Environmental Research in Macquarie Harbour

FRDC 2016/067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour

PROGRESS REPORT

Approved by the Project Steering Committee and FRDC on 3/10/2017

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September 2017

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EXECUTIVE SUMMARY

This report provides an update on the status of dissolved oxygen and benthic conditions in Macquarie Harbour. It follows on from the results reported in the IMAS reports released in January and May 2017 which described the deterioration of benthic and water column conditions in Macquarie Harbour in spring 2016 and subsequent observations in early 2017, respectively. This report presents the results and preliminary interpretation of dissolved oxygen (DO) monitoring data up until the end of August 2017, a repeat survey of benthic communities in May/June 2017 and findings from CSIRO's oxygen tracer modelling. This work is part of the research project (FRDC Project 2016-067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie Harbour to address these needs) funded by the Fisheries Research Development Corporation with the support of both industry and government (EPA and DPIPWE).

The replenishment of the deeper bottom waters reported in late 2016 and early 2017 has continued through spring and winter 2017, albeit intermittently. These oxygen recharge events were most evident at the sensor string deployed closest to the harbour entrance and in the deeper bottom waters at the Strahan monitoring site. There was also evidence of an increase in DO in the bottom waters at the Franklin site in the south of the harbour, but the influence of the DO recharge was clearly reduced with distance from the harbour entrance. DO levels were typically < 20% saturation at depths below 20m at the new string deployed in the World Heritage Area. Although there would appear to have been some improvement in the DO levels in the middle of the water column (i.e. between 20 - 30m depth), oxygen levels in this part of the water column still remain low. This is most pronounced at the monitoring sites furthest from the harbour entrance, with DO levels approaching 10% saturation in the mid-waters at the Franklin and World Heritage Area monitoring sites. It is also clear from the latest DO observations that bottom water concentrations are once again decreasing with the onset of spring and as a consequence there is still potential for DO concentrations to return to critically low levels.

In the January 2017 benthic survey there was little change in either the abundance or number of species of benthic fauna compared with the observations in October 2016. The results of the May 2017 survey showed some recovery in the number of species recorded at all four of our longer term study leases. This recovery was also evident in the faunal abundance data. However, the magnitude of recovery varied between leases; the faunal abundance at study leases 1 and 4 were consistent with levels observed prior to the faunal decline observed in October 2016, whilst leases 1 and 3 appear to have recovered to some extent, but not yet to levels equivalent to those prior to the faunal decline. At the external sites (> 1km from leases) the number of species and faunal abundance remained similar to those reported in previous surveys. Species numbers were generally greatest in the shallower regions of the harbour compared to the deeper central region. The decline in faunal abundance was most pronounced in the deeper central region of the harbour. The lowest faunal abundance and diversity (number of species) were observed in late 2016. At many sites, faunal abundance and species number had either increased in May 2017, or was consistent with historical observations. However, it is again important to note that DO levels in bottom waters are decreasing with the onset of spring and consequently the results from the next survey, in October 2017, will be critical to determine whether the system has really recovered since late last year.

The October 2016 and January 2017 videos clearly showed an increase in the prevalence of *Beggiatoa* around the leases compared with previous surveys. However, in the May 2017 survey *Beggiatoa* cover had declined at both lease and external sites. Over this period there was also an increase in the presence of Dorvilleid polychaetes at the lease sites relative to the previous two surveys. This would tend to suggest improved oxygen conditions on the seabed, and is consistent with the observed increases in faunal abundance and diversity (species number) observed in the May 2017 which also suggest a level of recovery relative to the previous two surveys.

The further development and application of the CSIRO hydrodynamic and oxygen tracer model will provide a greater understanding of the drivers and dynamics of low oxygen in the harbour. In this study the model continues to run in near real time and has been used to describe the three dimensional circulation within the harbour, the flushing rates of different water bodies (e.g. surface-, mid- and bottom -waters) and the seasonal influence of weather and river flow conditions on water column mixing and oxygen re-charge events. The model demonstrated that the primary mechanism for recharge of oxygen into the lower water column is oceanic water flowing over the sill at Hells Gates, mixing with resident fresher water but remaining at sufficient density to descend the slope into the deeper basins. Under normal river flow, the model suggests that the incoming ocean water mixes and 'slides' under the fresh surface layer at about 10m depth; in the absence of river flow the incoming ocean water mixes less, descends further and is more widely dispersed. Further tracer studies showed that river water can be entrained into the subducting dense water, and that some river sourced oxygen is likely to refresh the deeper water. However, concentrations are much lower, than those originating from the ocean. The model suggests that oxygen recharge into the deeper harbour is most likely to occur when river flows are low, which is consistent with recent observations. The current model superficially accounted for benthic-pelagic oxygen demand; further development of the model to more accurately determine the various contributions of biogeochemical processes to the oxygen dynamic is recommended.

Finally, as we highlighted in the previous reports DO levels appear to be a major determinant of benthic condition, and low DO levels are almost certainly responsible for the deterioration witnessed in spring 2016. Although the signs of recovery in the benthic fauna observed in the May survey are encouraging, the results of the next survey in October will reveal how far the system has actually recovered in the last 12 months. Having said this, it is important to remember that the mid water DO levels still remain very low and the bottom water oxygen levels are decreasing with the onset of spring and as such there is still the capacity for DO levels to return to critically low levels.

BACKGROUND

In light of deteriorating benthic conditions in Macquarie Harbour, and in particular the very low dissolved oxygen (DO) levels observed in the middle and bottom waters in spring 2016, the Institute for Marine and Antarctic Studies (IMAS) prepared a report for the Environment Protection Authority (EPA) and Department of Primary Industries, Parks, Water and Environment (DPIPWE) on the science and current status of the benthic and water column environments in Macquarie Harbour (Ross & Macleod 2017a). That report summarised the environmental research and observations from Macquarie Harbour and presented the latest observations of the benthic ecology and water column conditions in the context of the collective information.

A key observation from that report was the major decline in the total abundance and number of species collected from the benthic fauna in the spring (October 2016) survey compared to previous surveys. The increase in *Beggiatoa* bacteria mats on the sediments in and around marine farming leases in the spring 2016 ROV compliance surveys provided further evidence of deteriorating sediment conditions. This deterioration in sediment conditions was shown to coincide with very low DO levels in bottom and mid waters of the harbour. However, the decline in benthic fauna and DO (bottom and mid water) was not uniform through the harbour. The lowest levels of DO and the greatest changes in fauna occurred at sites in the mid- and southern end of the harbour, with the sites closer to the Harbour entrance and the ocean appearing to be less affected; this pattern was observed at both lease and external (harbour-wide) sites.

This review formed part of the information used by the EPA to support their decision to enforce fallowing of multiple cage sites across the harbour. A key challenge facing farmers and regulators is understanding and predicting the length of fallowing required for benthic recovery in this system specifically. This also has major implications for future stocking plans in the harbour. It is clear that DO levels have been, and will be, a major determinant of the benthic response over the coming months and years. As such, there is a clear need to better understand the drivers of oxygen dynamics, the influence of DO levels on benthic conditions and the effectiveness and duration of fallowing and remediation strategies. With a strong commitment from both industry and government, the Fisheries Research Development Corporation (FRDC) funded project FRDC 2016-067: Understanding oxygen dynamics and the importance for benthic recovery in Macquarie

Harbour to address these needs. This information is essential for both operational management of farming activities and the sustainable management of the harbour over the longer term.

FRDC 2016-067 comprises three work packages that together will provide a much clearer understanding of both the effectiveness of fallowing and passive remediation for benthic recovery and the drivers and importance of oxygen dynamics for recovery. Work package 1 (WP1) will assess benthic recovery over time, building on the 6 previous surveys, which documented benthic conditions up until the major decline in faunal abundance and diversity observed in October 2016, with repeat surveys of all lease and external sites every 4 months. Work package 2 (WP2) will see the further development of the real time dissolved oxygen observation network in the harbour. This includes deployment of i) three vertical strings of acoustic (real-time) DO sensors in the central region of the harbour, ii) a profiling mooring located at the deepest part of the main basin and iii) two additional logger strings (not real-time) to extend the observation network further south (inside the WHA) and north (close to the entrance to the ocean). The third work package (WP3) involves the further development of the CSIRO Near Real Time (NRT) Hydrodynamic and Oxygen Transport model to better describe the physical drivers of Macquarie Harbour circulation, stratification, mixing and DO drawdown and recharge.

In May 2017 we provided the first progress report from this project with a focus on work packages 1 and 2 (benthic and water column observations). In this report we provide an update on the benthic and water column conditions, and describe the development and findings from the CSIRO Near Real Time (NRT) Hydrodynamic and Oxygen Transport model

WATER COLUMN CONDITION

In Ross & MacLeod (2017a) we provided an overview of DO observations in the harbour since the early 1990s and outlined the steady decline observed in bottom and mid-waters since 2009 (Figure 1). In spring 2016 DO levels were extremely low throughout the harbour; in fact the lowest on record. Whilst a range of independent data sets confirmed this observation the Sense-T environmental strings provided the most detail on the evolution of these DO levels through the centre of the harbour. These strings provided real time data on DO and temperature changes throughout the water column at 3 farm sites along the centre of the harbour; Table Head Central closest to the influence of the ocean, Franklin near the boundary of the World Heritage Area (WHA), and Strahan, a site midway between the two (Figure 2). These three strings were refurbished and updated with the latest technology in early June 2017 and the observation network extended further south and north, with additional delayed mode data loggers deployed on a string inside the WHA to the south and on a string in the King River Basin in the north (see Figure 2). These additional strings provide important insight into the influence of boundary conditions (e.g. Gordon River and the ocean).

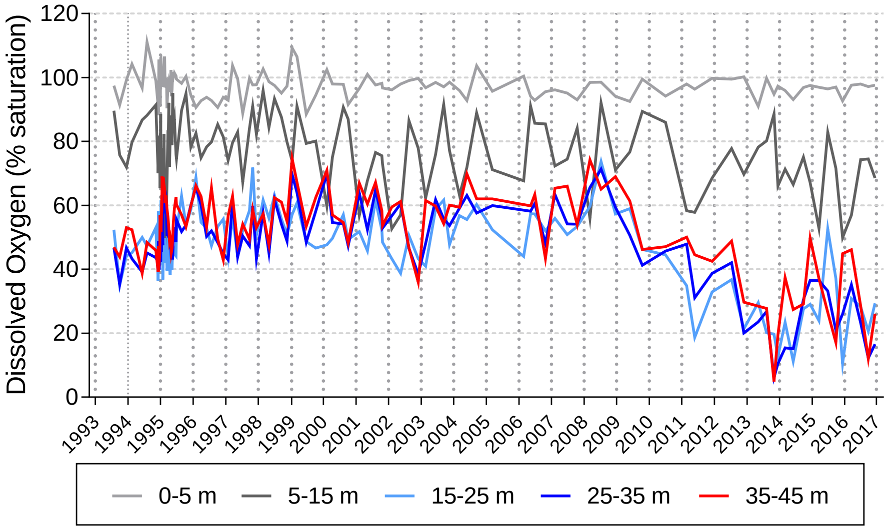

Figure 1 Long term trend in DO within a number of depth ranges at EPA site 12 (updated from MHDOWG 2014).

