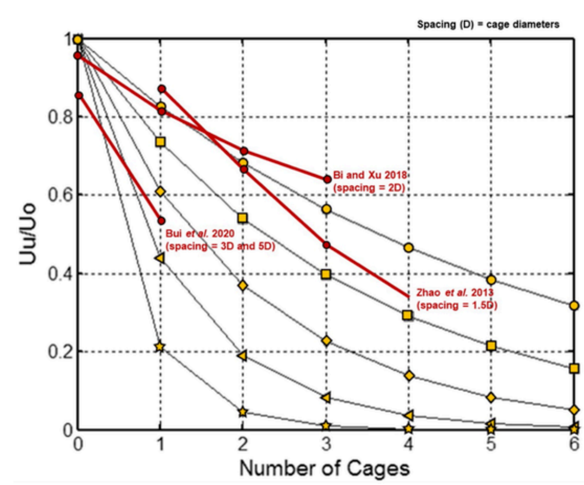

Fig. 8. The ratio of the downstream U_d to the upstream U_u velocity for the solidities ranging from 0.15 (circles), 0.20 (squares), 0.25 (diamonds), 0.30 (triangles) to 0.35 (pentagrams). We have added several other studies to this figure which include Zhao et al. (2013); Bi and Xu (2018); Bui et al. (2020): Note the model presented assumed no spacing between cages such as found at the site, in Australia and New Zealand. Other studies have presented cage spacings ranging from 1-5 diameters.

The nets are somewhat porous but do have some solid structure and so can, and do, influence the flow of water. The drag force is given by (*after* Hartstein et al., 2004; Gansel et al., 2008):

$$F = \frac{\rho}{2} C_d A_{net} U^2 \tag{1}$$

Where C_d is the drag coefficient of the net, A_{net} is the projected, cross-sectional area of the net and the velocity is U. Previous work (Lader et al., 2003; Lader and Enerhaug, 2005) has led to the estimation of the drag coefficient as a function of the solidity of the net S where the solidity is the ratio of the net thickness to the total mesh area, that is

$$S = 2t/M \tag{2}$$

Where: t is the mesh diameter and M is the mesh size.

On the basis of Bernoulli's equation (Kundu and Cohen, 2002) we can derive a simple model for the flow through the cages. We will apply one energy equation following a streamline going through the cages and one going parallel to the cages outside the boundary layer, and only consider the energy loss caused by the cages. The energy equation along the streamline going through the cages is given by:

$$\rho g h_u + \rho \frac{U_u^2}{2} = \rho g h_{di} + \rho \frac{U_{di}^2}{2} + \rho g H_l \tag{3}$$

Where H_l is the energy loss associated with the presence of the nets.

Water flowing around the sides of the nets will not lose energy (outside the boundary layer), and the energy equation reads

$$\rho g h_u + \rho \frac{U_u^2}{2} = \rho g h_{do} + \rho \frac{U_{do}^2}{2} \tag{4}$$

For geometrical reasons we assume that perpendicular to the streamlines the sea level is constant, *i.e.* that at a given distance $h_{di} = h_{do} = h_d$.

We can calculate the energy loss directly by (1) since it is the force exerted by the nets that causes the loss. Combing (3), (4) and (1) and applying that U_u and U_{do} are approximately equal we derive at:

$$\rho \frac{U_d^2}{2} = \rho \frac{U_u^2}{2} - \frac{\rho}{2} C_d U_u^2 \tag{5}$$

or the ratio of the downstream to upstream velocity (this is for the effect of the front of the cage)

$$\frac{U_d}{U_u} = (1 - C_d)^{1/2} \tag{6}$$

We can also calculate the expected drag of the fish by adding up the drag of the individual fish. Not all the fish will contribute equally to the drag so it is likely that the assumption that they do lead to an overestimate of the drag. The swimming of the fish will also play some role, in the most extreme situation leading to solid body rotation of the water in the fish cage (*e.g.* torus flow as described in Bjordal et al. (1993), Gansel et al. 2014), however we have no way to account for this effect through this analysis.

If we furthermore add the drag from the front and back of the cage, and the drag associated with the fish the equation can be generalized for the number of cages

$$\frac{U_n}{U_u} = (1 - C_d)^n \left(1 - \frac{N C_{fish} A_{fish}}{A_{net}}\right)^{n/2} \tag{7}$$

Where there are N fish in the cage and we assume that each has a cross-sectional area A_{fish} and drag coefficient C_{fish}.

We can now use these results to estimate the way in which the velocity should decrease as the result of the presence of the cages. As one might expect the downstream velocity should decline as the number of cages increases (Fig. 8).

