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Investigating Dissolved Oxygen Drawdown in Macquarie Harbour

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Executive summary

There have been a number of recent reports on, and reviews of, oxygen in Macquarie Harbour (e.g. MHDOWG 2014, ADS 2015, Knight et al. 2015). These identified some potentially large and unquantified processes that are likely to be important in the oxygen balance in Macquarie Harbour. Here we review some observations of dissolved oxygen in Macquarie Harbour and report on the first measurements of biological oxygen demand (BOD) from the water column. Although spatially variable BOD was ~ 2 times benthic respiration.

A comparison between long term net drawdown and measured gross rates of oxygen consumption highlights the role of surface exchange in maintaining oxygen levels above the halocline while extended periods without mixing lead to significant periods of low dissolved oxygen in the mid-water column. Elevated levels of labile organic carbon with fatty acid profiles characteristic of farm derived material were detected at a depth of 3m close to the cages and coincident with increased rates of oxygen consumption when compared to the far field site. Based on this study it is recommended that sufficient measurements of BOD be conducted to determine the spatial variability of oxygen drawdown and farm derived organic material throughout the Harbour. In addition a simple model should be developed to better understand processes important to oxygen cycling; particularly mixing which resupplies most of the oxygen. This combination would provide a superior capability to manage oxygen in Macquarie Harbour for the benefit of its many users, the environment and its ecology.

1 Introduction

Macquarie Harbour is a roughly rectangular harbour (30 km by ~ 8 km and up to ~ 50 m deep) located on the west coast of Tasmania. It is connected to the ocean through a relatively narrow and shallow entrance channel. It has two major west coast rivers (King River and Gordon River) discharging to it. Macquarie Harbour fits into the 'fjord' category of water bodies that have well studied hydrodynamics. These include stratification associated with the inflow of low density fresh water on top of more dense salty water (Figure 1).

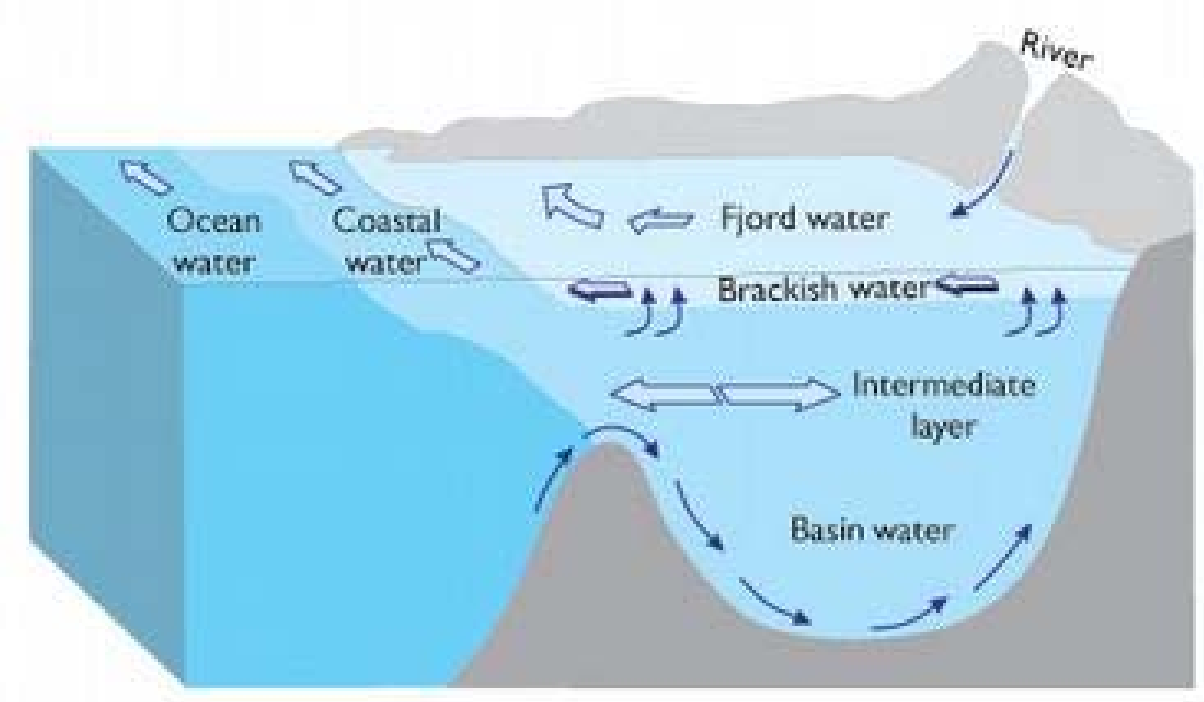


Figure 1 Classic circulation pattern for a fjord and applicable to Macquarie Harbour. Note intrusion of dense (cold, salty) oceanic waters at the bottom and outflow of fresher (less dense) water at the surface.

There are similar water bodies around the world and many along the Australian coast. A large portion of these also have low dissolved oxygen (DO) in their bottom waters. Like Macquarie Harbour the typical bottom water resupply is by a combination of low atmospheric pressure and high tide pushing oceanic water inwards. Low atmospheric pressure is increasingly important in regions with small tidal amplitudes. The process of bottom water resupply can be increased when the amount of freshwater entering the Harbour from rivers is low and/or the wind is from the oceanic end of the harbour (northwest in this case). The oceanic water entering the Harbour is cold and salty (dense) so it mostly sinks to the bottom (Figure 1). As the atmospheric low pressure system moves away and the oceanic tide falls the fresher surface water runs out of the Harbour even harder than normal.

The physics of this system are amenable to a hydrodynamic model. There is an uncalibrated model of the Harbour running (Figure 2) with a range of output products at http://www.marine.csiro.au/~and371/macq/ and as a longitudinal section (Figure 3) at http://www.cmar.csiro.au/cem/macq/anim_macq_sect.gif.

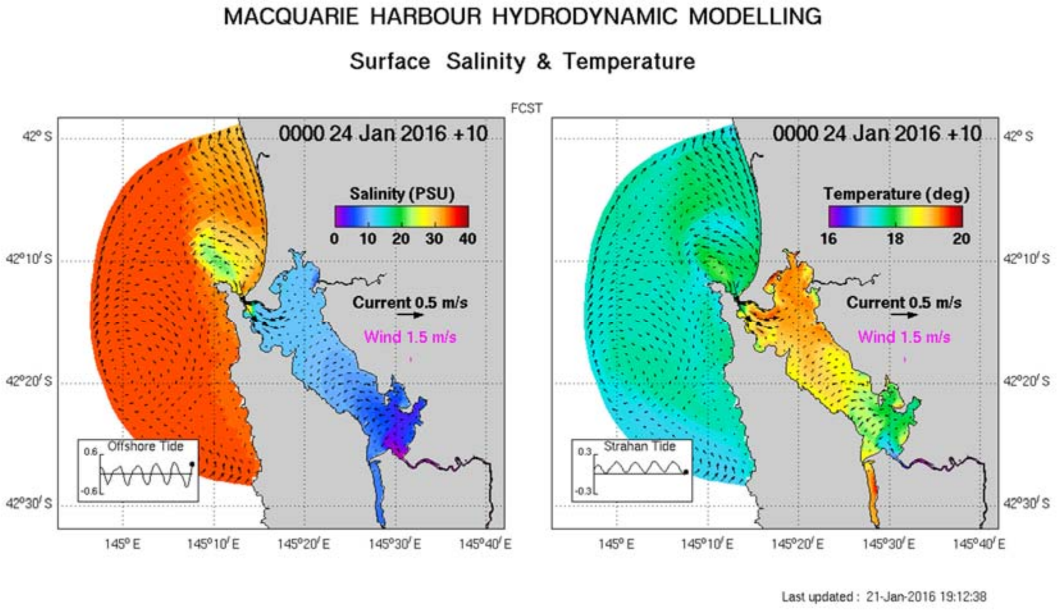


Figure 2 A sample of the uncalibrated CSIRO hydrodynamic model of Macquarie Harbour. Dynamic real time and forecast model output can be found at: http://www.marine.csiro.au/~and371/macq/

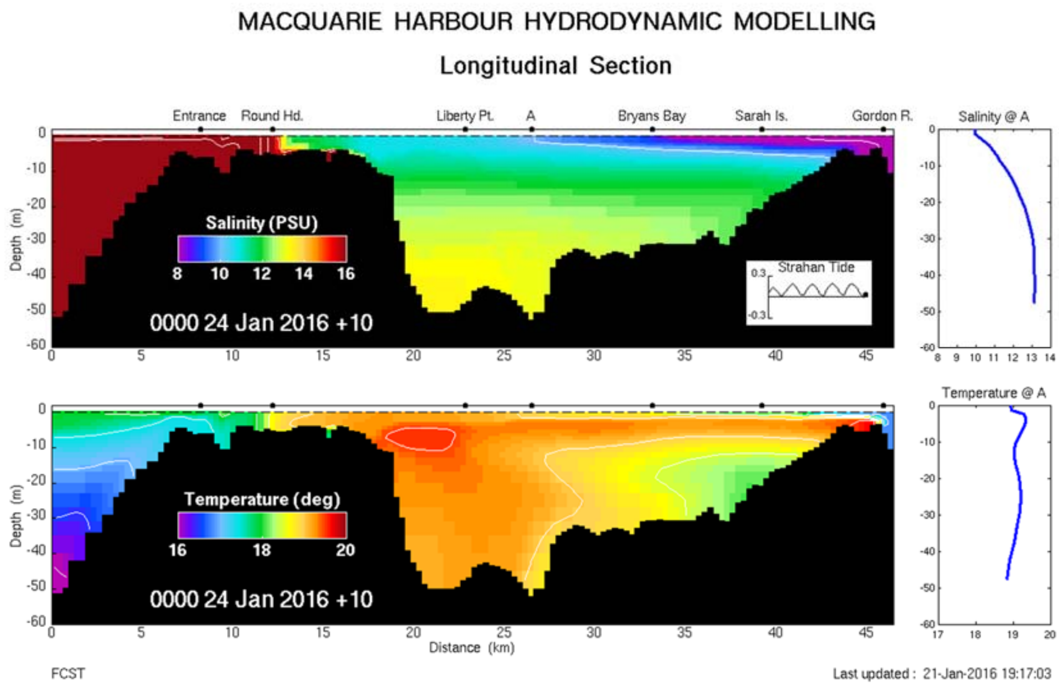


Figure 3 . An example longitudinal section of Macquarie Harbour showing temperature and salinity as predicted by the uncalibrated CSIRO model. Dynamic real time and forecast model output can be found at http://www.cmar.csiro.au/cem/macq/anim_macq_sect.gif.

1.1 Dissolved Oxygen

There have been a number of reports on, and reviews of, dissolved oxygen in Macquarie Harbour. In total these have been very thorough. A number of processes that consume oxygen were identified. Some of these were shown to be well measured and we can be reasonably confident about their magnitude (e.g. respiration within sediments) and some had been calculated with reasonable precision (e.g. respiration by farmed fish). It seems likely that further investigation of these processes will produce a diminishing return with only modest increases in our ability to manage DO in the Harbour. Other processes that have a potential for a significant influence on DO had no measurements. For example Knight et al. (2015) estimated water column respiration might be 2/3 of the total respiration in the Harbour. In this report we describe the first measurements of water column biological oxygen demand (BOD) for this water body. We make the initial estimates of this process for the Harbour and relate these to other processes that consume or replace oxygen in the waters of Macquarie Harbour.

One of the challenges in building an oxygen budget for Macquarie Harbour has been the lack of rate measurements for a range of important processes that determine the oxygen concentrations. When oxygen has become such a critical factor in the Harbour it is sensible to invest in a greater understanding of these process. Some can be readily observed, such as the intrusions of oceanic water into the bottom carrying with it a great concentration of DO. Similarly the inflow of fresh water often also carries with it an increased concentration of DO. The largest DO input is from the atmospheric, often called ventilation. Unfortunately this source remains unquantified for Macquarie Harbour.

1.1.1 Spatial and temporal oxygen dynamics

The previous conceptual model for oxygen in Macquarie Harbour focused on the importance of respiration and oxygen consumption at the sediment-water interface due to the decline in deep-water dissolved oxygen levels (MHDOWG 2014). More recently, the decline in mid-waters has become more evident, despite some recharge of the bottom waters. These events suggest that oxygen demand in the water column is a significant driver of declining oxygen levels; a key knowledge gap identified in MHDOWG (2014).

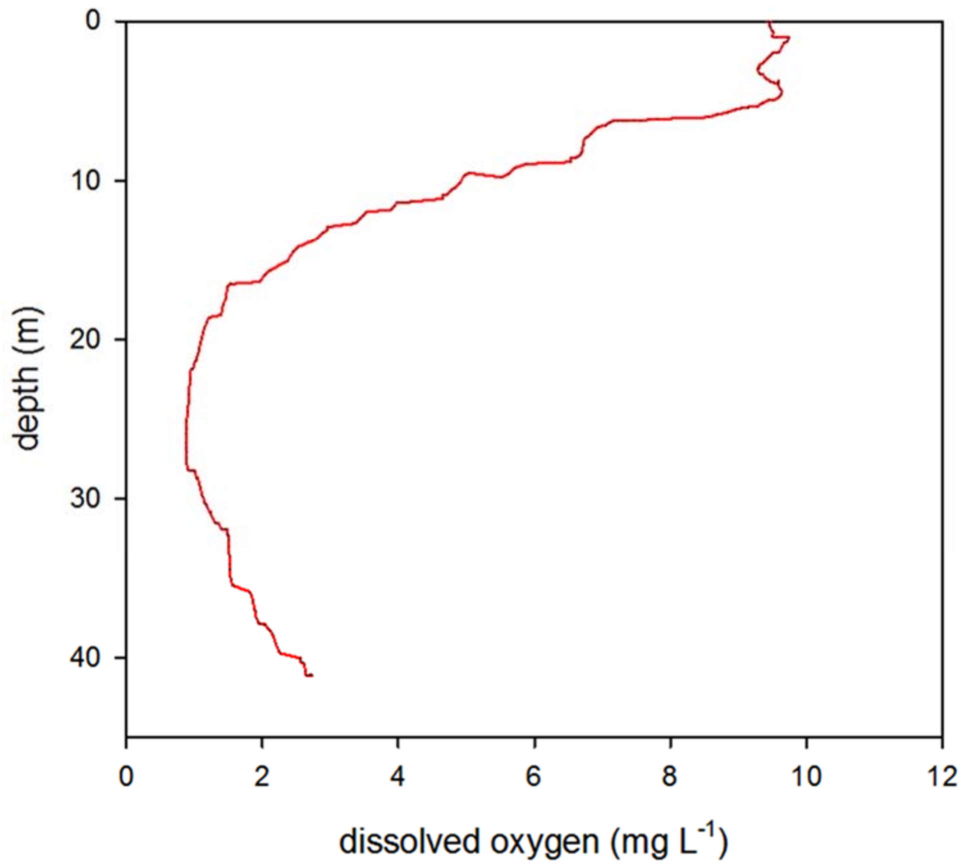


Figure 4 Dissolved oxygen profile at a lease site in Macquarie harbour during December 2015

Water column DO has fallen quite consistently since the winter of 2015 but benthic DO has been persistently greater than midwater DO (Figure 4). This observation makes it clear that significant respiration must occur in the water column.