Figure 2 Map of Macquarie harbour showing location of the environmental strings. The yellow sites provide data in near real time and the red sites use delayed mode data loggers. The CSIRO profiling mooring is directly adjacent to the Strahan environmental string.

The contour plots produced from these strings have been updated to include data up until the end of August 2017 (Figure 3). These figures again demonstrate the particularly low DO levels that were reached at depths below 20m from the middle of 2016. They also show the differences depending on the location in the harbour; with DO levels reaching lower levels sooner at the southern end of the harbour (i.e. Franklin string site) as a result of both the increased distance from the oceanic influence and longer residence times. From late 2016 and through autumn and winter 2017 periodic recharges to the deeper bottom water oxygen were apparent. This is most obvious at the Strahan site where the environmental string measures oxygen in a deeper area in the middle of the harbour, but can also be seen at the new string deployed in the King River Basin. Being in the upper region of the harbour this string is closer to where oxygenated ocean water penetrates into the harbour. For the June – August period (shown in detail in Figure 4 for all 5 environmental strings) recharge of bottom water oxygen levels is evident at both of these sites in early June and August. This highlights the fact that the more stable and persistent low DO levels in the mid waters extend to greater depths and lower levels with increasing distance from the ocean.

Overall, DO levels do appear to be better than observed this time last year, but mid water DO levels remain very low and bottom water levels are decreasing with the onset of spring (i.e. see Figure 5 for DO plots updated to September 28). Therefore, there is still the capacity for DO concentrations to return to critically low levels, particularly moving further south along the harbour.

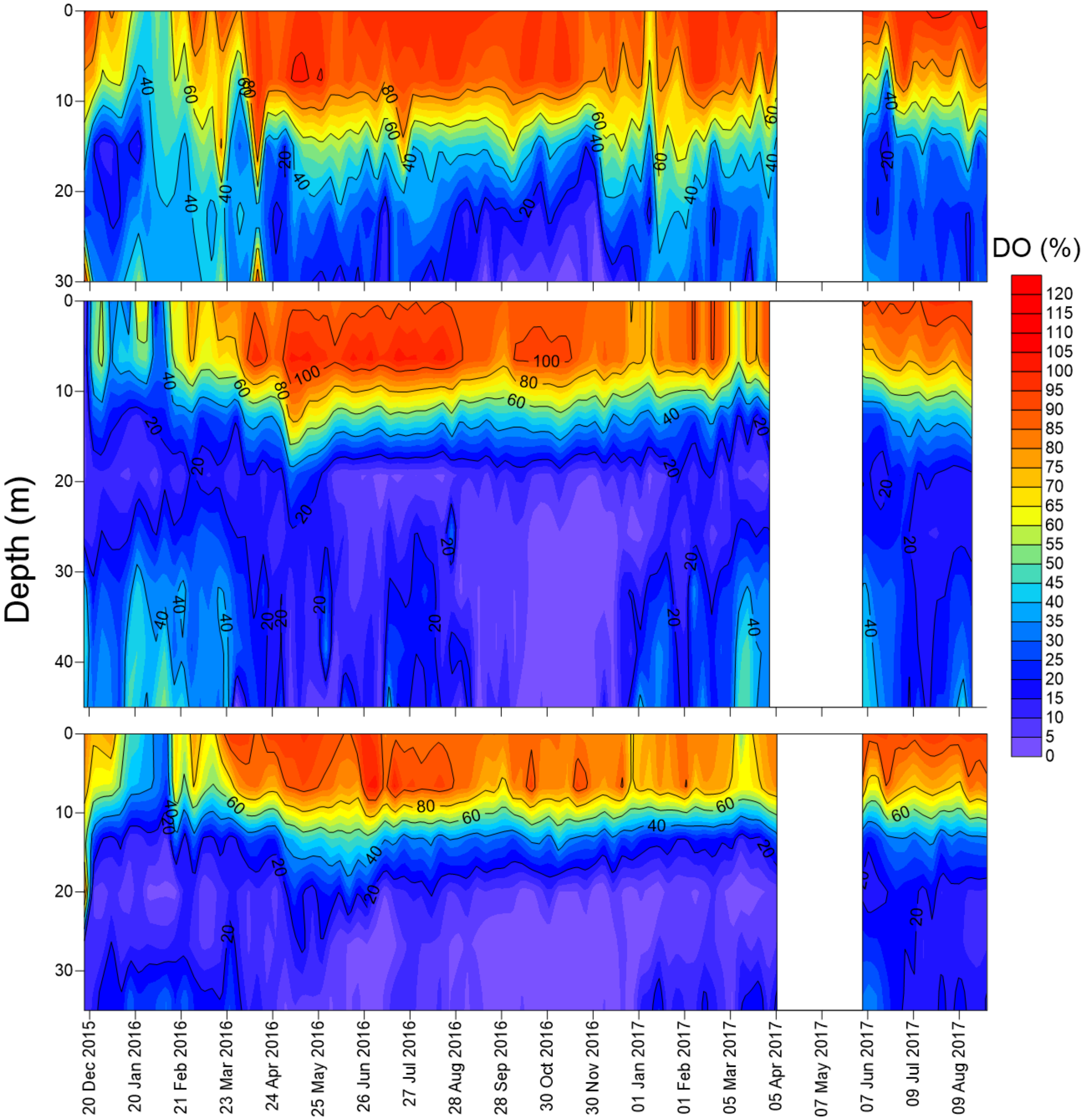

Figure 3 Contour plots showing DO profiles through the water column from the environmental strings at Table Head Central (top panel), Strahan (middle panel) and Franklin (bottom panel) over the period from December 2015 to the end of August 2017. Note, the data that underpins these plots for the period Dec 2015 to April 2017 is from the environmental sensors deployed under the Sense-T project. The sensors and associated infrastructure were replaced and updated in June 2017 as part FRDC project (FRDC 2016-067).

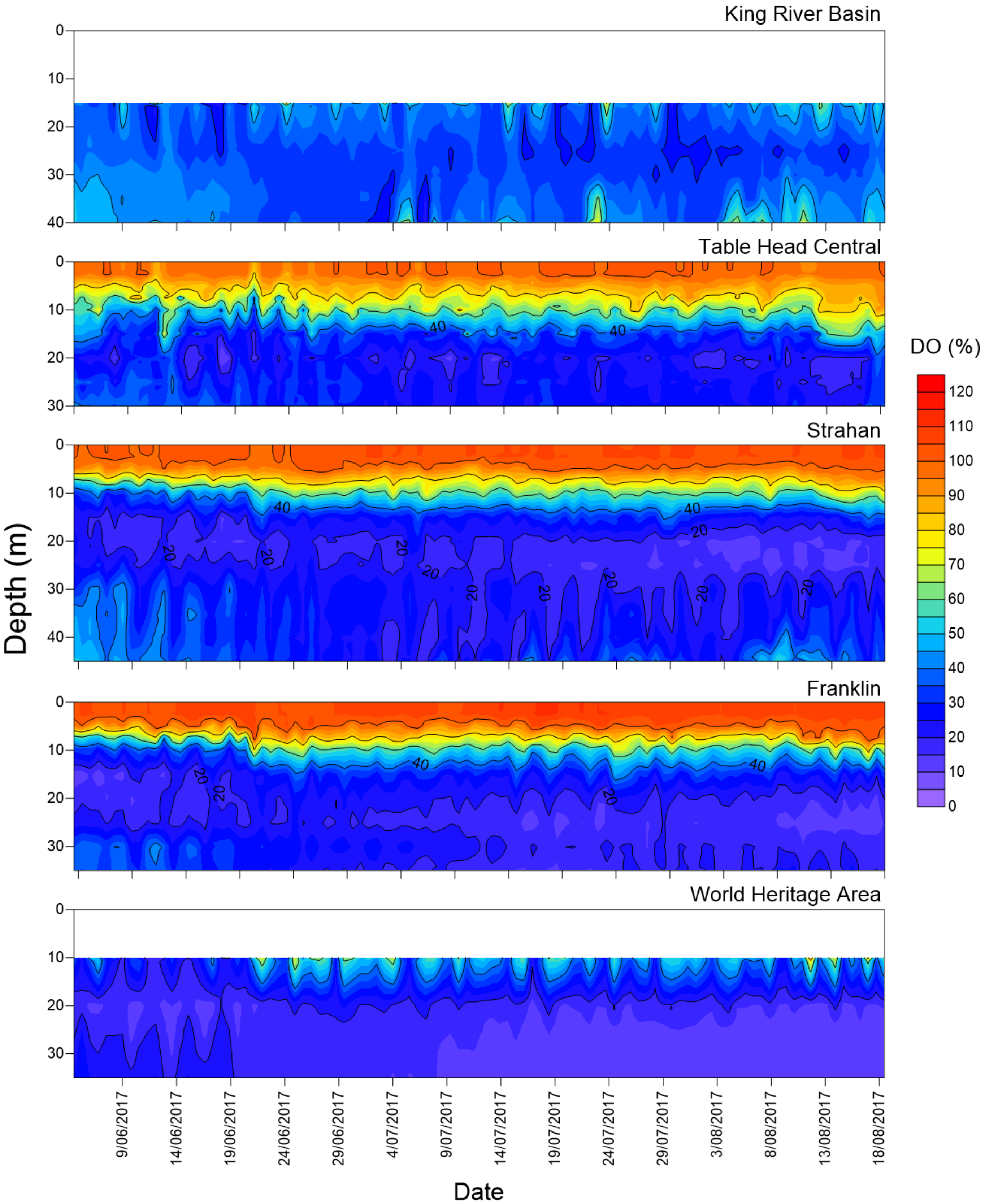

Figure 4 Contour plots showing DO profiles through the water column from the environmental strings at King River Basin, Table Head Central, Strahan, Franklin and the World Heritage Area over the period from the beginning of June 2017 to the end of August 2017. This represents the data from the upgrade to the three near real time strings and the two additional strings deployed as of part FRDC project (FRDC 2016-067). Note, the two additional strings don't measure to the surface because they are in high traffic waters.