If we take the geometry of the present nets with a depth of 20 m and a diameter of 38 m. There are 60,000 fish with an average weight of 5.0 kg. Each fish has an approximate diameter of 0.15 m and so the cross-sectional area is roughly 0.02 m^2. We take the drag coefficient for each individual fish to be $C_{fish} = 0.005$ (Unpublished data Fisheries and Marine Institute of Memorial University of Newfoundland). We can then calculate the ration of the downstream to the upstream velocity U_d/U_u using the equation above (and depicted in Fig. 8).

Using this simplistic flow reduction model for a single cage, the velocity is reduced by somewhere between 20 % to just under 80 % as the solidity ranges from 0.15 to 0.35. Thus, if the cages are arranged into a single row, as they are in Pools Cove, then cross-line flow will be reduced by a factor of between 20–80 %. For flow in the along-line sense, where the number of cages is six or more, then the reduction factor is somewhere between 30 % and over 95 %.

There are several implications for farm debris (fish food and faeces) dispersal given by the large change in flow predicted by the model and our own field observations of flow change. Firstly, flow reductions on the lee side of the farm will likely lead to greater deposition and build-up of biodeposits on that downstream side, subsequently worsening the impact on benthic communities and prolonging seabed recovery / fallowing periods. The side of the farm most heavily impacted by the deposition of organic matter is thus a product of farm scale hydrodynamics. At the Fortune Bay farm, the key hydrodynamic drivers are the predominant westerly flows which suggest the possible accumulation of farm-derived solid waste, and subsequently greater benthic community impact, on the east side of the farm.

Regarding mitigating or promoting the spread of the farm bio-depositional impact there seems to be two obvious farm management practices available. The first practice is to maximize the spread of farm-derived wastes by aligning elongated cage-sets perpendicular to the dominant flow direction, as the Fortune Bay farm was aligned during the observational period of this study. If current speeds were sufficiently high, farm-derived deposits may be spread over a wide area, reducing the total organic matter load for any given area within the depositional footprint, reducing the worst benthic community impacts, and potential aiding shorter recovery times between fallowing periods. The second farm management practice is to contain farm-derived wastes near the boundaries of the farm by aligning the cage sets parallel to the current, by taking advantage of cage-induced flow reductions to minimize bio-deposit spread. For instance, if fish food were being dosed with pharmaceutical products which may not have any adverse effects on the fish or consumers of the fish, but may effect sensitive nearby aquatic habitats. Such a farm alignment would also be useful if the farm was found to be nearby sensitive seabed habitats.

Our observations have significance in terms of their downstream impact as it is clear in the lee of the farm there is a clear reduction in current flow. Currently there are a number of offshore and off-coast farms proposed in a number of countries including Australia, Canada and New Zealand. The size of these proposed farms is in the order of 1 km with often large cages more than 50 m in diameter. Based on our observations we would expect to see some measurable impact on the nearby coastlines to both wave climate and current energy which will in turn may potentially impact sediment transport along the coast.

4. Conclusions

Our observations indicate that dissolved oxygen concentrations can be reduced in farm cages by up to 20–30 % compared to areas upstream of the farm. Farm orientation seems to have an effect in determining the distribution of dissolved oxygen within the farm, which may lead to differentiated growing conditions between cages on a given lease.

Temperature and salinity conditions in and around cages indicate that the farm structure itself acts to divert water from deeper in the water column up into the cages. This has implications for farms situated in heavily stratified environments, where water quality may be significantly different between layers, and is one of the most interesting observations of this study. To the best of our knowledge this has not been reported to date.

Flow measured within individual cages was found to be 22–28 % lower than flow outside of those cages. Flow reduction was observed to occur even during stronger current flow events (related to strong winds). Fin-fish farm cages can have a clear shadowing effect on currents. Currents up stream were found to be considerably faster than those recorded downstream during the sampling period. *In situ* current speeds were found to be similar to those predicted by previous CFD and hydrodynamic modelling studies.

Modeling was also undertaken to calculate the energy lost as currents enter and leave a series of fish cages on this farm type (connected gravity type circular cages in a single row). In comparison to the observed flow our model compares relatively well for flows downstream, inside, and outside the cages.

These observations are some of the first of their kind in regard to commercial farm scale using connected polar circles in single rows and have implications for the siting of future farms in regard to the dispersal of farm faeces, oxygen, soluble inorganic nitrogen, in cage and down-stream hydrodynamics.

Author statement

As the corresponding author I can attest that each of the contributors presented below play a significant part in this study. Each have given me permission to include them as authors in this research paper and agree to their position within the author order.

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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