There are numerous examples of high rates of respiration at density interfaces or fresh water to salt water transition zones. Typically these zones are associated with greater abundances of bacteria that are respiring organic matter. The combination of lower DO and labile organic matter can also establish conditions conducive to nitrification ($2NH_4 + 3O_2 \rightarrow 2NO_3$), which can consume significant amounts of oxygen. As shown later in this report there is good evidence of surface and mid depth respiration at a number of sites in Macquarie Harbour at the same time as DO concentrations were stable or increasing at depths ≥ 25m. These observations indicate that benthic respiration is not the major source of oxygen consumption in this water body.

1.1.2 Oxygen resupply.

The salinity, temperature and DO balances in Macquarie Harbour suggest that deep water intrusions periodically resupply DO to the deeper waters while fresh water inputs, wind mixing and the reduction in stratification due to cooling are likely to determine resupply in surface waters. While there are no measurements or direct observations of these processes quite a lot of useful information can be obtained from the monitoring of temperature, salinity and DO. To build a robust budget or predict the future DO concentrations in Macquarie harbour would require a model that incorporates these processes.

The major process that routinely supplies DO into Macquarie Harbour is exchange with the atmosphere. Unfortunately oxygen diffusion is so slow that while this is important for the surface layer, it is nearly irrelevant as a supply of DO for the majority of the water column. In addition O_2 is much less soluble in water than some other gases, for example CO_2 (Liss, 1973). For the bulk of the Harbour oxygen exchange with the atmosphere is almost entirely dependent upon mixing processes. Mixing is increased by reducing stratification (typically surface cooling) and increasing wind speed especially along the long axis of the water body. As with bottom water resupply calculating the rate of DO input from the atmosphere is well suited to a relatively simple model and can be validated by simple observations for a relatively modest cost.

In this report we have taken two approaches to try and understand the importance of water column respiration to Macquarie harbour. We have used long term DO profiles taken regularly at two lease sites within Macquarie harbour. Analysis of any long term trends in this data are useful background to the current situation and allow us to document the **net** change in oxygen at two locations and multiple depths. In addition we have measured **gross** biological oxygen demand (BOD) at multiple depths from 3 sites. The BOD measurements add quantification for the previously un-measured pelagic component of the oxygen cycle in Macquarie Harbour. In combination, these two approaches may fundamentally change our conceptual understanding of the relative importance of benthic and pelagic processes in drawing down oxygen in Macquarie harbour.

2 Methods

2.1 Determination of Net Pelagic DO

Observations of dissolved oxygen concentrations were collected at two sites where Huon Aquaculture operates fish farms in Macquarie Harbour. The sites were: Middle Harbour Gordon South (Gordon), Middle Harbour Strahan (Strahan) and Pelias Cove. Data were from mid October 2015 to early January 2016. Observations were obtained from multiple depths.

A simple statistical analysis was undertaken to estimate the change in DO at 1, 5, 10, 15, 20 and 25m depths over the duration of the observations by fitting a linear regression to the data with the slope of the line providing the net rate of change in DO at that depth.

The measured concentrations of DO were corrected for salinity and temperature using simultaneously collected data following the methods of Benson and Krause (1980, 1984).

2.2 Determination of Gross Pelagic BOD

In order to assess rates of pelagic biological oxygen demand (BOD) samples were collected at 3 sites (Table 1; Figure 5) from 4 depths (3m, 13m, 23m and 2-3m off the bottom).

Table 1 Co-ordinates of sample sites for gross pelagic BOD measurements in Macquarie harbour

Site	Latitude	Longitude
1	-42° 22.412	145° 28.289
2	-42° 18.898	145° 22.628
3	-42° 18.792	145° 22.800

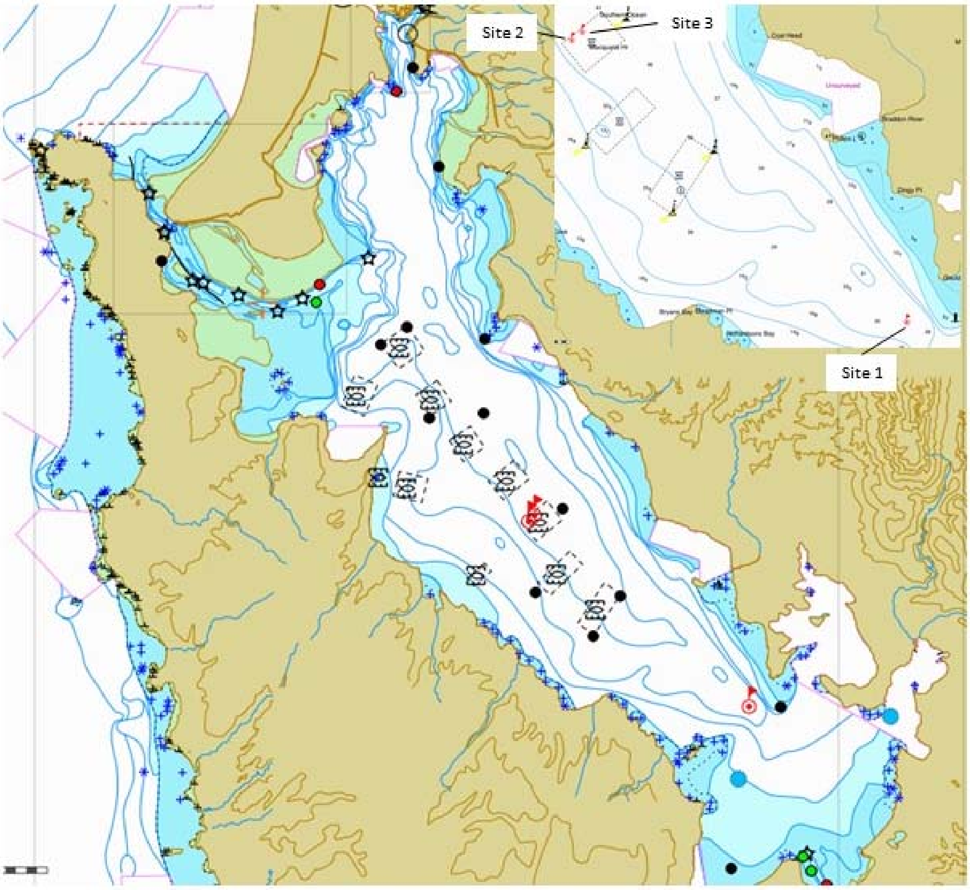


Figure 5 Relative sample locations (red flags) within Macquarie harbour

Site 1 was chosen as the furthest site away from the farm leases towards the Gordon River input while still being in a suitable water depth (30m). Site 2 was adjacent to a double stocked pen and site 3 adjacent to a single stocked pen. Samples were collected using a 10L niskin bottle and transferred to conventional glass dissolved oxygen bottles. Samples were collected for measurement by DO probe and Winkler titrations (to verify probe data). For DO probe measurements 8 bottles were collected at each depth, their DO values recorded and then sealed with 4 to be measured at 24h and 4 at 48h. For winkler titrations, 4 bottles from each depth were fixed immediately (T0) and 4 bottles sealed and fixed 48h later. Bottles that were to be incubated were secured in wire cages and suspended at appropriate depths from the feed barge.

In addition, at each site sonde profiles were recorded and water samples collected from each depth for nutrient analyses, fatty acid analysis as a proxy for labile organic carbon and to characterize suspended organic matter and genomics to identify key bacterial groups.

3 Results

3.1 Pelagic DO

At Gordon the rates of change in oxygen indicated a net loss at all depths except 25m between October 2015 and January 2016 (Figure 6). At the Gordon site the rates of net DO loss were quite low at the surface and increased ~ 3 times with depth peaking at 15m before falling again with increasing depth. Net consumption rates were lower at 20m than 15m and rates at 25m were slightly positive; although not significantly different from zero (Table 2). There was more variability in the rate of net DO loss at 5m than other depths (Table 2).

At Strahan over the same time period the rate of net oxygen loss was again relatively low at 1m and increased by a factor of ~3 with depth peaking at 15m. Below 15m net oxygen loss rates declined becoming slightly positive (not significantly different from zero) at 25m (Figure 7; Table 2).

Table 2 Rates of oxygen decline from two locations estimated from daily measurements of oxygen concentrations at two locations in Macquarie Harbour, Tasmania. (data shown in Figures 6 and 7).

Site	Depth (m)	Net rate of O_2 change (mg/L/day)	Standard error	Probability	Change in % DO saturation (%/day)	Probability	R^2
Gordon	1	-0.012	0.001	<0.0001	-0.003	<0.0001	0.28
Gordon	5	-0.023	0.004	<0.0001	Variable		
Gordon	10	-0.027	0.002	<0.0001	Variable		
Gordon	15	-0.033	0.002	<0.0001	-0.37	<0.0001	0.78
Gordon	20	-0.012	0.001	<0.0001	-0.135	<0.0001	0.71
Gordon	25	0.002	0.001	0.1622	Variable		
Strahan	1	-0.013	0.001	<0.0001			
Strahan	5	-0.018	0.002	<0.0001			
Strahan	10	-0.030	0.003	<0.0001			
Strahan	15	-0.036	0.003	<0.0001			
Strahan	20	-0.015	0.002	<0.0001			
Strahan	25	0.002	0.002	0.1766			

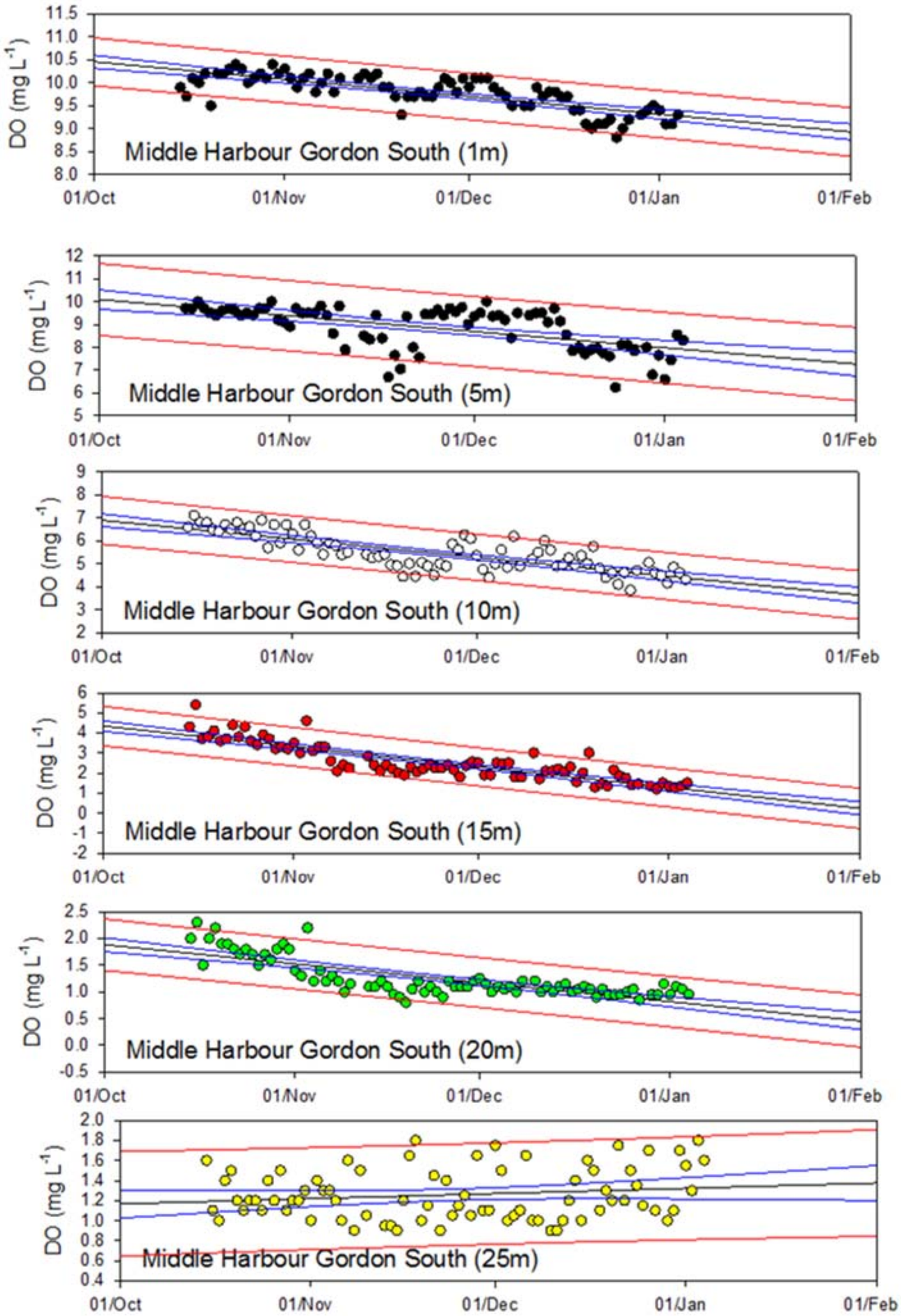


Figure 6 Plots of oxygen concentrations versus time from the middle harbour Gordon South lease at 5 depths. Data from Huon Aquaculture over the period 13/10/2015 to 05/01/2016. Linear regressions are shown fitted to the data to estimate the long term oxygen consumption rate at each depth