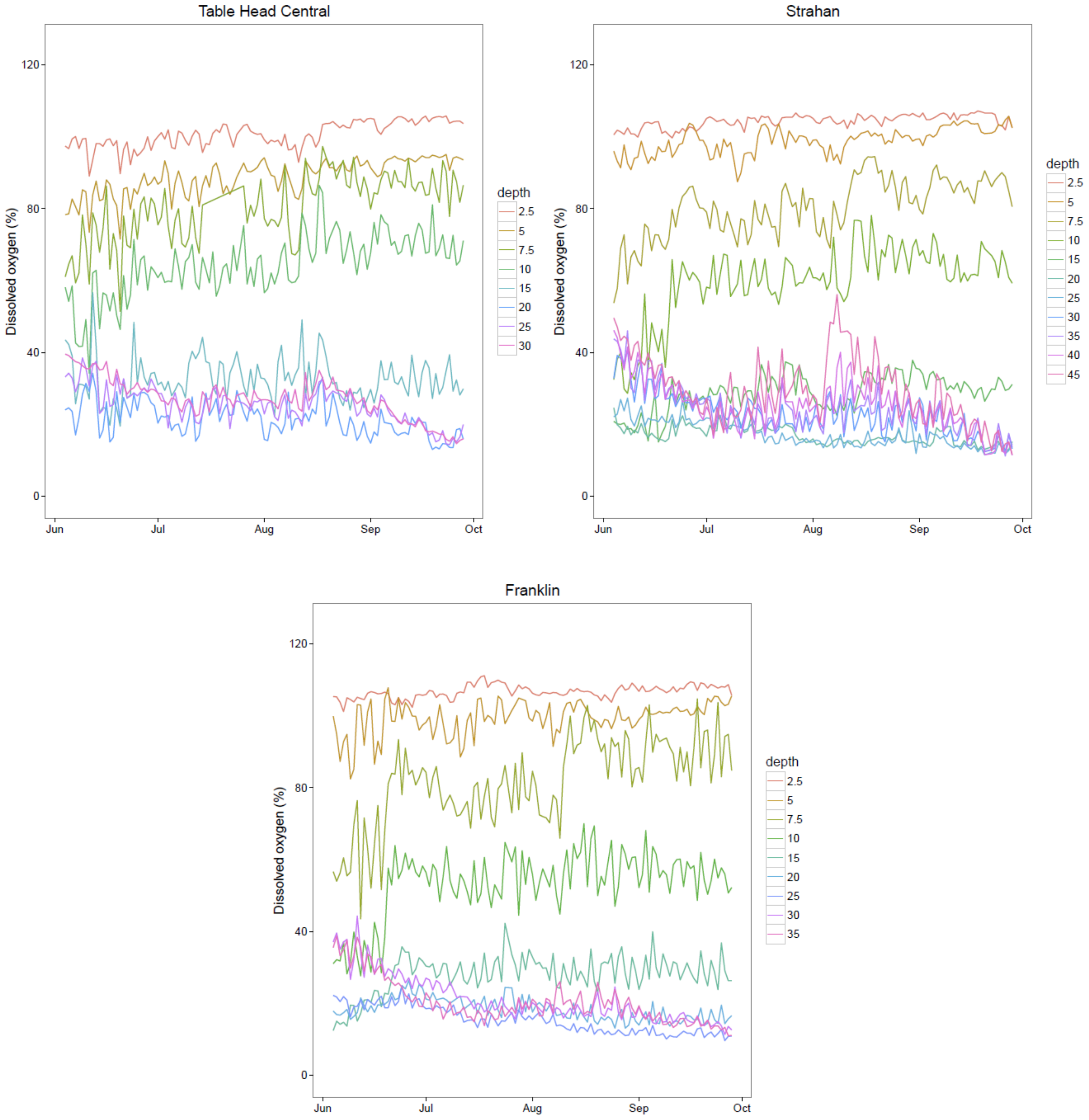

Figure 5 Daily mean DO (% saturation) levels at sensor depths from strings at Table Head Central, Franklin and the World Heritage Area over the period from the beginning of June 2017 to the 28th of September 2017.

BENTHIC CONDITION

In mid-2017, IMAS conducted a benthic survey of 5 leases and 24 external sites as part of FRDC 2016-067 (Figure 6, Table 1). This represents the 8th benthic survey conducted under consecutive FRDC projects (FRDC 2014-038, FRDC 2015-024, FRDC 2016-067) since the beginning of 2015. The work was initiated (via. FRDC 2014-038) when video footage identified an increase in abundance of Dorvilleid polychaetes. In addition, it was noted that there were two Dorvilleid species in the video footage and given that these species were used as indicators of enrichment it was felt that it was important to understand the distinction between these two species and whether their environmental responses were comparable. FRDC 2014-038 identified four sites (leases) for assessment. FRDC 2015-024 was commissioned to review the effectiveness of current monitoring protocols in new farming areas (i.e. Macquarie Harbour and Storm Bay in Southern Tasmania), and undertook a broader suite of sampling at the same sites (leases) employed in project 2014-

038. The major decline in the abundance and number of species of benthic fauna observed in October 2016 was the final survey of the Macquarie Harbour component of FRDC 2015-024 but it was felt that it was important to extend the research to assess benthic recovery and the effectiveness of fallowing, and as such FRDC 2016-067 was initiated. FRDC 2016-067 extended the benthic sampling to include an additional lease (lease 5) and more external sites[1].

Table 1 Benthic survey details

Survey	Survey period	Reference in report	Study
1	6/1/2015 - 30/01/2015	January 2015	FRDC 2014-038
2	25/5/2016 - 4/06/2016	May 2015	FRDC 2015-024
3	8/9/15 - 18/9/2015	September 2015	FRDC 2015-024
4	9/2/2016 - 18-2-2016	February 2016	FRDC 2015-024
5	31/5/2016 - 21/06/2016	June 2016	FRDC 2015-024
6	11/10/2016 - 3/11/2016	October 2016	FRDC 2015-024
7	17/1/2017 - 16/2/2017	January 2017	FRDC 2016-067
8	16/5/2017 - 7/6/2017	May 2017	FRDC 2016-067

The first survey of FRDC 2016-67 in early 2017 (January 2017) found no obvious change (i.e. neither improvement nor deterioration) in the abundance and number of species of benthic fauna since the October 2016 survey, with the exception of lease 3 where there was a further decline (Ross and MacLeod 2017b). In the May survey we have observed an increase in the total abundance and number of species collected from the benthic fauna relative to the previous two surveys at both lease and external sites.

At lease 4, the most northern of the study leases, both total abundance and the number of species have increased at all distances, and now sit within the range recorded prior to the decline observed in late 2016 (Figure 7). Dissolved oxygen levels recorded on the bottom during the May survey were also more typical of the levels recorded previously. At lease 3, a further decline in total abundance and number of species was observed between the October 2016 and January 2017 survey, however in the latest survey in May, both total abundance and the number of species have increased, most notably at the sites 50m or more from the cages (Figure 8). Whilst abundance hasn't reached some of the peaks observed at the intermediate distances in previous surveys, the number of species (and identity) are comparable to that recorded prior to the October 2016 decline. Similarly, bottom water oxygen levels at the time of the survey were more typical of the levels recorded previously. At lease 2, both total abundance and the number of species have increased at all distances, and now sit within the range recorded prior to the decline observed in late 2016 (Figure 9). At this lease, peak abundance occurs directly adjacent to the cages, indicating that sediment conditions within the lease boundaries are relatively good. Dissolved oxygen levels recorded on the bottom during the May survey were also more typical of the levels recorded previously.

Lease 1, which is the most southern lease in the harbour where both abundance and the number of species was observed to have declined the most (of the 4 study leases) in October 2016, has also seen the early stages of faunal recovery (Figure 10), albeit to a lesser extent than the aforementioned leases. In the first 5 surveys (Jan 15 – June 2016) at lease 1 there was an average of ~556 individuals per m^2 and ~4 species per grab; this declined to an average of less than 1 individual per m^2 and 1 species per grab in surveys 6 and 7 (Oct 16 and Jan 17). In survey 8 (May 17) we recorded ~160 individuals per m^2 and ~3 species per grab. Similar to the other leases, DO

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[1] All external sites are at least 1km from active leases and allow comparison of benthic changes in the harbour as a whole alongside changes associated with farming, and provide a means to assess temporal changes in benthic ecology.

levels measured during the latest faunal survey were more typical of the levels recorded previously at this lease. Lease 5 was sampled for the first time in the January 2017 survey and the distinct differences between the two transects were noted, with lower abundances and species numbers on the deeper NW transect. In May this pattern remained (Figure 11); the sites from 0 to 100m on the NW transect were relatively depauperate, typical of highly enriched sediments, and the dorvilleid *Schistomeringos loveni* was the dominant species from 100-500m, reaching peak abundances at 250 and 500m. In the May survey, the increase in abundance at 250-500m relative to the January survey was predominately due to greater numbers of *Schistomeringos loveni* (see later discussion on the distribution of dorvilleids). Dissolved oxygen levels on the NW transect were similar at the time of sampling for both surveys, but lower on the SE transect in May relative to January.

As we have highlighted elsewhere in the report the results of the next benthic survey in October will reveal how far the system has actually recovered in the last 12 months. This survey will be at the same time of the year that oxygen levels reached their lowest levels last year and sediment conditions deteriorated.

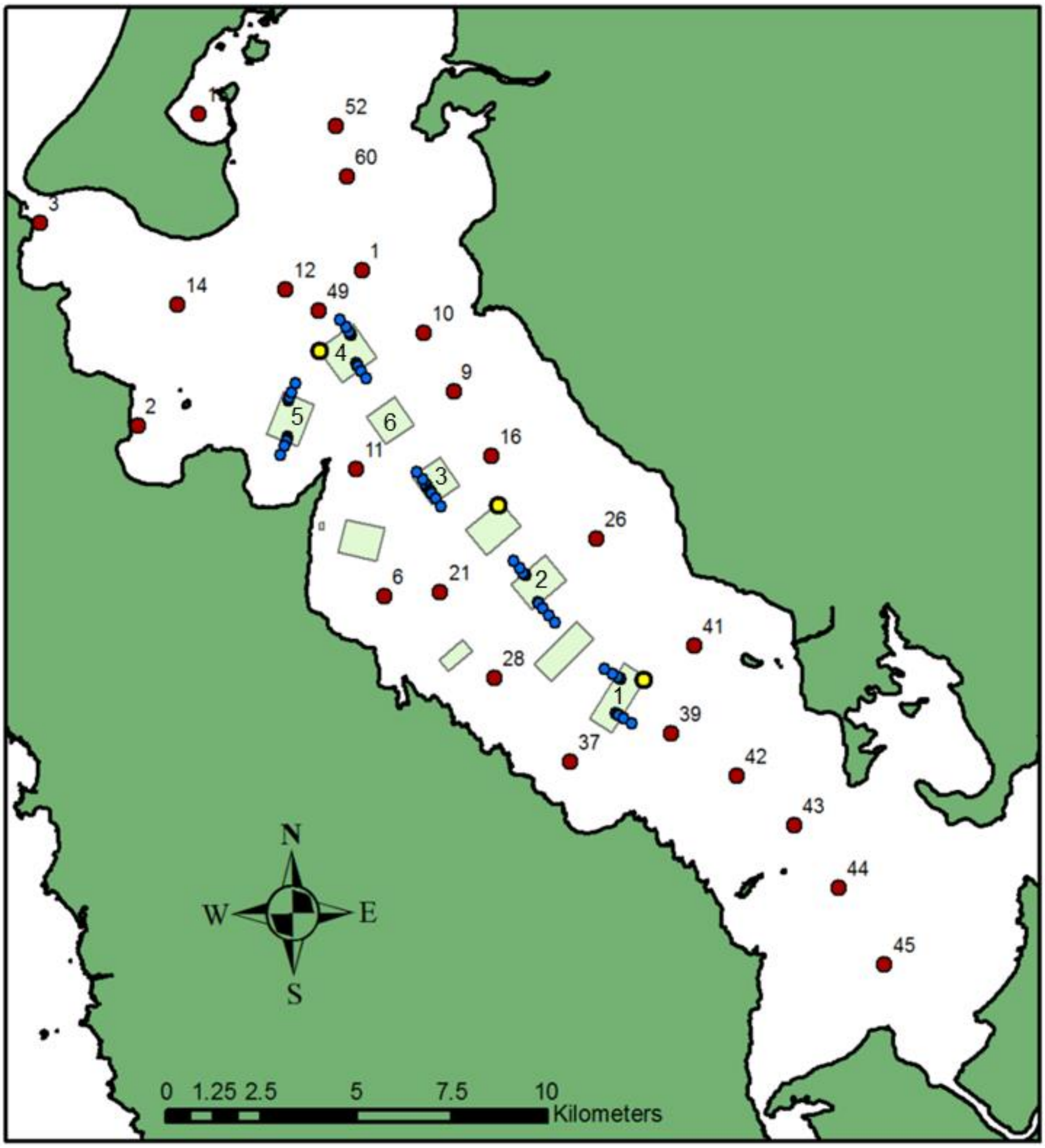

Figure 6 Maps showing external (red), lease (blue) and environmental string (yellow) sites. There are 2 transects from each of the study leases with five sites (at 0, 50, 100, 250 and 500m) on each transect.

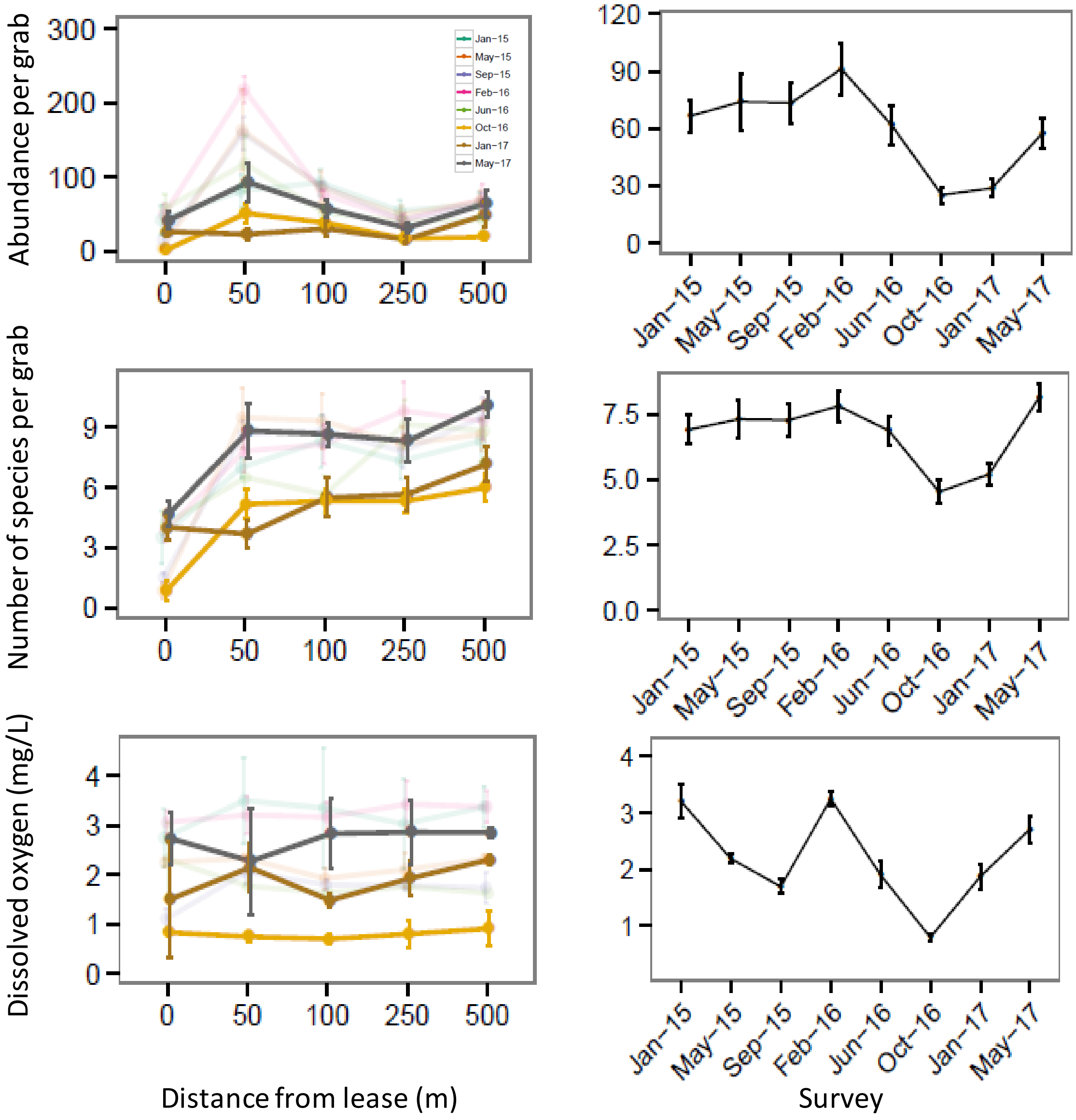

Figure 7 Lease 4 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m^2; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date (distances pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean from (±SE) the two transects and five distances. In the left hand panels the last 3 surveys have been emphasised to show the change since the decline in fauna and low oxygen levels observed in the October 2016 survey.

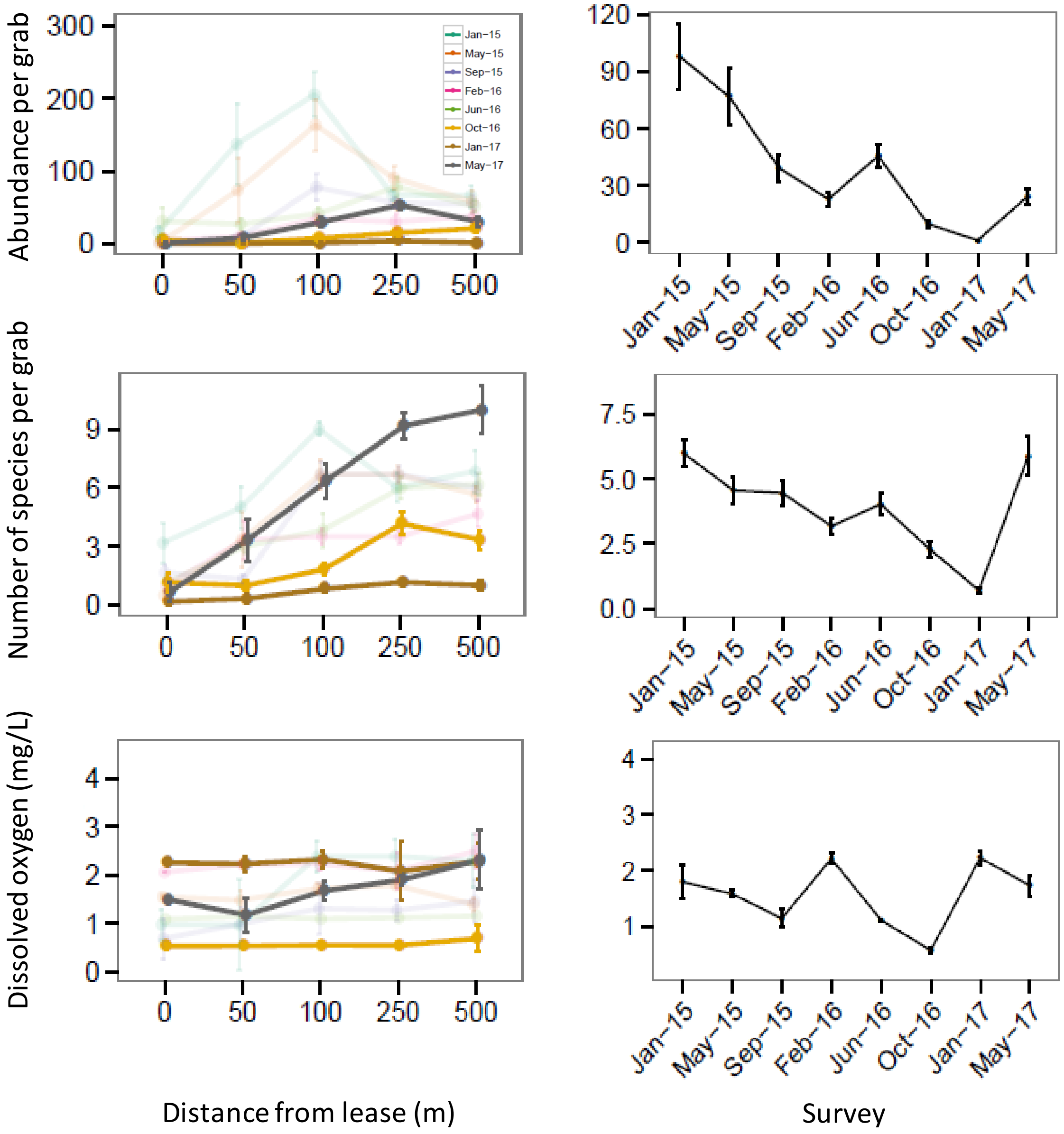

Figure 8 Lease 3 plots of total infaunal (>1mm) abundance (per grab = ~ $0.0675m^2$; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date (distances pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean from (±SE) the two transects and five distances. In the left hand panels the last 3 surveys have been emphasised to show the change since the decline in fauna and low oxygen levels observed in the October 2016 survey.