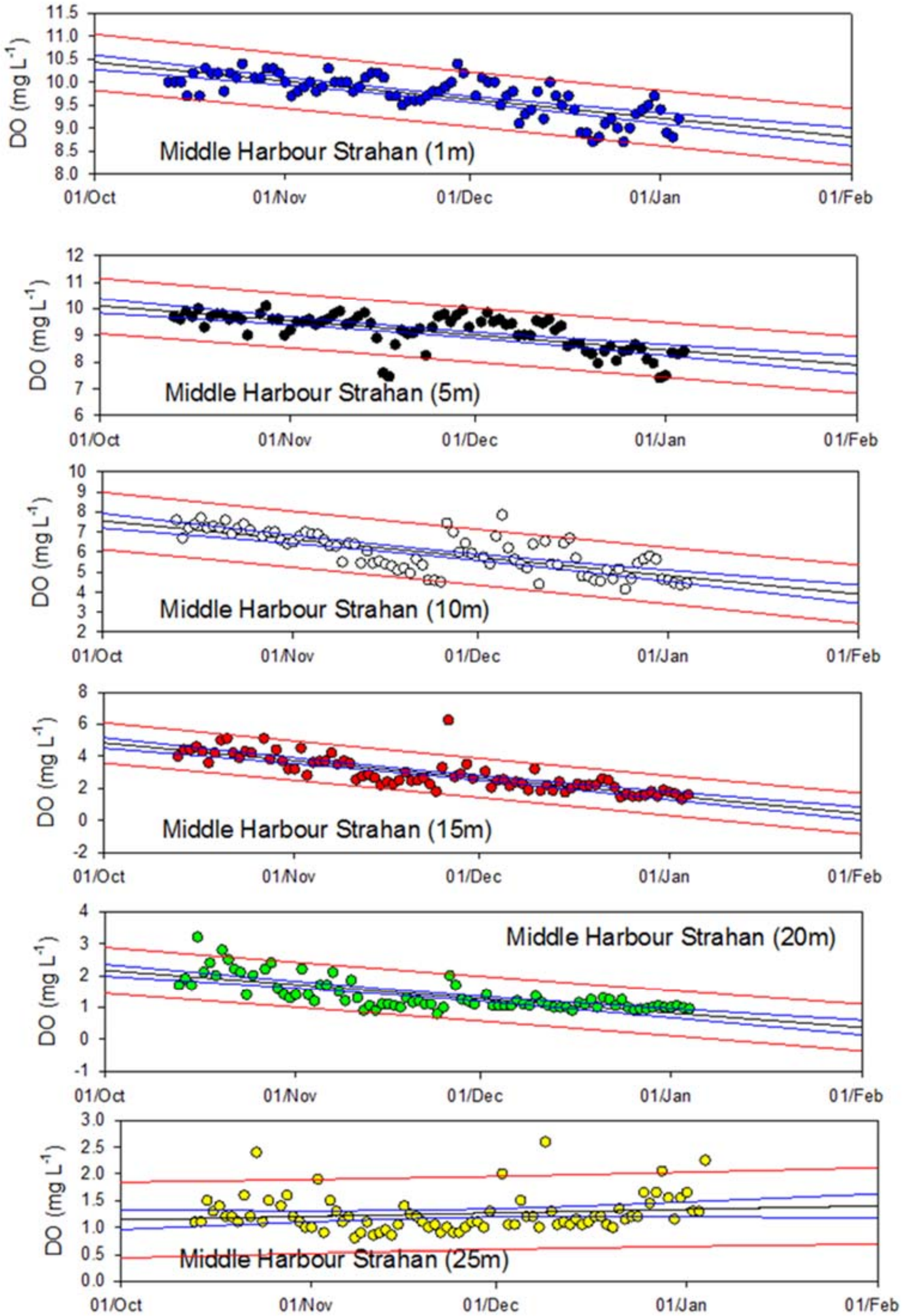
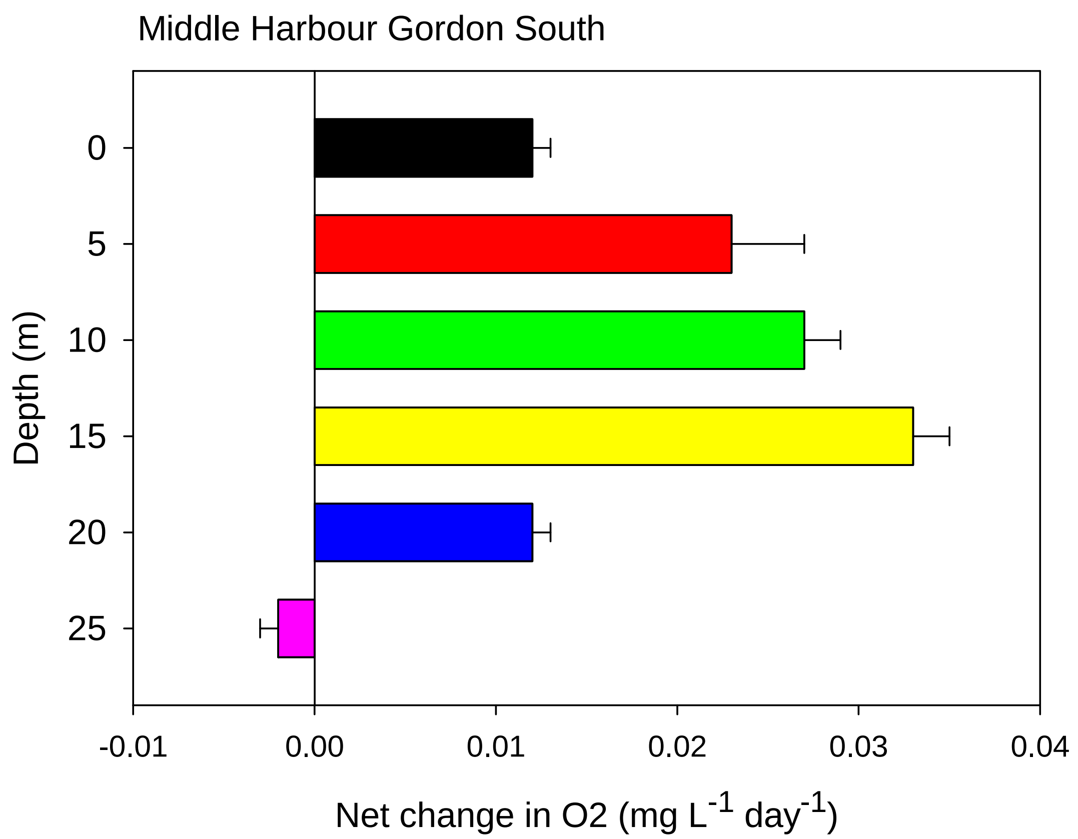


Figure 7 Plots of oxygen concentrations versus time from middle harbour Strahan lease at 5 depths. Data from Huon Aquaculture over the period 13/10/2015 to 05/01/2016.

The results clearly show (Figure 8) that net oxygen consumption was greatest at intermediate depths during the period from October 2015 to January 2016 at both sites.



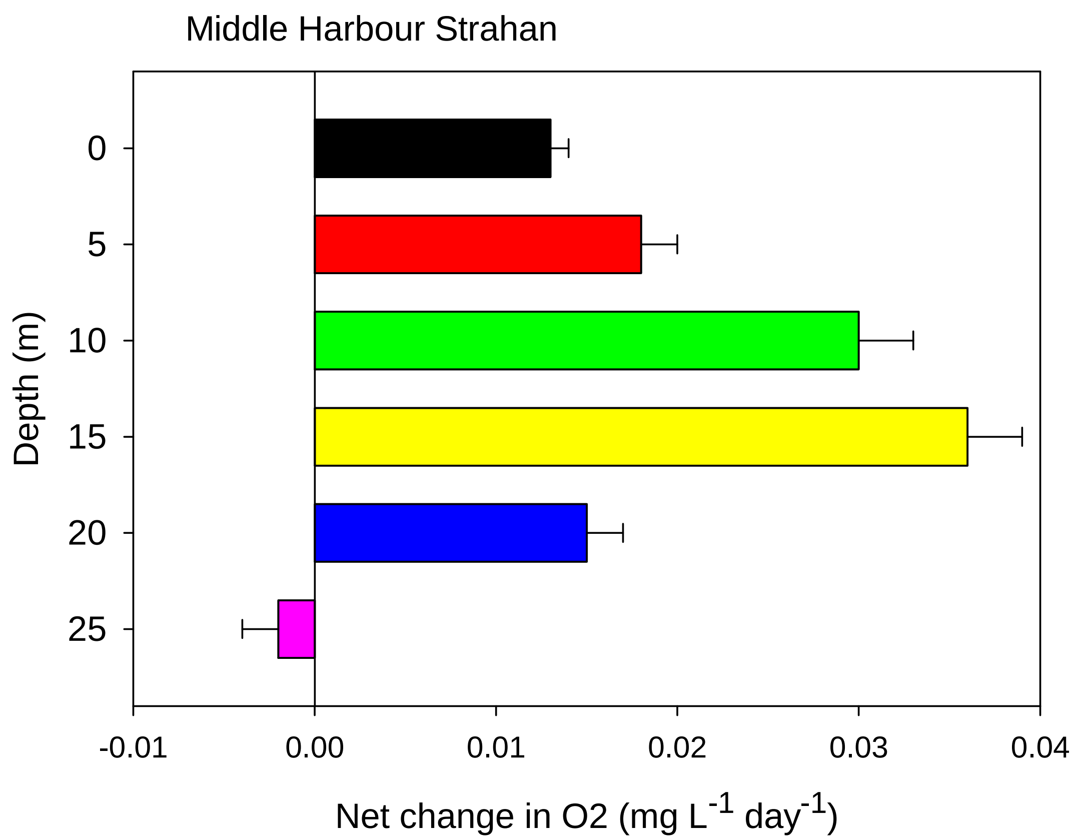


Figure 8 Summary plots of declines in oxygen concentrations at 6 depths and 2 locations (derived from linear regressions Data from Huon Aquaculture over the period 13/10/2015 to 05/01/2016

3.2 Other factors influencing oxygen inputs for Macquarie Harbour

DO data from 2013 and 2014 at Middle Harbour Gordon South showed the maximum DO concentrations were reached in August for all depths < 20m (Figure 9). At depths > 30m DO concentrations peaked in February; presumably due to bottom water recharge. For all depths < 20m the annual minima in DO was during late summer or early autumn (February to March). Following from these annual minima is a long slow recharge of waters < 20m with DO that is likely to be driven by several factors.

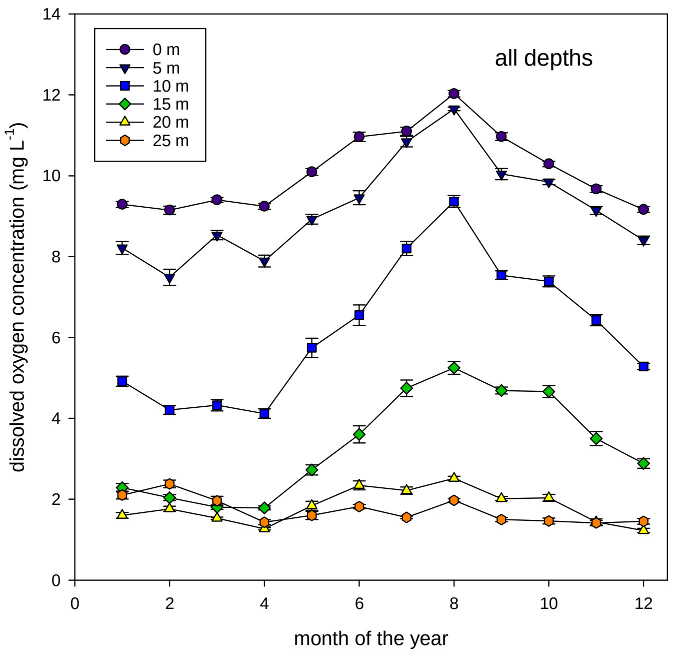


Figure 9 Seasonal patterns of dissolved oxygen with depth for Middle Harbour Gordon South.

Wind speed makes a significant contribution to oxygen supply into natural waters. There are a range of predictive equations relating the 'piston velocity' of various gases to the wind (e.g. Liss and Merlivat, 1986; Liss and Slater 1974, Wanninkhof, 1992) where the input is proportional to the square of the wind speed. For Macquarie Harbour wind speed is typically minimal in February and rises quite steadily until September (Figure 10).