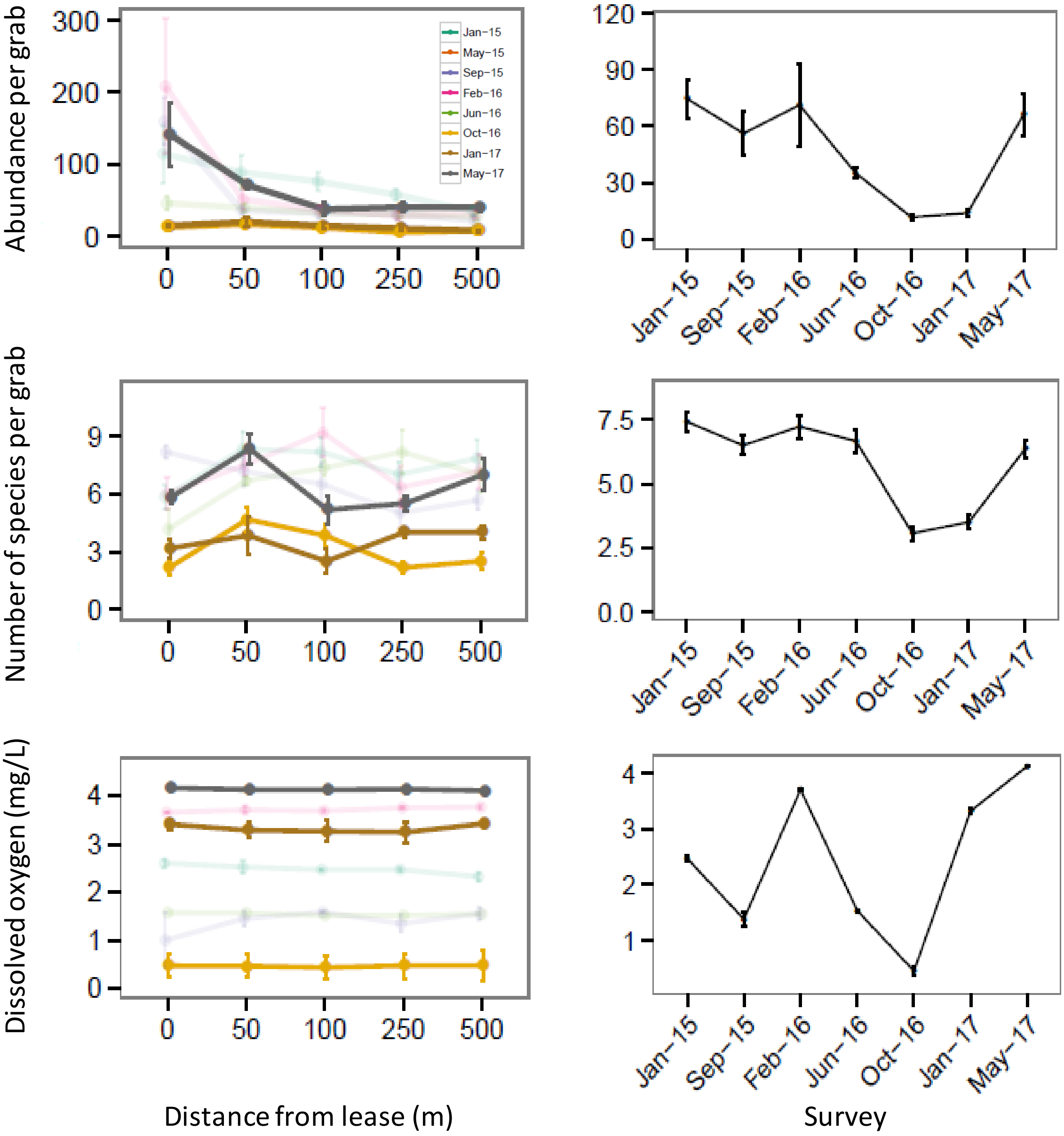

Figure 9 Lease 2 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date (distances pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean from (±SE) the two transects and five distances. In the left hand panels the last 3 surveys have been emphasised to show the change since the decline in fauna and low oxygen levels observed in the October 2016 survey. Note, lease 2 was not surveyed in May 2015.

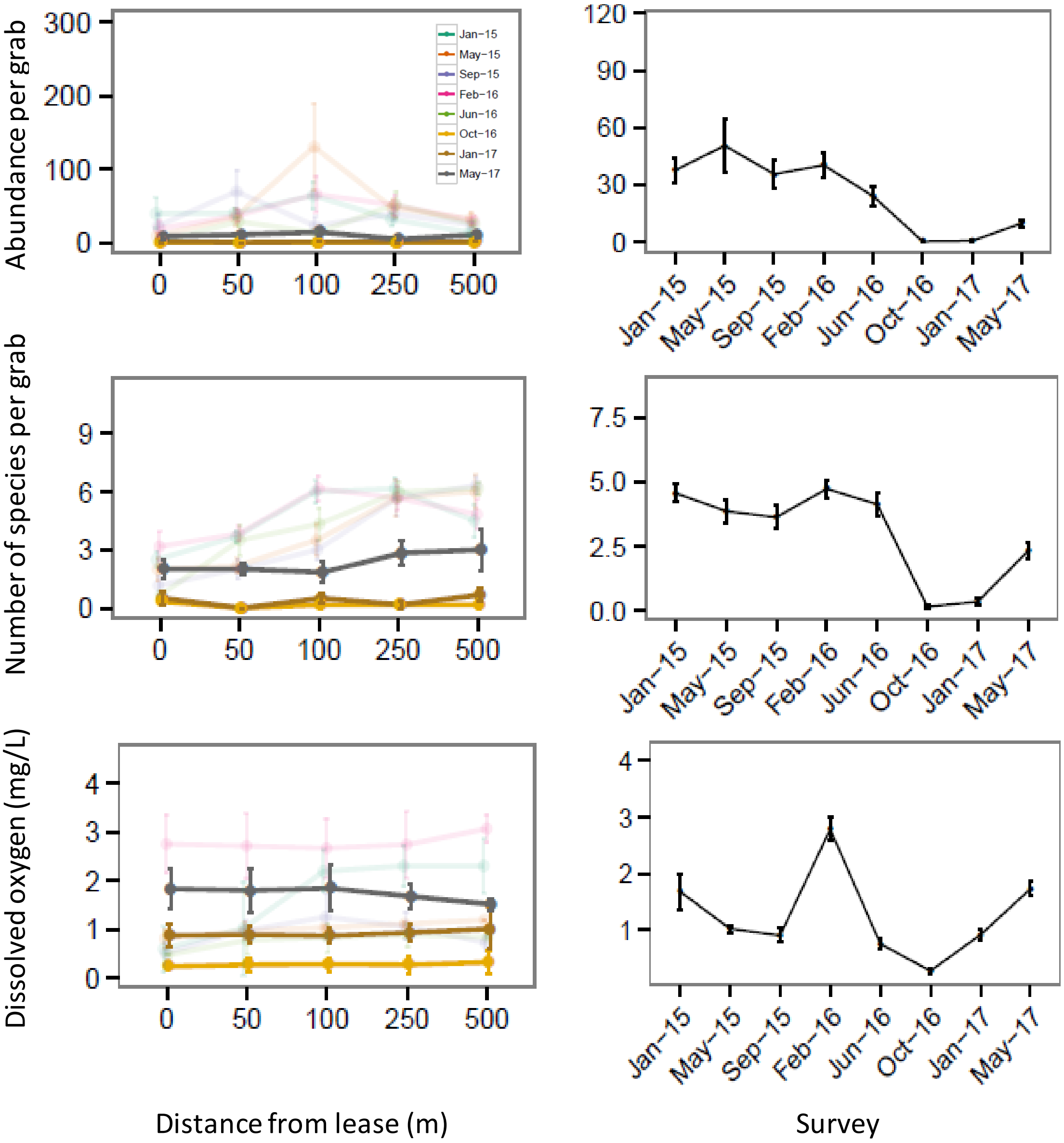

Figure 10 Lease 1 plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²; top panel), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (bottom panel) in relation to 1 (left panels): distance from the cage (0, 50, 100, 250 and 500m from cages) for each survey, and 2 (right panels) survey date (distances pooled). In the left hand panels the data represents the mean (±SE) from two transects that radiate out from cages on opposite sides of the lease, and in the right hand panels the data represents the mean from (±SE) the two transects and five distances. In the left hand panels the last 3 surveys have been emphasised to show the change since the decline in fauna and low oxygen levels observed in the October 2016 survey.

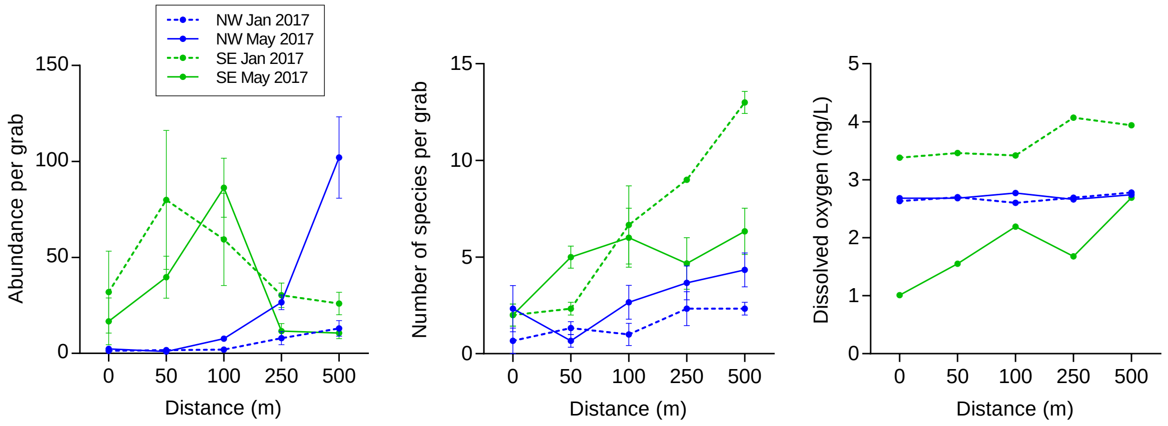

Figure 11 Plots of total infaunal (>1mm) abundance (per grab = ~ 0.0675m²), number of species collected in grabs (n=3; middle panel) and the dissolved oxygen (mg/L) overlying the bottom (at 0, 50, 100, 250 and 500m from cages at lease 5 during the January and May 2017 surveys. The data shows the mean (± SE) for the North-western (green line) and South-eastern (blue line) transects.