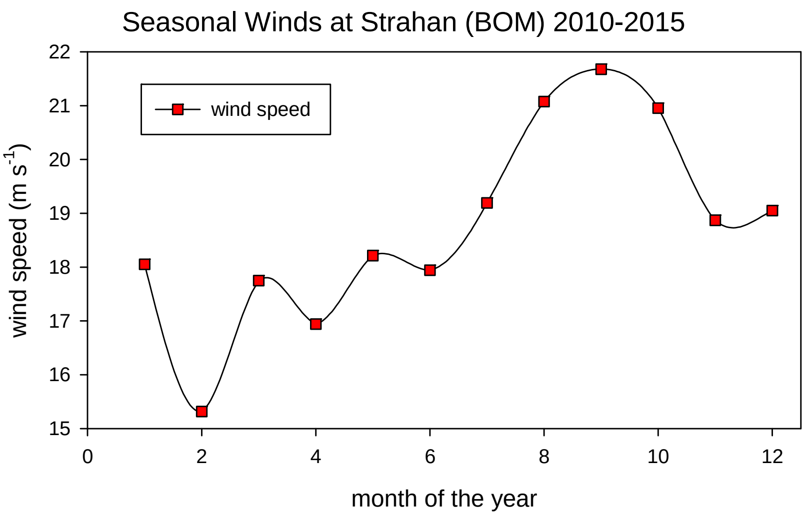


Figure 10 Monthly mean wind speed for Strahan Airport.

Temperature will influence DO in a number of ways. First it has a direct influence on the solubility of oxygen. Oxyen is significantly more soluble in cold water and the maximum DO concentrations are typically reached at the time of minimum water temperature for waters in equilibrum with the atmosphere. For example the surface waters in Macquarie Harbour underwent a ~ 3 mg L^{-1} change in DO from their peak in August to late summer (Figure 9). Over the same time period these surface waters maintained ≥100% oxygen saturation virtually the whole time (Figure 11, top panel).

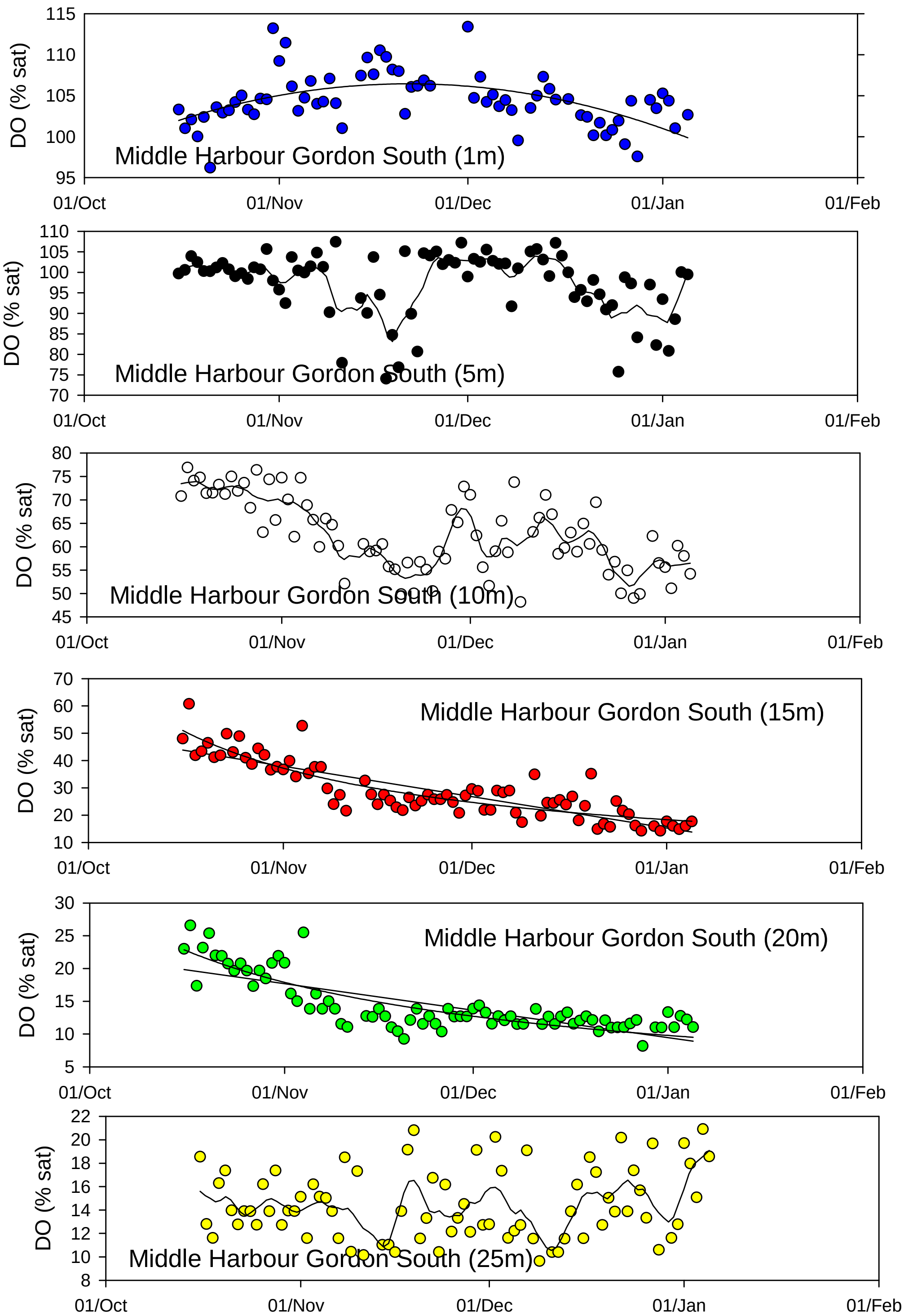


Figure 11 Trends in percent oxygen saturation at one site in Macquarie Harbour from October 2015 to January 2016 at 6 depths. Where a trend was likely a model was fit or a locally weighted regression (see Table 2).

Given that DO at 1m was always ~ 100% saturated it seems reasonable to suggest the surface of Macquarie Harbour is most often in equilibrium with the atmosphere. Also that changes in the concentration of oxygen in this surface layer are driven largely by changes in solubility determined mostly by temperature (Benson and Krause 1984).

The temporal pattern of oxygen concentration (Figure 6) and percent saturation (Figure 11) at 5 and 10m suggests that both depths experience sporadic net respiration. For example percent saturation fell from October through much of November at both depths. Given the increasing temperatures percent saturation would rise if net respiration was zero. At both depths oxygen concentration and percent saturation recovered somewhat during December. This recovery was likely due to the input of additional fresh water high in DO into Macquarie Harbour; and possibly the ~ 2x higher than normal winds in late November 2015 (19^{th} to 26^{th}, BOM data, not shown).

It was the depths of 15 and 20m that showed the greatest reduction in DO concentrations and percent saturation over the period from October 2015 to January 2016 (Figure 11, Table 2). The falling % saturation was ~ 3 times greater at 15m than 20m (Table 2). These declines appeared to slow down with the onset of summer such that a nonlinear model was a modestly better predictor of the trends.

The temporal pattern of DO at 25m was quite erratic. There are indications of periodic increases in percent saturation probably reflecting intrusions of sea water from outside Macquarie Harbour.

Temperature and salinity also influence DO concentrations because of their role in stratification. The surface waters of Macquarie Harbour are much warmer in summer such that it requires much more wind energy to overcome the increased difference in density and mix oxygen downwards. Similarly, increased freshwater inputs to the surface will reduce the effectiveness of a given wind speed to mix oxygen to depth.

In conclusion, given that February is normally the month of lowest wind speeds and some of the highest temperatures it can be anticipated that during this month the ventilation of Macquarie Harbour will be less efficient than other months of the year.

3.3 Gross Pelagic DO

At the time of sampling all three sites exhibited strong haloclines in the top 10m which were also accompanied by a thermocline (Figure 12). DO profiles showed a marked decrease in the top 15-20m, reaching a minimum around 25m. Sites 2 and 3 then had a subsequent increase in DO at depth.

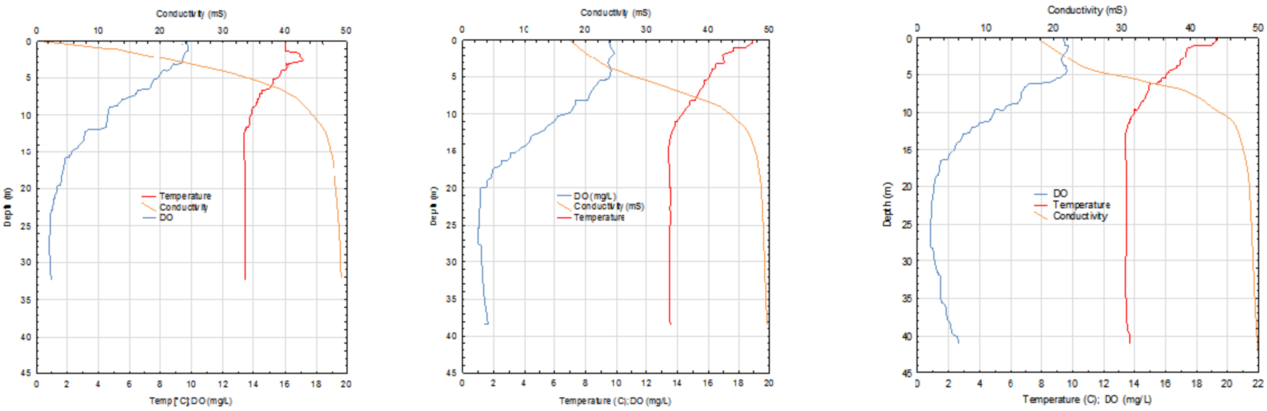


Figure 12 Sonde profiles from Site 1 (L), Site 2 (M) and Site 3 (R) sampled in Macquarie Harbour, Tasmania

Table 3 Rates of oxygen change during incubations of samples from three locations in Macquarie Harbour, Tasmania

Site	Depth (m)	DO change ($mgO_2/L/h$)	Standard error	Probability
1	3	-0.0015	0.0009	0.1301
1	13	-0.0010	0.0065	0.8766
1	23	0.0021	0.0031	0.5069
1	30	-0.0081	0.0029	0.0152
2	3	-0.0038	0.0004	<0.0001
2	13	0.0004	0.0029	0.8991
2	23	0.0027	0.0008	0.0044
2	39	-0.0004	0.0013	0.7798
3	3	-0.0023	0.0005	0.0004
3	13	-0.0018	0.0052	0.7418
3	23	0.0006	0.0007	0.4419
3	41	-0.0013	0.0007	0.0730

Results from the BOD incubations as measured using the probe are shown in Table 3. Most samples exhibited a decline in DO over the 48 hour period but notably samples from 23m exhibited a slight increase in DO over the incubation period though mechanisms for this to occur at depth are unclear. However, only 4 of the sample sets are statistically significant (site 1 @ 30m; site 2 @ 3m and 23m and site 3 @ 3m) due to the low replication that was possible in this field campaign. Several results determined using Winkler titrations were unusable due to end point interferences from the high DOC content. A comparison between the gross measured pelagic BOD at the two cage sites and the long term net DO change calculated from data collected at middle harbour Gordon is given in Table 4. At 3-5m gross rates appear to be greater than net rates while at other depths gross and net rates appear to be of a similar magnitude. While this is potentially informative, the comparison is tentative and based on a very small data set with little replication and includes some unexplained measured increases in DO.

Table 4 Comparison of long term calculated net rate of O2 change and gross change measured over 48 hours at the closest comparable depth.

Site	Depth (m)	Long term net rate of O_2 change (mg/L/day)	Measured O_2 change cage sites (mg/L/day)	
			Site 2	Site 3
Gordon	1	-0.012		
Gordon	5	-0.023	-0.0912	-0.0552
Gordon	10	-0.027		
Gordon	15	-0.033	0.0096	-0.0432
Gordon	20	-0.012		
Gordon	25	0.002	0.0648	0.0144
	Deep		-0.0096	-0.0312

3.4 Fatty acid content

Total fatty acid concentrations from each depth at the three sites are shown in Figure 13. Concentrations were greatest in samples from 3m with site 1>>site2>site3 suggesting greatest labile carbon occurred at the pen sites. Site 1 had only slightly higher concentrations at 3m than at 13m with minimum values at 23m before an increase again at depth. At site 2 after the 3m samples the next highest concentrations were close to the bottom while at site 3 all samples deeper than 3m were similar.

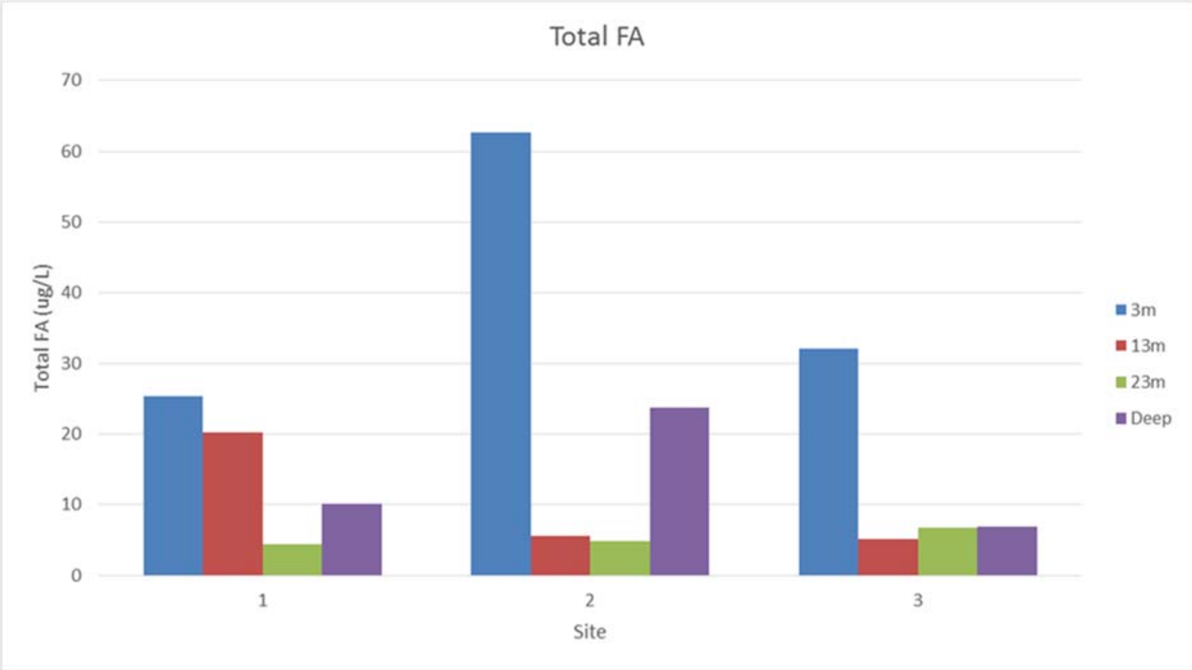


Figure 13 Total fatty acid concentration (ug/L) in samples from different depths at three sites in Macquarie harbor.

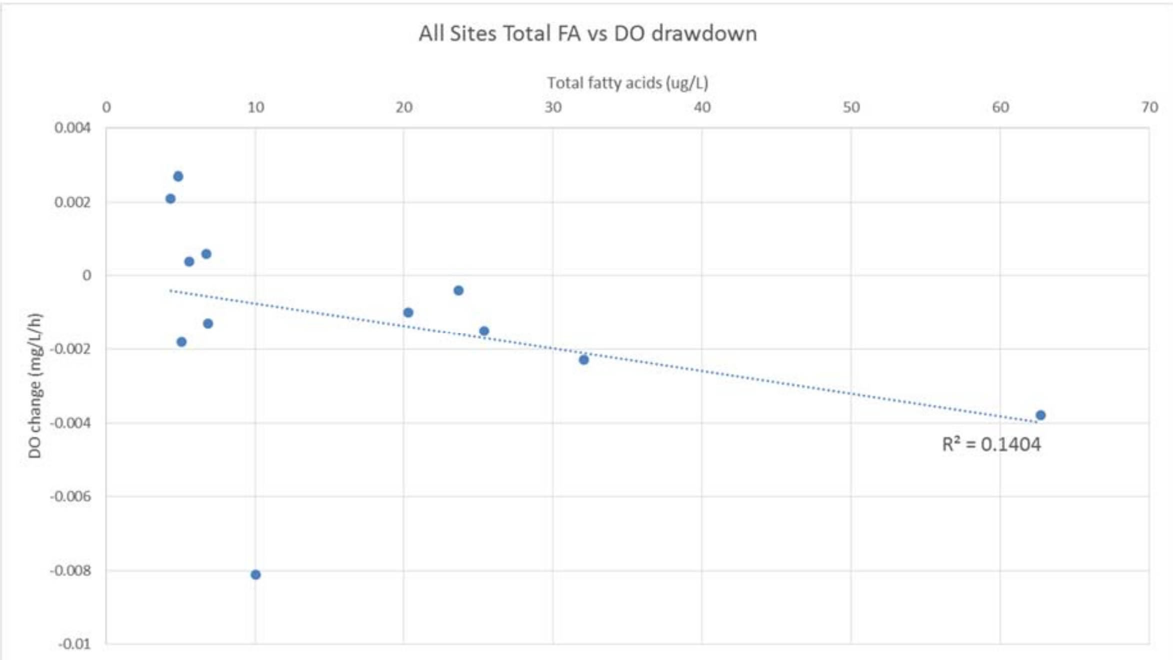


Figure 14 Measured DO drawdown (mg/L/h) versus total fatty acid concentration (ug/L) in samples from different depths at three sites in Macquarie harbour.

A comparison between fatty acid content and measured gross DO change suggests there is some correlation between measured DO drawdown and total fatty acids (a proxy for labile organic carbon) measured in the water column (Figure 14), and this relationship is strongest when considering the cage sites alone (Figure 15)

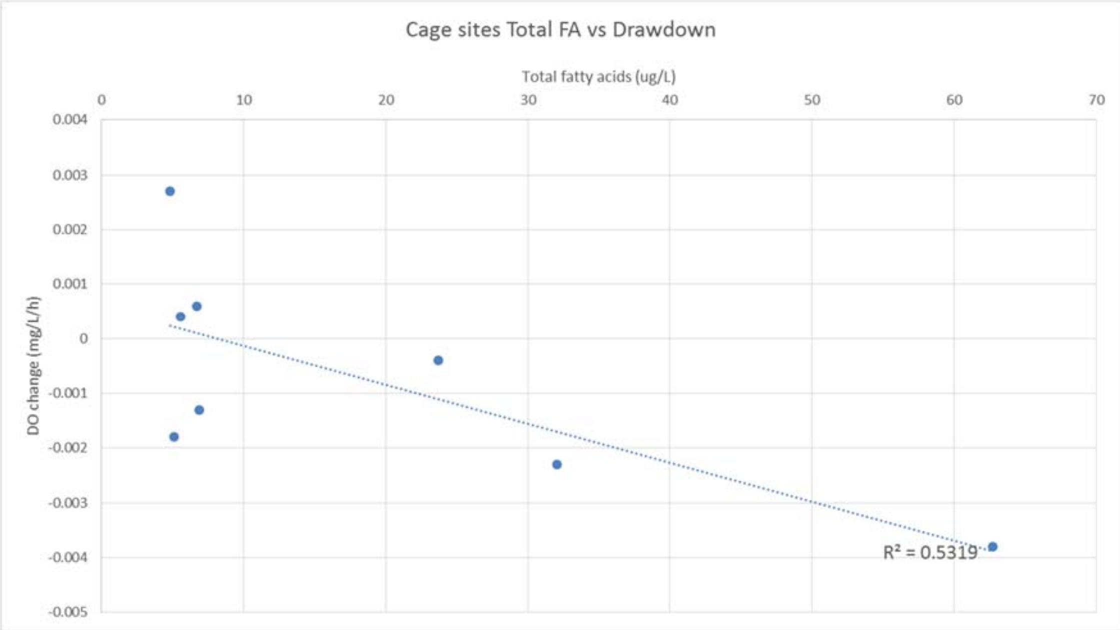


Figure 15 Measured DO drawdown (mg/L/h) versus total fatty acid concentration (ug/L) in samples from different depths at two cage sites in Macquarie harbour.

3.5 Sources of organic matter

One compound that has previously been shown to be elevated in sediments collected close to farms in Macquarie harbour is Linoleic acid (LA; 18:2w6 fatty acid; Revill et al. 2015). Concentrations of this compound were greatest at site 2, then site 3 with site 1 exhibiting the lowest concentrations with site 2 approximately double site 1 (Figure 16). At all sites, greatest concentrations of LA were in the 3m samples, with site 1 also showing an increase at depth, though still less than at 3m.

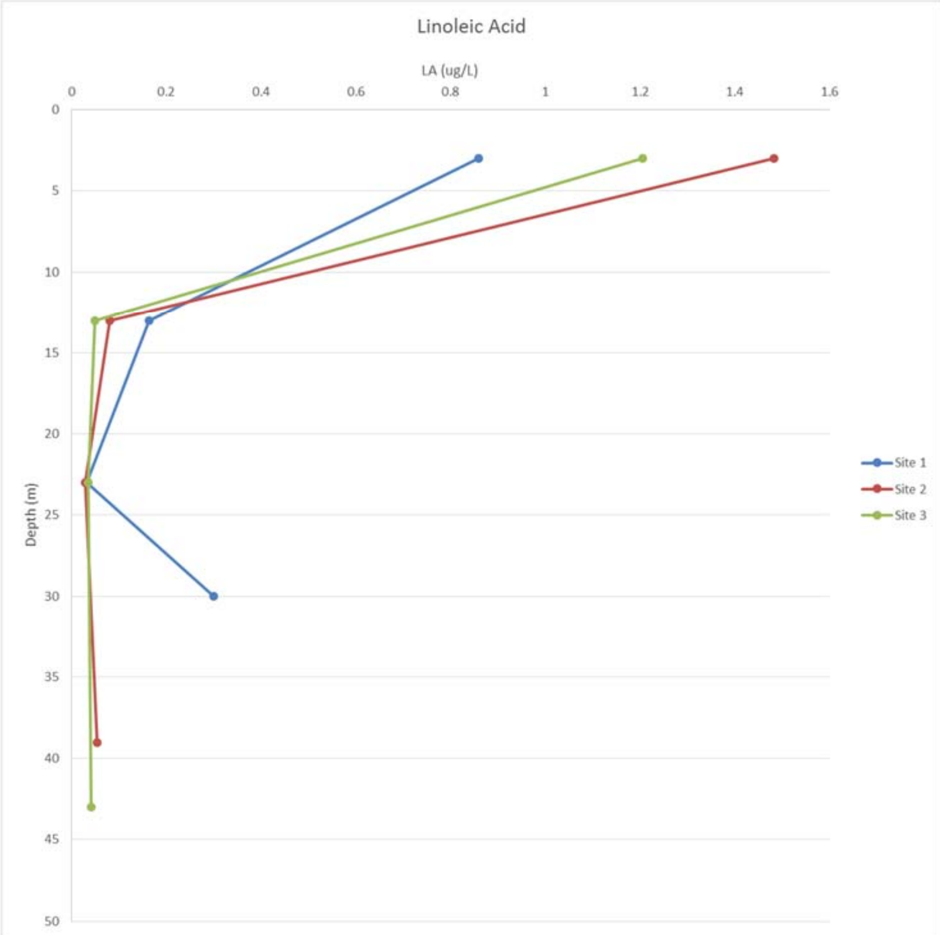


Figure 16 Presence of Linoleic acid in water samples collected from different depths at three sites in Macquarie harbour

3.6 Pending Results

At the time this report was prepared samples were still being analysed for dissolved nutrients and genomics. When these are available the results will be included in an updated report.

4 Discussion

4.1 Comparison of gross and net DO

Calculated long term net DO drawdown provides an indication of the average rate of consumption (or production) over an extended period of time. However, these observed rates of net consumption do not provide much insight into the gross rates of respiration or oxygen resupply. It is difficult to know from these calculations alone whether the decline in DO is a function of an increase in oxygen consumption or a decrease in resupply. Measured rates of gross pelagic BOD in this study were relatively low, averaging approximately 2.4 mmol/m^3/d compared to the frequency mode value of 4 mmol/m^3/d from a study of global estuarine pelagic respiration rates by Hopkins and Smith (2005). A direct comparison of these different data sets is difficult, especially allowing for the low level of replication in the gross measurements but it does suggest that the magnitude of measured gross rates are within the range that would facilitate the calculated long term net changes. Importantly, measured gross BOD rates are approximately twice those measured for the benthos[1], confirming the pelagic system as the key driver in oxygen drawdown.

A further major finding from this study is that gross pelagic BOD is greatest at 3m but net oxygen consumption is greatest at ~ 15m. This highlights the role that surface exchange of oxygen (probably wind driven) plays in maintaining DO levels above the halocline, while below this depth, exchange is limited. However, it also highlights the capacity of surface waters above the halocline to decline rapidly should exchange processes become limited over an extended period as has recently been observed.

4.2 Sources of Organic Matter Driving DO Drawdown

In this study the analysis of fatty acids associated with water column particulate material was utilised for two purposes. Fatty acids are labile organic compounds and as such provide a reasonable proxy for the total labile particulate organic carbon pool. In addition, the profile of compounds present can be used to provide information on the likely important sources of that organic carbon. Total fatty acid content was greatest closest to the cage sites with the double stocked cage (site 2) being twice that of site 1, while samples adjacent the single stocked cage (site 3) were 50% greater than site 1. This is consistent with elevated inputs of labile organic carbon close to the cages, which also correlated with increased respiration at 3m. More replication is required to fully understand the spatial and temporal extent of farm effects on organic matter supply and oxygen consumption

Fatty acid profiles isolated from water samples in Macquarie Harbour are complex with compounds sourced from terrestrial inputs and phytoplankton as well as aquaculture influences and there is often overlap in the presence of many compounds in all possible sources. While there is no single unique “tracer” of farm derived material, it is often possible to associate increased farm derived inputs with elevated levels of particular compounds. Current feed formulations are a mixture of marine and terrestrially (poultry) derived material. The presence of carbon from poultry results in feed containing Linoleic acid (LA; 18:2w6 fatty acid) and while this is a naturally occurring terrestrial fatty acid, elevated levels can often be associated with farm inputs. Site 1 cannot strictly be described as a control site due to the fact that material in the water column is likely to be mixed through the Harbour, however it does give an indication of far-field concentrations for compounds of interest. Elevated total fatty acid concentrations close to the cages are accompanied by elevated concentrations of LA which is further evidence that elevated labile organic

[1] Relative amounts of oxygen consumption were calculated using the measured BOD rates, assuming the same aerial zone of influence used in the benthic survey (MHDOWG 2014) and converting each depth interval to a volume. Importantly this is only a preliminary comparison and requires much greater replication to increase confidence.

carbon at these sites is most likely derived from farm inputs. Low concentrations in the mid-water column, even close to the cages, may represent greater dispersion at depth compared to at the surface though it is also possible that only a small proportion of the material is dense enough to penetrate the halocline but sufficiently buoyant to not rapidly sink.

As with pelagic BOD measurements, interpretation of the fatty acid data is hampered by a lack of replication which would increase certainty. In addition, there needs to be more work on methods (for example compound specific stable isotopes) which may distinguish LA and other fatty acids sourced from farm inputs with those derived naturally from the surrounding catchment. This would then facilitate a better understanding of the broader spatial distribution of farm derived material.

4.3 Implications for Macquarie harbour

Declines in DO are occurring throughout the world's oceans due to increased stratification (Stramma et al. 2010). In the open ocean this is most often associated with warming. In coastal seas it has also been associated with more precipitation and freshwater runoff (Malone 1991). In the coastal zone declining DO has also been associated with eutrophication (Ketchum 1969, Diaz and Rosenberg 2008). All of these external factors are likely to be important in Macquarie Harbour as it's a highly stratified system with limited exchange with the ocean. In addition, an increase in oxygen consumption is a reasonable expectation given the direct respiration of the substantial increase in farmed fish and the increased input of associated organic matter and ammonium.