Harbour wide change

The surveys undertaken since January 2015 included a number of additional external sites to facilitate a better assessment of harbour wide changes. These sites are at least 1km from the nearest lease and cover similar depth ranges and habitats. These sites allow comparison of benthic changes in the harbour as a whole alongside changes associated with farming and provide a means to assess temporal changes in benthic ecology. The results suggest that the greatest changes in faunal abundance and number of species at the external sites occurred at the southern end and in the middle of the harbour, i.e. similar to the pattern observed on lease. In the most recent survey, May 2017, there has been an increase in the abundance and number of species at a number of these sites since October 2016 (Figure 12). However, as discussed in the last report the limited number and depth range of external sites sampled across all of the surveys restricts our ability to evaluate and infer the potential for broadscale changes in the benthic ecology in other depth ranges and regions of the Harbour. The January 2017 survey included an additional 16 external sites (Figure 6) that overlap with those sampled in the larger harbour wide surveys conducted at the start of 2015 and 2016, this survey highlighted that the greatest area of decline in late 2016 would appear to be towards the deeper central region of the harbour (this includes the deeper sites 39, 42 and 43 in the south), with relatively little change occurring in the shallower regions around the margins of the harbour. In May 2017 we repeated the survey of the full set of external sites and the broad patterns with respect to depth and location in the harbour were similar (Figure 13). However, in the May survey, faunal abundance and species number had increased at many of the sites and/or was within the range recorded historically. At the three deeper sites (39, 42 and 43) to the south in the WHA there has generally been a small increase in abundance and the number of species since the survey in January.

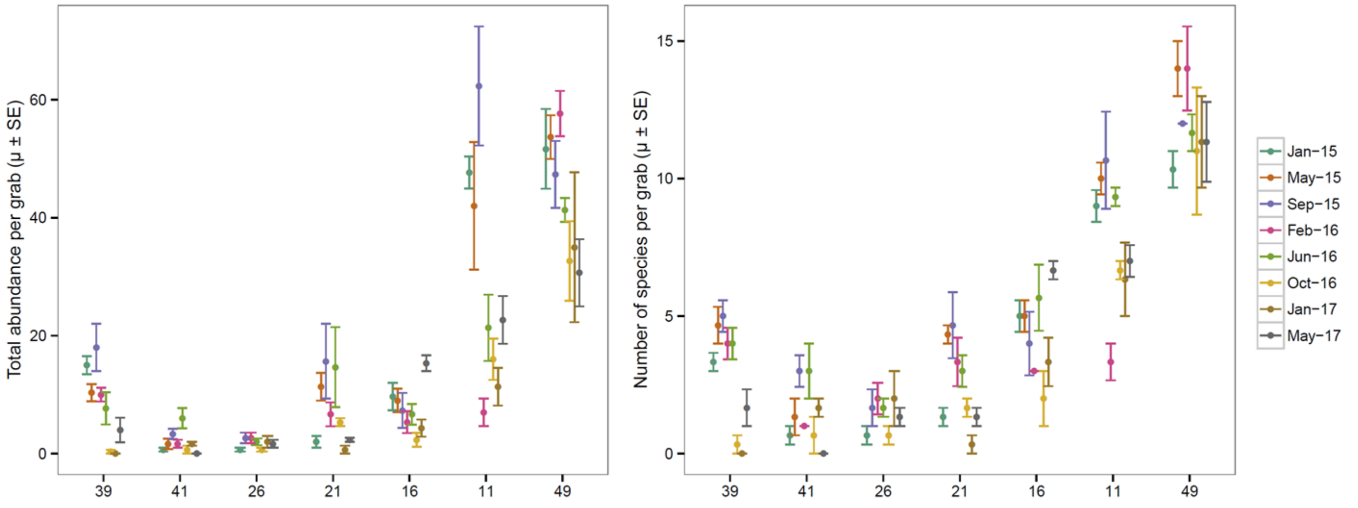

Figure 12 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m2) and number of species collected in grabs (n=3) at 7 external sites in Macquarie Harbour from surveys between January 2015 and May 2017. The data for each lease represents the mean (±SE) from three replicate grabs. Note that site 26 was not surveyed in May 2015.

Video assessments

As part of the ongoing benthic faunal surveys video assessments of the study sites using an ROV have been conducted in parallel with the infaunal sampling[2]. Three minutes of footage was collected at each site and the footage assessed following the methods described by Crawford et al. (2001). In Macquarie Harbour the scoring categories have been expanded for Dorvilleids to provide greater detail on their distribution and relative abundance (Table 2); the scoring categories for *Beggiatoa* are shown in Table 3.

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[2] ROV assessments have generally been conducted within 2-3 weeks of the benthic grab sampling. The ROV assessments are conducted by the 3 growers, and in some cases by Aquenal Pty. Ltd. They are then independently assessed by DPIPWE and EPA staff.

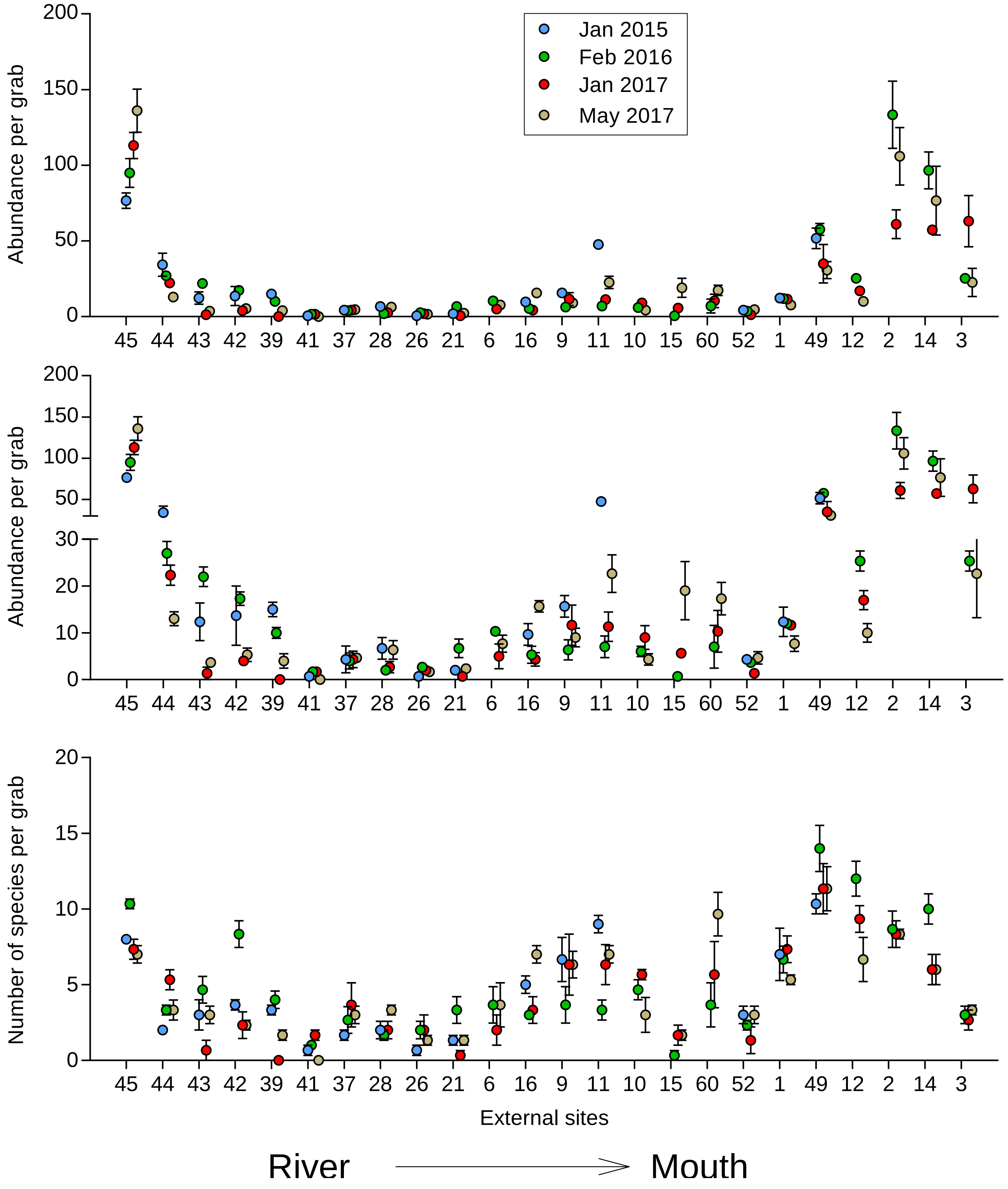


Figure 13 Plots of total infaunal (>1mm) abundance (per grab = ~0.0675m²; top 2 panels) and number of species collected in grabs (n=3; bottom panel) at 23 external sites in Macquarie Harbour from surveys in January 2015, February 2016, January 2017 and May 2017. In the middle panel the axis is split to better show differences between surveys at the sites with lower abundances; the depth of each sites is also shown in this panel. The data for each lease represents the mean (±SE) from three replicate grabs. Note that sites 2, 3, 10, 14 and 15 were not sampled in the January 2015 survey.

The results of the first seven surveys were provided in the last report, highlighting the increase in the prevalence of *Beggiatoa* around the leases in the October 2016 and January 2017 surveys relative to the previous surveys. In the May survey there was a clear reduction in the presence of *Beggiatoa* at both lease and external sites (Table 4). Of the 51 lease dives, *Beggiatoa* was observed on 37% (19) of dives, down from 57% and 48% in January 2017 and October 2016 respectively. The majority of the occurrences in May were on leases 3 and 5; well within the lease boundaries on lease 3 and mainly on the NW transect at lease 5. At lease 5 it is known that currents at this site tend to disperse more of the farm waste to the NW and both the prevalence of *Beggiatoa* and the depauperate fauna out to 100m are consistent with elevated levels of enrichment in this direction. At the external sites, *Beggiatoa* was only observed at one of the 28 sites in the May survey, compared with five and six of the 28 sites in the October 2016 and January 2017 surveys, respectively. The increase in bottom water DO concentrations at both the lease and external sites leading up to the May survey is likely to be a key driver behind improvements in the *Beggiatoa* status and the patterns seen in Figure 14.