The topography of Macquarie Harbour is such that it is conceivable that while surface water may have a relatively short residence time the strong halocline and shallow sill may conspire to retain much of the mid water for a significant period of time. Oxygen diffusion is a very slow process such that a body of water sandwiched between oxygenated fresh water at the surface and occasional intrusions of oxygenated water at the bottom is essentially "isolated" with no opportunity for horizontal exchange with the ocean and therefore may be considered a closed system leading to a slow decline in dissolved oxygen. In this situation it may only require consumption of relatively small quantities of organic matter to drive dissolved oxygen down to the levels measured. The strong seasonal cycle in DO makes it clear that processes consuming oxygen dominate from spring to autumn with significant resupply typically occurring during winter. The multiyear pattern of seasonal decline in DO below the halocline implies a consistent seasonal change in the balance of oxygen consumption and resupply.

5 Recommendations for Future Work

The ongoing management of DO in Macquarie Harbour requires a more thorough assessment of the processes described in this report. A targeted field campaign to measure a few unquantified, or poorly quantified, processes combined with a simple model is recommended. From the data presented here and the conceptual model developed, there are several key questions in order to better understand and manage inputs into Macquarie Harbour:

- What are the rates and primary controls on oxygen exchange with surface water?
- On average how long is the mid-water column “isolated” from oxygen exchange and what are the main mechanisms for “recovery” of oxygen levels?
- What is the spatial variability of DO drawdown across the harbor?
- Over what spatial scales can farm influences be detected in the water column?

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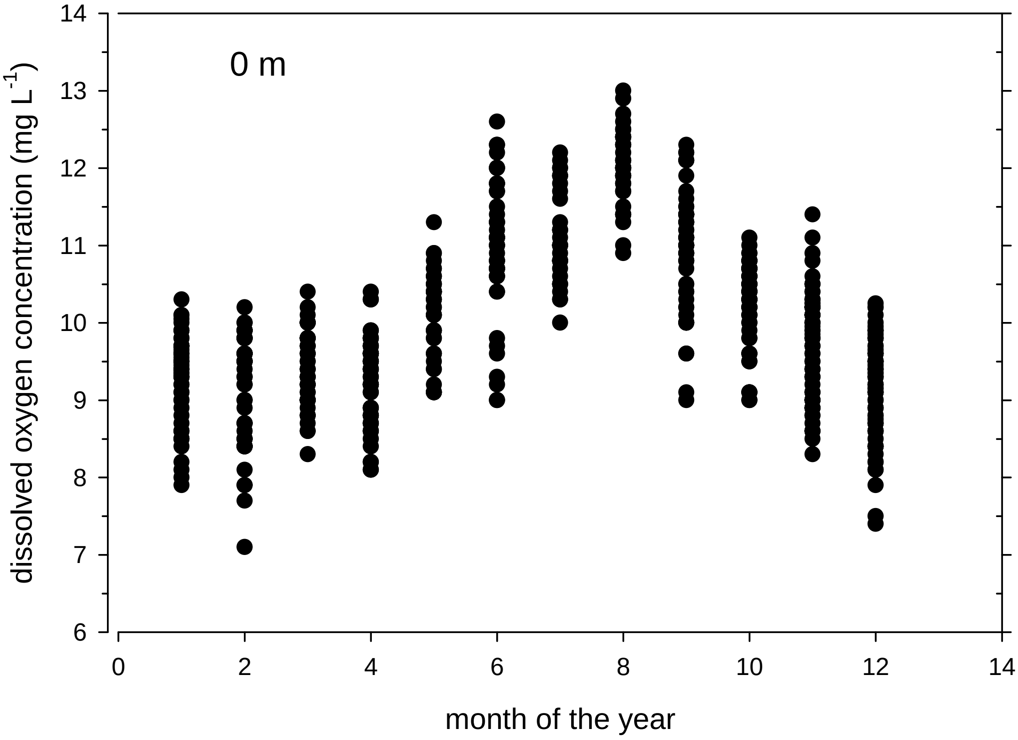
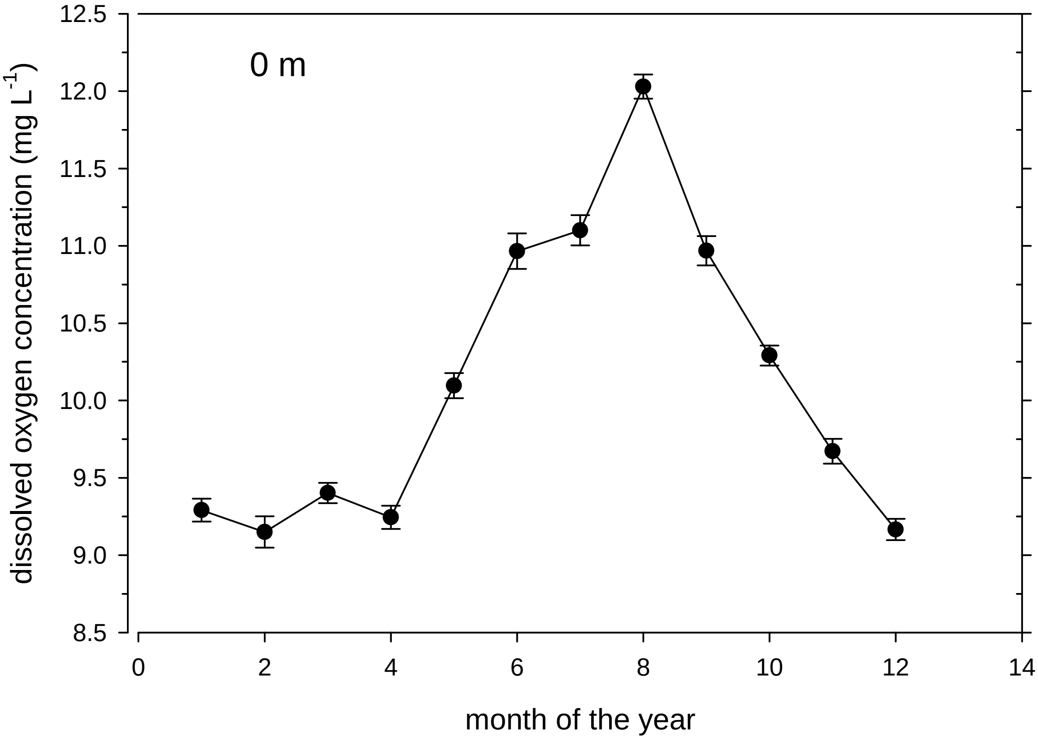
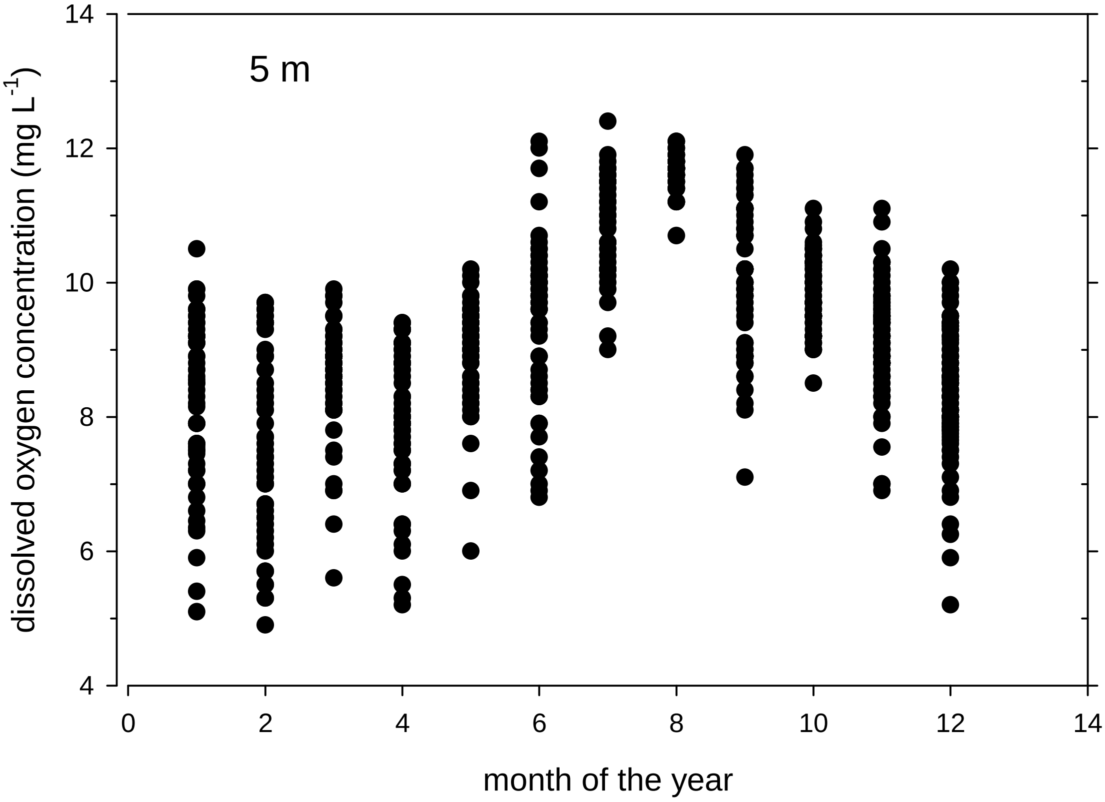
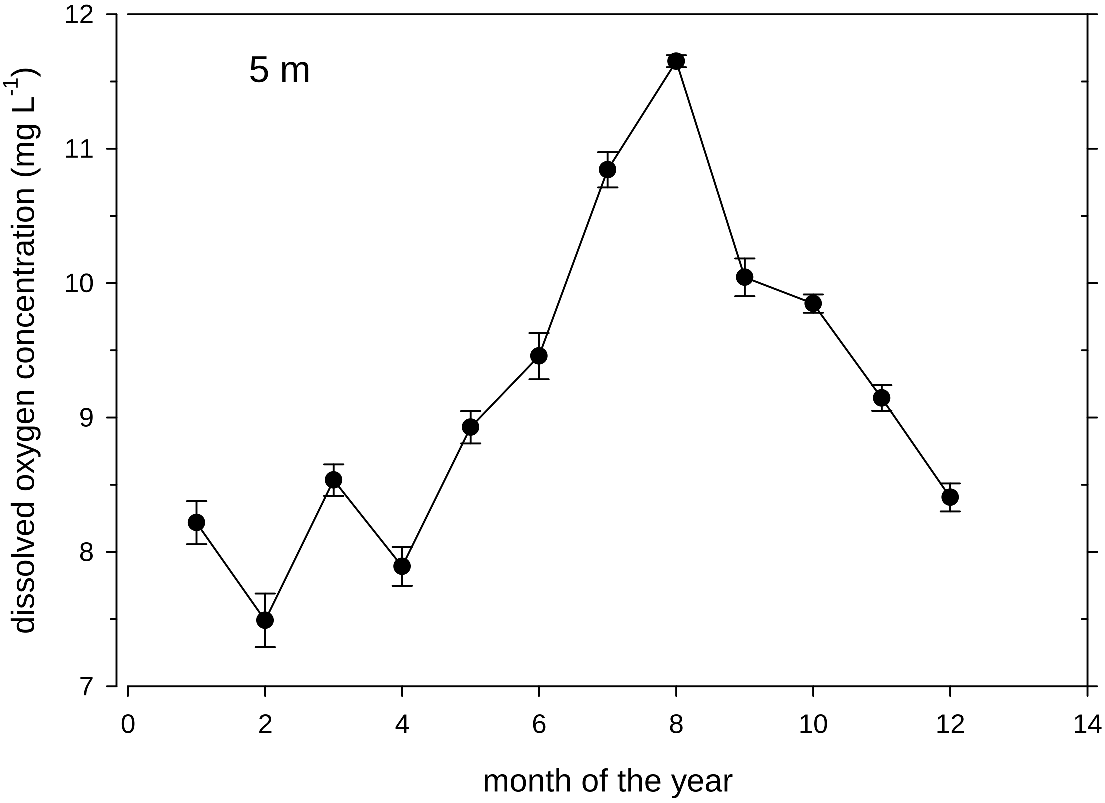
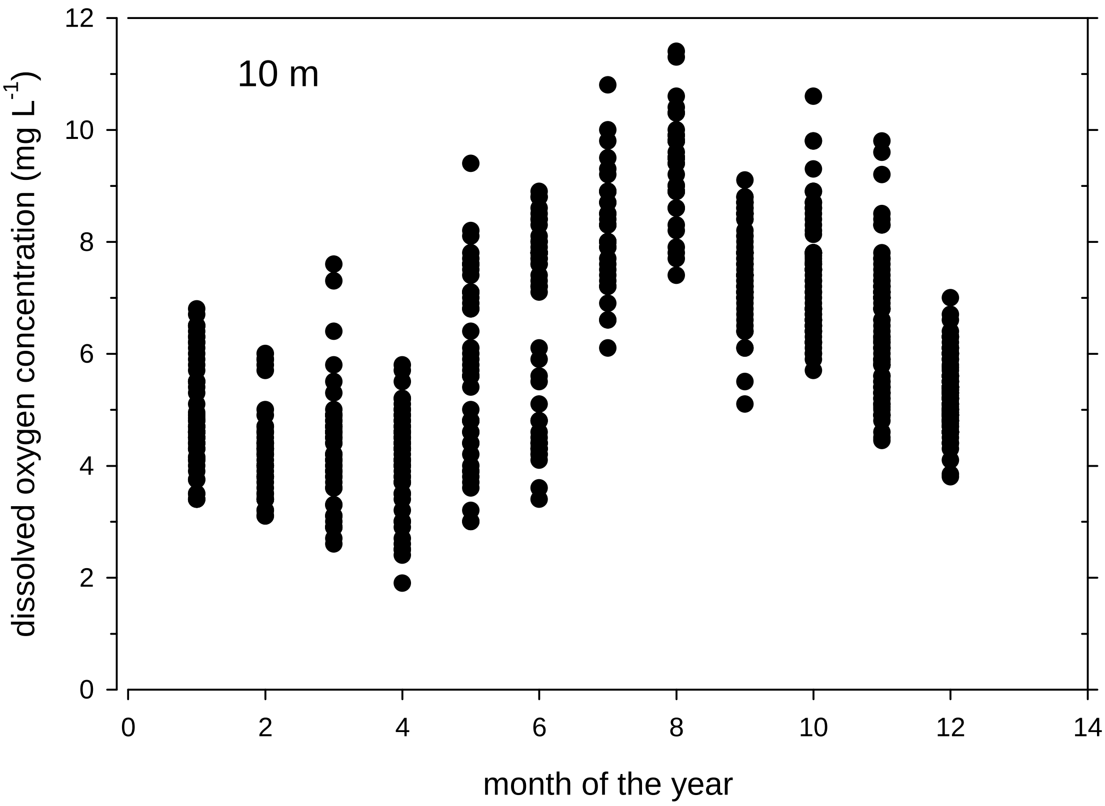
7 Appendix 1. Analysis of seasonal patterns in Dissolved Oxygen from Macquarie Harbour Middle South.