Table 2 Scoring categories of Dorvilleid abundance for video assessment

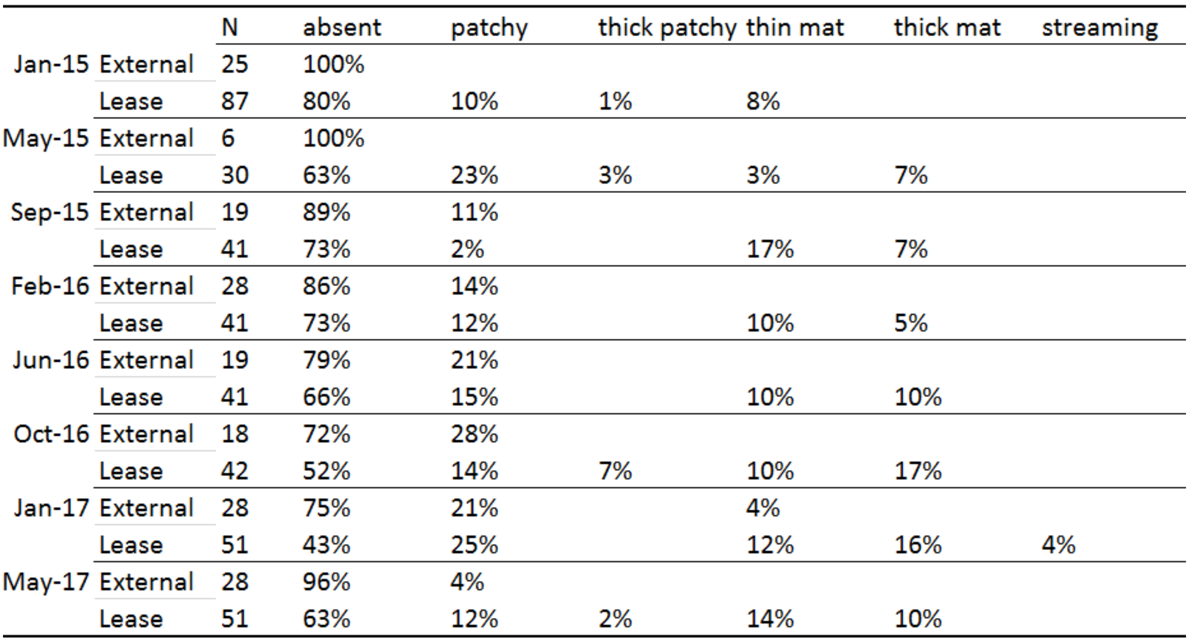
Dorvilleid abundance
0
1-30
31-100
101-300
301-1000
>1000

Table 3 Scoring categories of *Beggiatoa* cover for video assessment

Beggiatoa cover
absent
patchy
thick patches
thin mat
thick mat
streaming

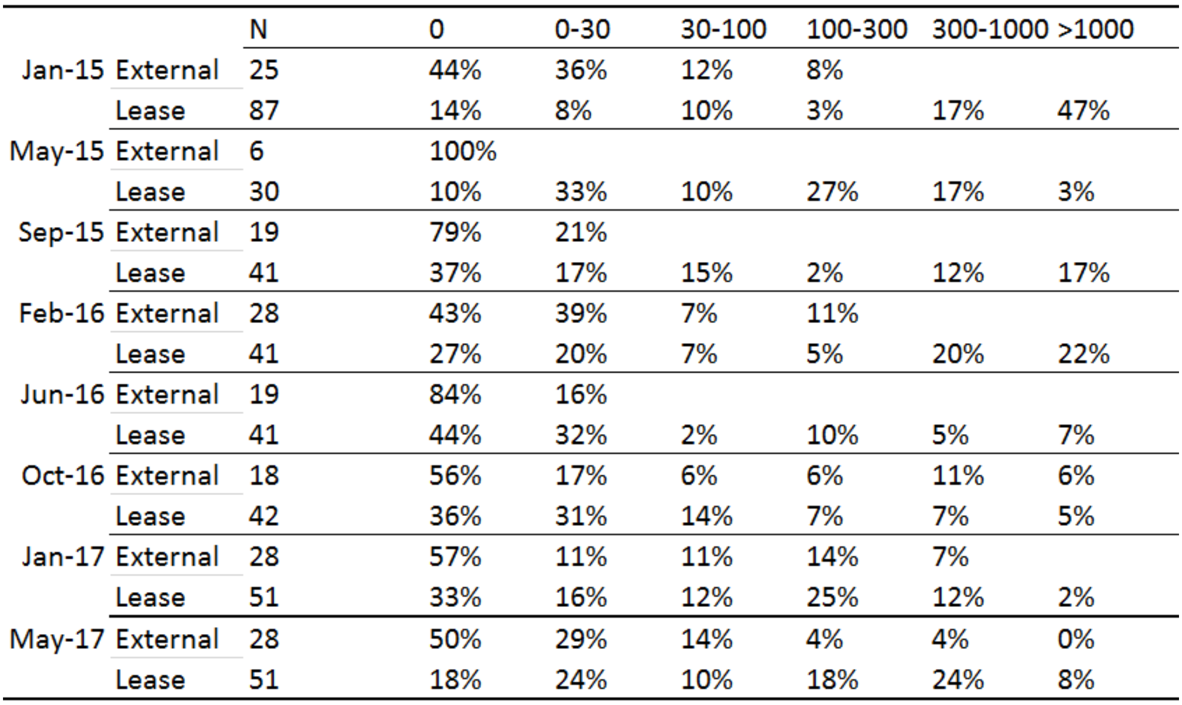
As we described in the last report, the ROV footage also shows the association between the presence of Dorvilleid polychaetes and farming (see Table 5). However, relative to *Beggiatoa* the distribution of Dorvilleids typically extends further from the cages and Dorvilleids are more commonly observed at external sites. Of the 79 ROV dives in the recent survey in May, Dorvilleids were observed on 82% of lease dives and 50% of external dives. At the external sites Dorvilleids were more commonly observed in the southern region of the Harbour, similar to the pattern observed in the previous surveys. Ross et al. (2016) noted that the broader distribution is largely associated with the Dorvilleid *Schistomeringos loveni* which appears to be less tolerant of highly enriched sediments than the colony forming Dorvilleid *Ophryotrocha shieldsi* that is typically found closely associated with stocked cages. In the May 2017 survey colonies were only observed on four of the 79 dives and always within 50m of the cages. Thus, the distribution of Dorvilleids seen in Figure 15 is largely associated with *Schistomeringos loveni*, and arguably the patterns associated with the study leases reflect its preference for more moderately enriched sediments. For example, at leases 1 and 2 that had both been fallowed for at least a month prior to the survey, Dorvilleids were more common, and notably closer to the cage sites. At lease 3 that was stocked at the time of sampling, the peak abundance of Dorvilleids is further from the cage sites. At lease 5, their peak abundance is further from the cage site on the NW compared to the SE transect, consistent with greater levels of enrichment to the NW at this lease.

Table 4 Percentage of lease and external sites for each category of Beggiatoa cover for each survey.



		N	absent	patchy	thick patchy	thin mat	thick mat	streaming
Jan-15	External	25	100%					
	Lease	87	80%	10%	1%	8%		
May-15	External	6	100%					
	Lease	30	63%	23%	3%	3%	7%	
Sep-15	External	19	89%	11%				
	Lease	41	73%	2%		17%	7%	
Feb-16	External	28	86%	14%				
	Lease	41	73%	12%		10%	5%	
Jun-16	External	19	79%	21%				
	Lease	41	66%	15%		10%	10%	
Oct-16	External	18	72%	28%				
	Lease	42	52%	14%	7%	10%	17%	
Jan-17	External	28	75%	21%		4%		
	Lease	51	43%	25%		12%	16%	4%
May-17	External	28	96%	4%				
	Lease	51	63%	12%	2%	14%	10%	

Table 5 Percentage of lease and external sites for each category of Dorvilleid abundance for each survey.



		N	0	0-30	30-100	100-300	300-1000	>1000
Jan-15	External	25	44%	36%	12%	8%		
	Lease	87	14%	8%	10%	3%	17%	47%
May-15	External	6	100%					
	Lease	30	10%	33%	10%	27%	17%	3%
Sep-15	External	19	79%	21%				
	Lease	41	37%	17%	15%	2%	12%	17%
Feb-16	External	28	43%	39%	7%	11%		
	Lease	41	27%	20%	7%	5%	20%	22%
Jun-16	External	19	84%	16%				
	Lease	41	44%	32%	2%	10%	5%	7%
Oct-16	External	18	56%	17%	6%	6%	11%	6%
	Lease	42	36%	31%	14%	7%	7%	5%
Jan-17	External	28	57%	11%	11%	14%	7%	
	Lease	51	33%	16%	12%	25%	12%	2%
May-17	External	28	50%	29%	14%	4%	4%	0%
	Lease	51	18%	24%	10%	18%	24%	8%

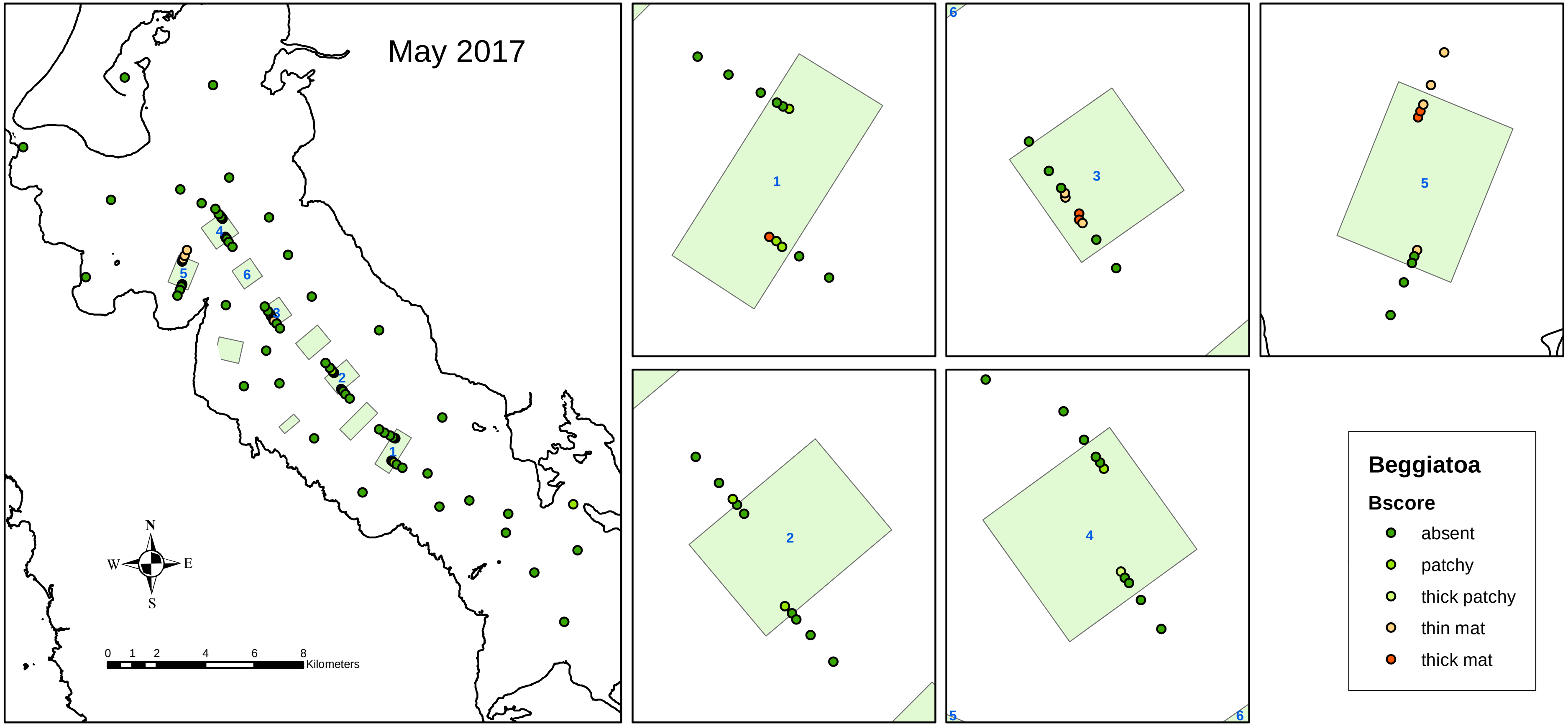


Figure 14 *Beggiatoa* score (severity) from ROV footage at study sites across the harbour on the left panel, and shown in more detail for each of the study leases in the panels on the right.