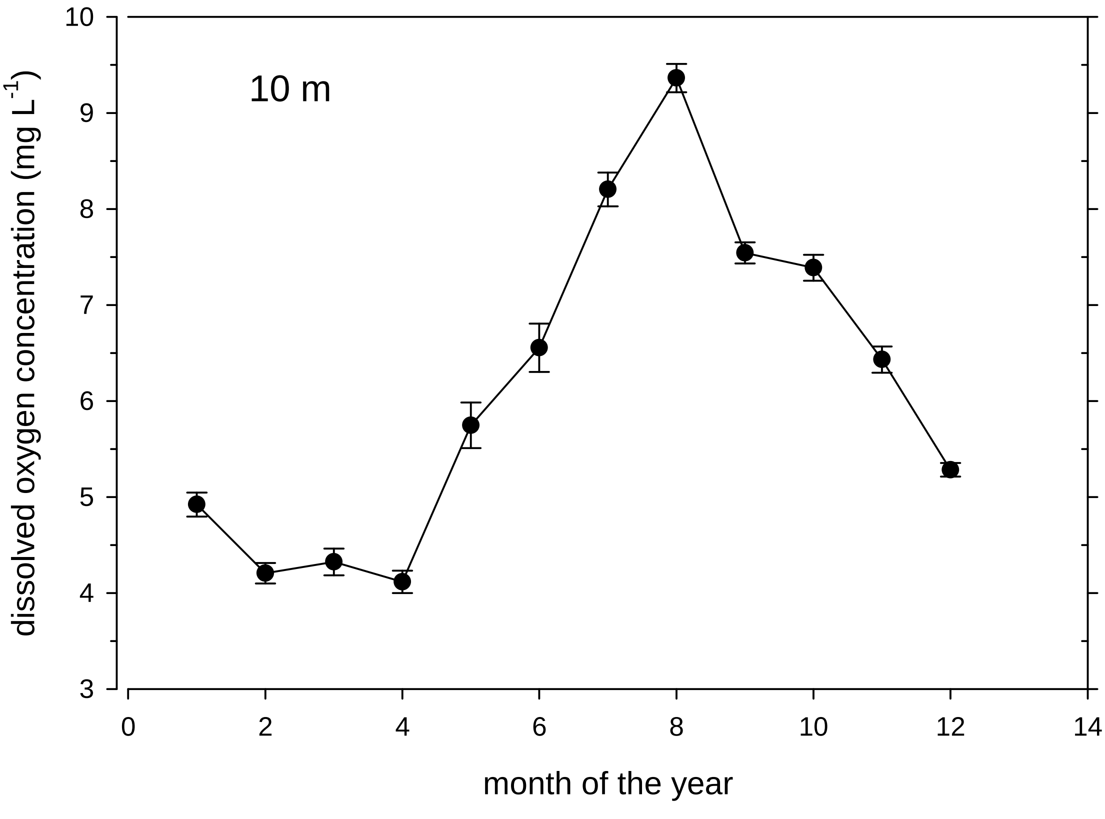


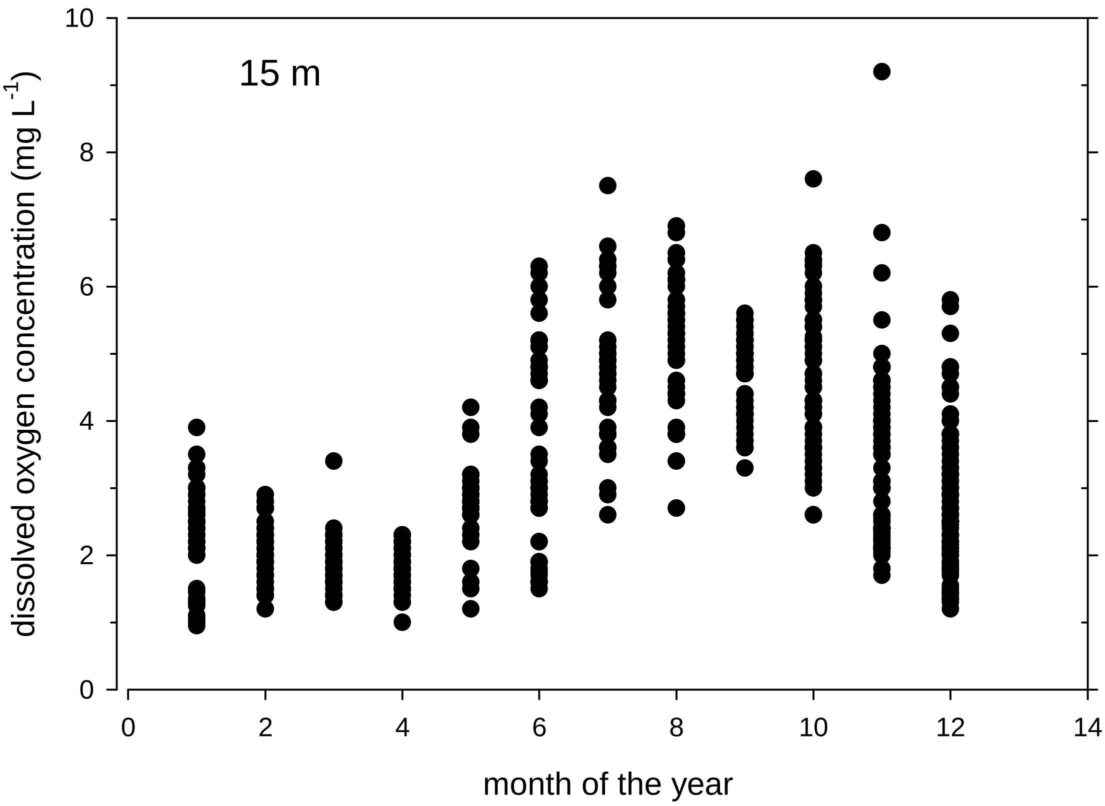


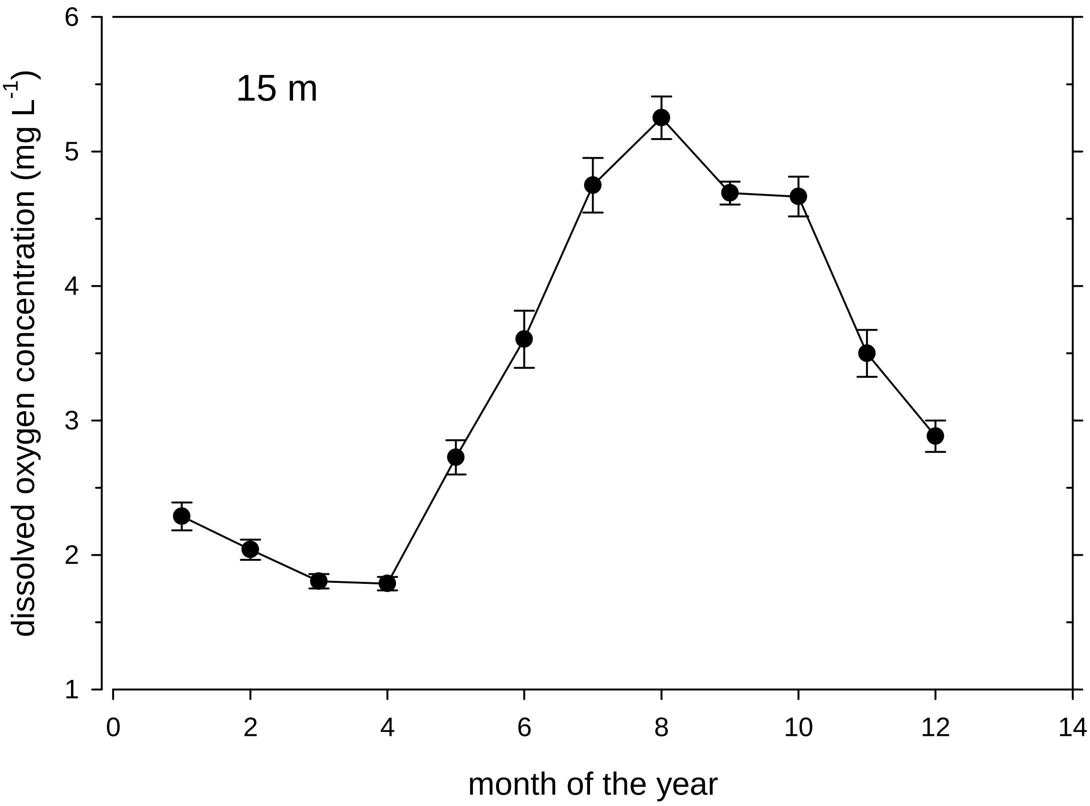

5 m
dissolved oxygen concentration (mg L-1)
month of the year
14
12
10
8
6
4
0
2
4
6
8
10
12
14

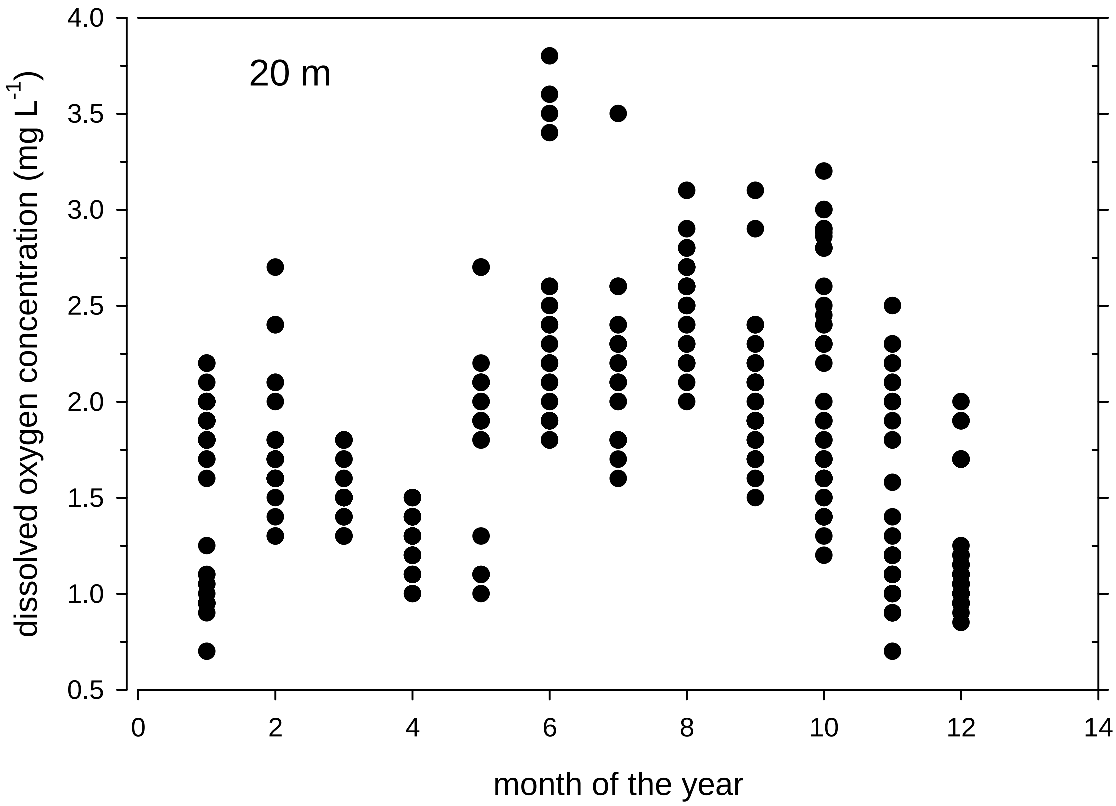

5 m
dissolved oxygen concentration (mg L-1)
month of the year
12
11
10
9
8
7
0
2
4
6
8
10
12
14

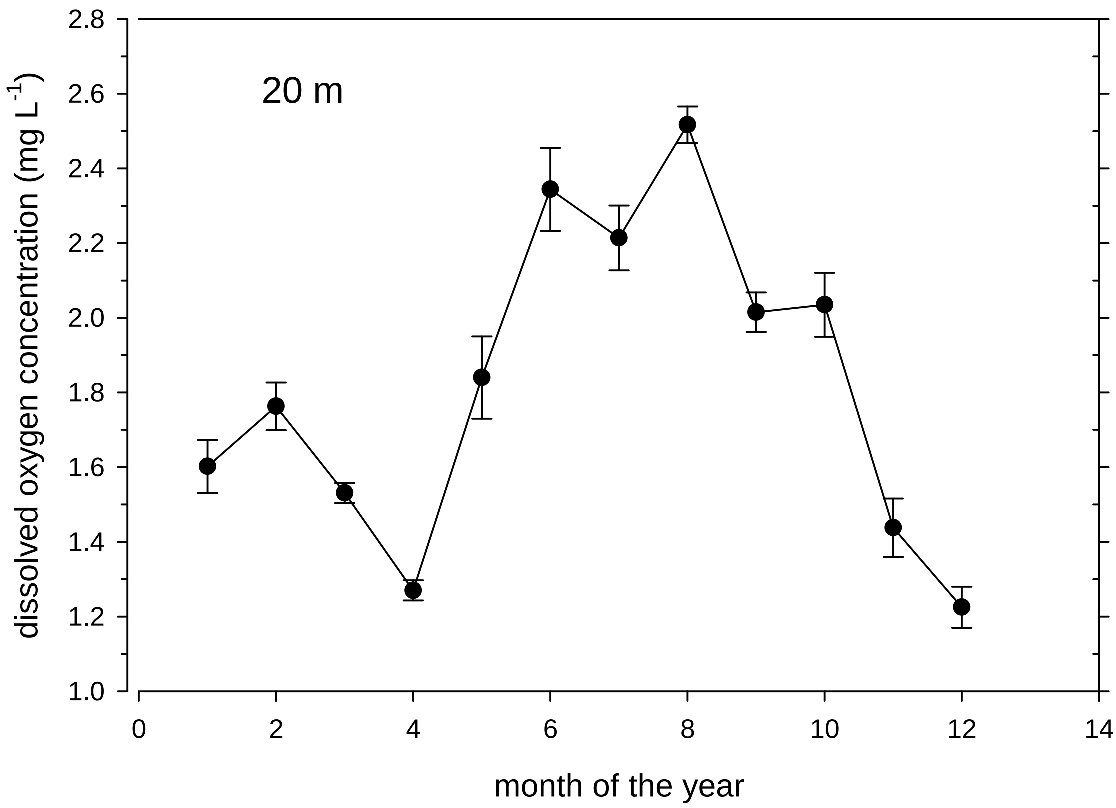

10 m
dissolved oxygen concentration (mg L-1)
month of the year
0
2
4
6
8
10
12
14

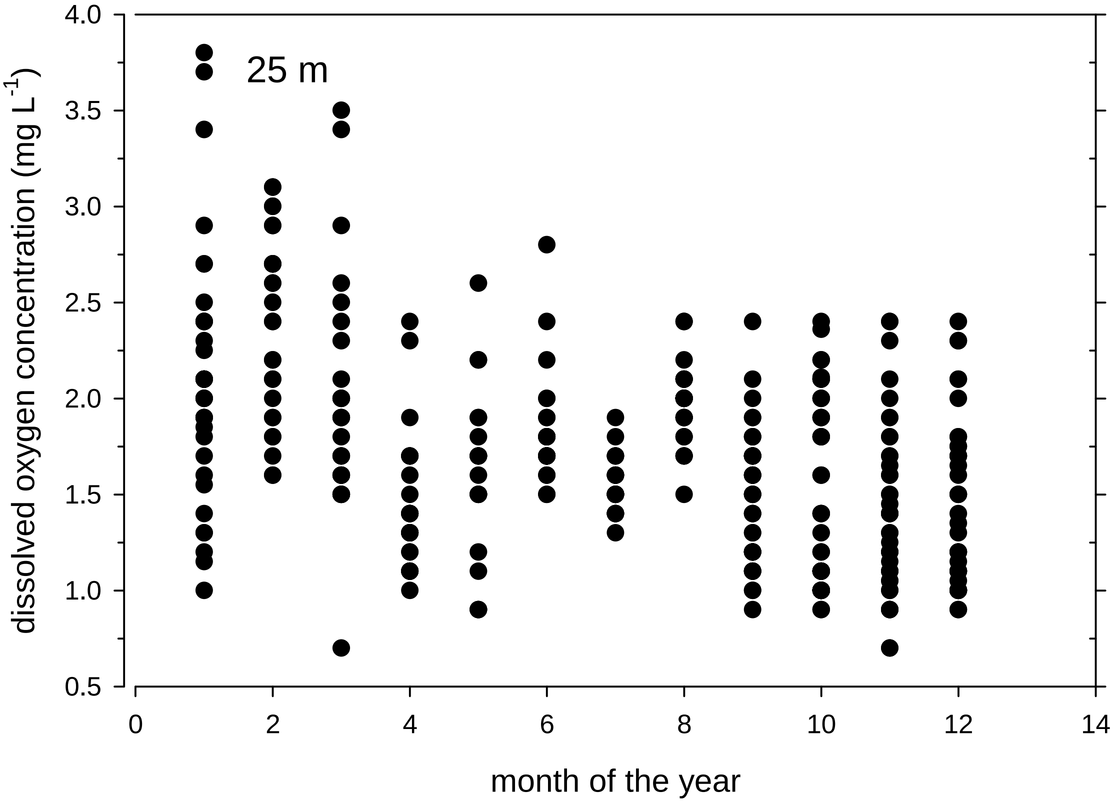

10 m
dissolved oxygen concentration (mg L-1)
month of the year
3
4
5
6
7
8
9
10
0
2
4
6
8
10
12
14

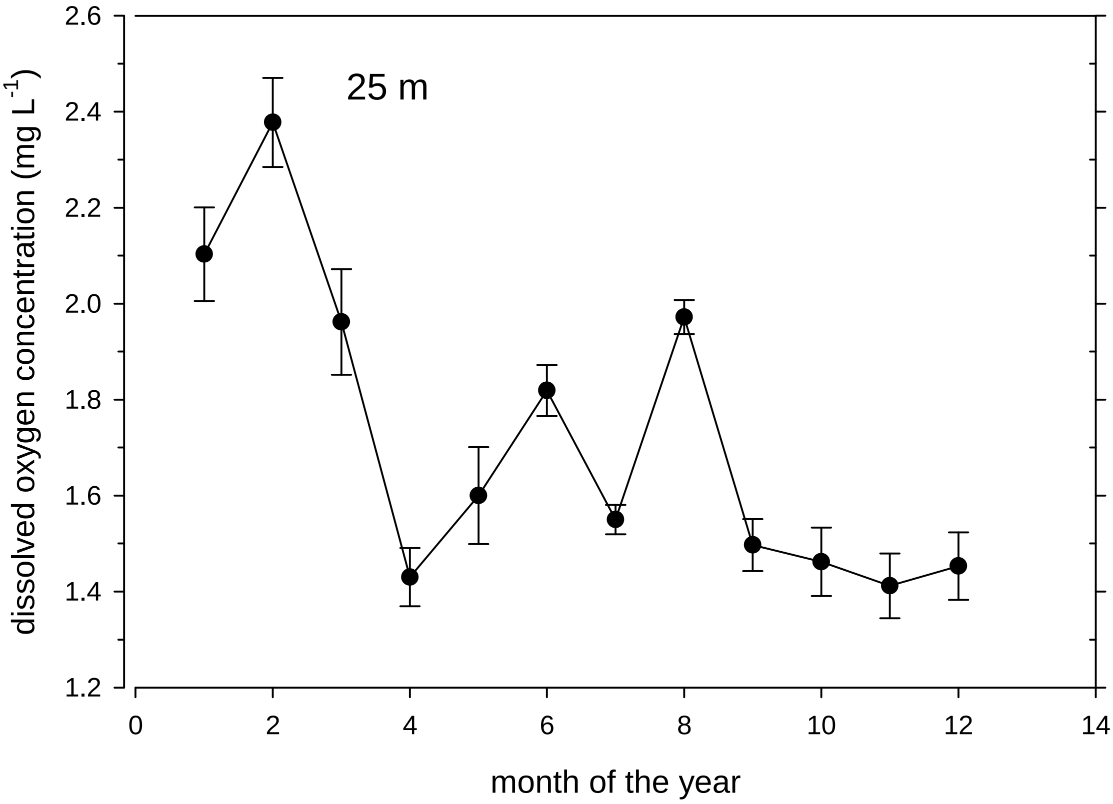

15 m
dissolved oxygen concentration (mg L-1)
month of the year

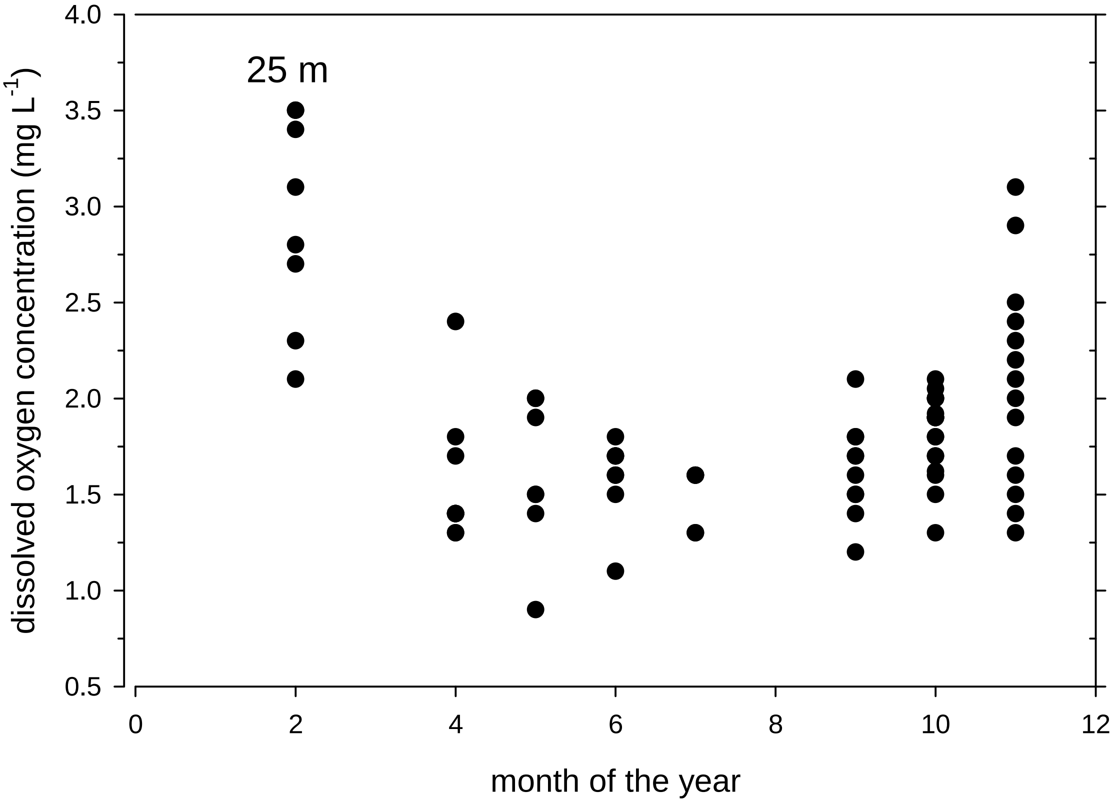

15 m
dissolved oxygen concentration (mg L-1)
month of the year

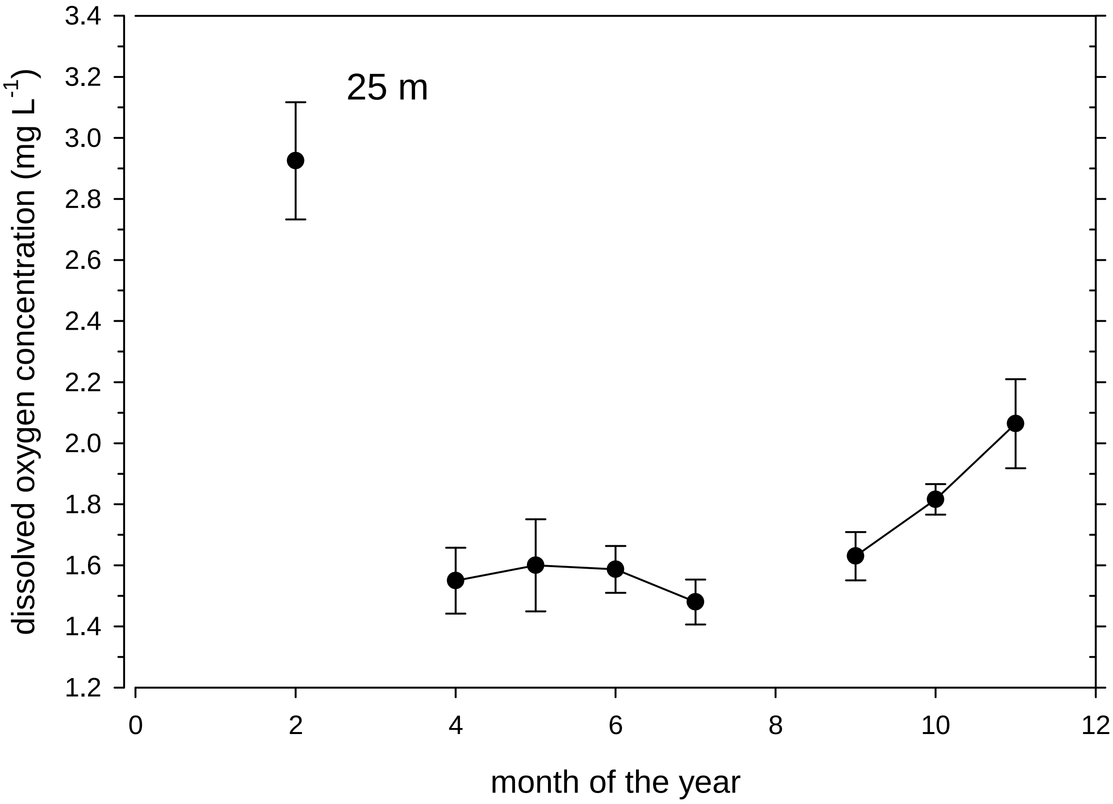

20 m
dissolved oxygen concentration (mg L-1)
month of the year


20 m
dissolved oxygen concentration (mg L-1)
month of the year


25 m
dissolved oxygen concentration (mg L-1)
month of the year
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
2
4
6
8
10
12
14


25 m
dissolved oxygen concentration (mg L-1)
month of the year
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
0
2
4
6
8
10
12
14


25 m
dissolved oxygen concentration (mg L-1)
month of the year


25 m
dissolved oxygen concentration (mg L-1)
month of the year

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