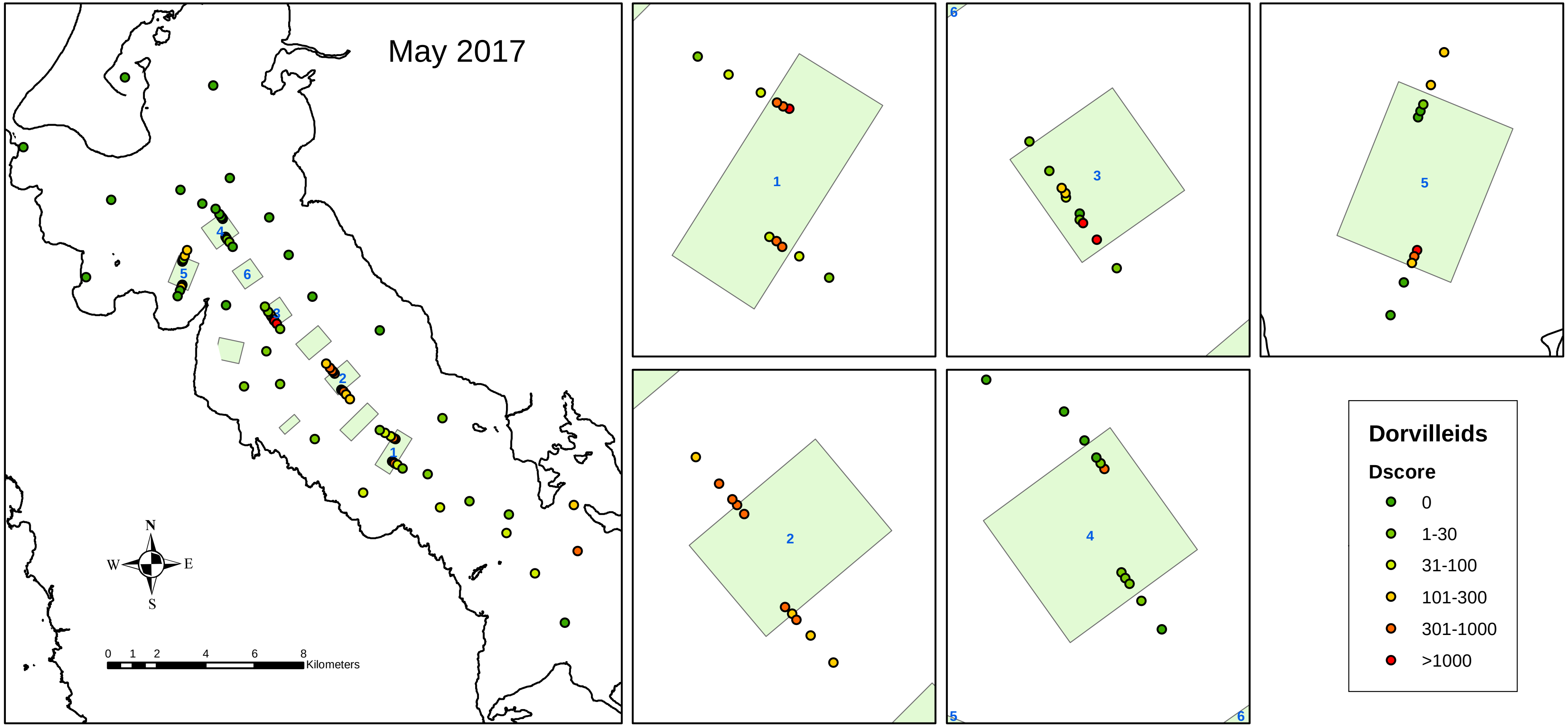


Figure 15 *Dorvilleid* score based on counts from ROV footage at study sites across the harbour on the left panel, and shown in more detail for each of the study leases in the panels on the right.

MODELLING

The CSIRO hydrodynamic model of Macquarie Harbour is capable of simulating 3D currents, sea-level, salinity and temperature, as well as 'oxygen concentration' via an oxygen tracer (see Figure 16 for brief description of the model configuration). The oxygen tracer incorporated into the current model includes air-sea gas exchange at the surface, oxygen forcing at both the offshore and river boundaries, and a nominal benthic-pelagic consumption[3]. The performance of the model is assessed via comparison of output with observational data from both the farming industry, and from a profiling mooring installed by CSIRO. The model has been run for over 12 months in hindcast mode to investigate the residual circulation of the harbour, and also residence time of the various water column layers. Model outputs have been studied to help identify mechanisms by which oxygen can be replenished in the deeper waters of the harbour. The model currently runs in near real-time mode (NRT) with a 3-day forecast.

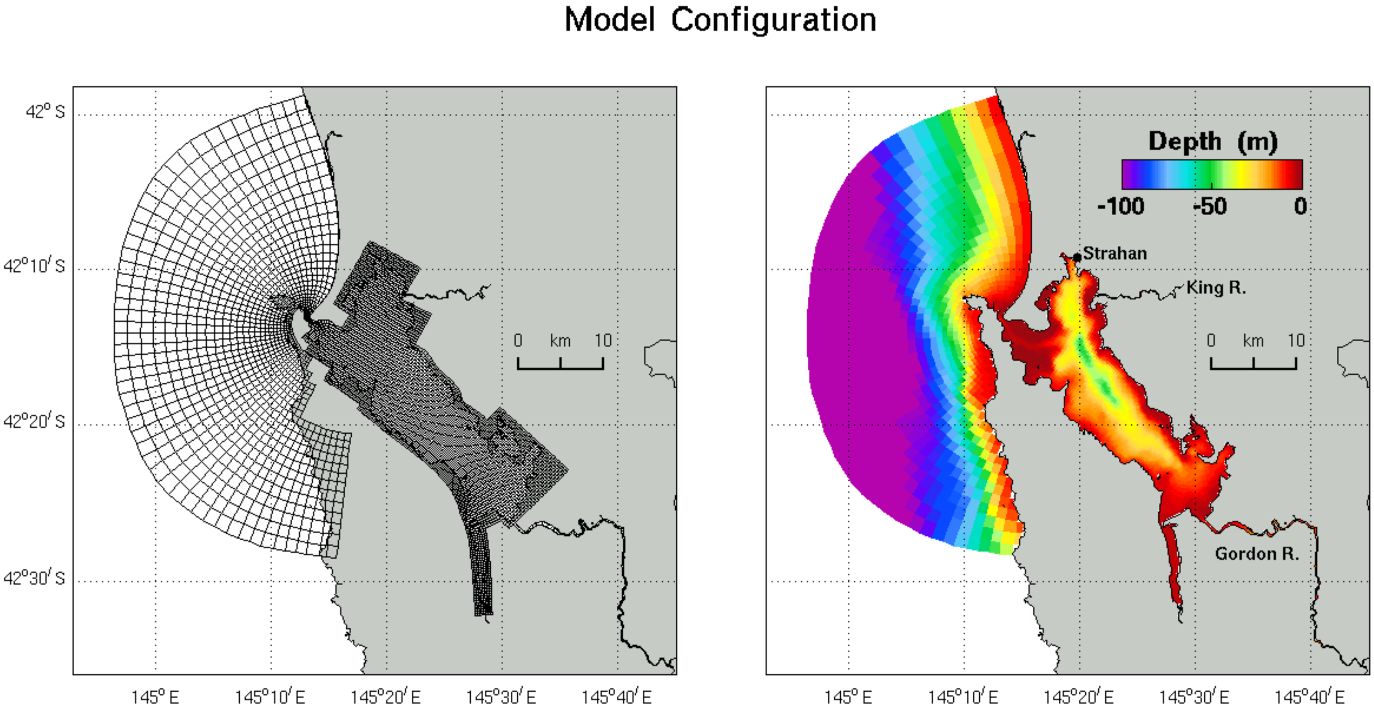


Figure 16 Macquarie Harbour model grid (left) and bathymetry (right). The model domain includes 3 components combined into a single grid - the entire harbour itself, the major rivers to the toes of their salt wedges, and that part of the Indian Ocean which can exert any significant influence. A curvilinear grid was used as this enabled constant resolution in the harbour, expanding resolution offshore to enable nesting inside a coarser global model, and 2 single rows of coarse cells to represent the rivers where detail was not required. The resolution within the harbour is approximately 250m. It is similar in the longitudinal direction for the rivers, but increases to 2km at the offshore boundary. There are 22 layers in the vertical – beginning at 1m resolution at the surface, decreasing to 0.4m at the halocline, and then increasing to 3m at the sea-bed of the harbour, and 20m at the offshore sea-bed. See Andrewartha and Wild-Allen (2017) for further details.

Mooring observations

A profiling mooring system was deployed in the harbour at the end of August 2016 (see Figure 2) providing live *in situ* observations of temperature, salinity and dissolved oxygen from the full water column. The profiling interval is 4 hours and the oxygen sensor has been calibrated against a Seabird profiling CTD and lab analysis of preserved oxygen samples. Example raw data for two weeks are presented in Figure 17, and interpolated data for the entire deployment to date, in Figure 18. Consistent with the pattern already described from the environmental strings, the latter clearly shows that very low levels of oxygen existed below 15m in August 2016, that these persisted

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[3] It is important to note that the model employs a constant nominal biological oxygen demand corresponding to benthic-pelagic drawdown. Although this has proven to superficially account for the complex biological processes associated with detrital sedimentation, remineralization and resuspension, improved model accuracy and insight into the relative contributions of the various biological processes can only be obtained, from implementation of a more fully resolved biogeochemical model.

for the remainder of the year, and then recovered from January 2017 to reach a peak in May 2017. They now appear to be slowly decreasing in August 2017. This trend is accompanied by a corresponding variation in surface salinity which begins the period at very low levels, increases to a maximum in April-May 2017, and is now in decline as winter rains set in and river flows increase. The temperature at 35-45m depth also follows the oxygen behaviour. From January through to August, whenever there is a recharge of bottom oxygen, there is a corresponding change in bottom temperature, either an increase if surface temperatures are warmer, or a decrease if surface temperatures are cooler.

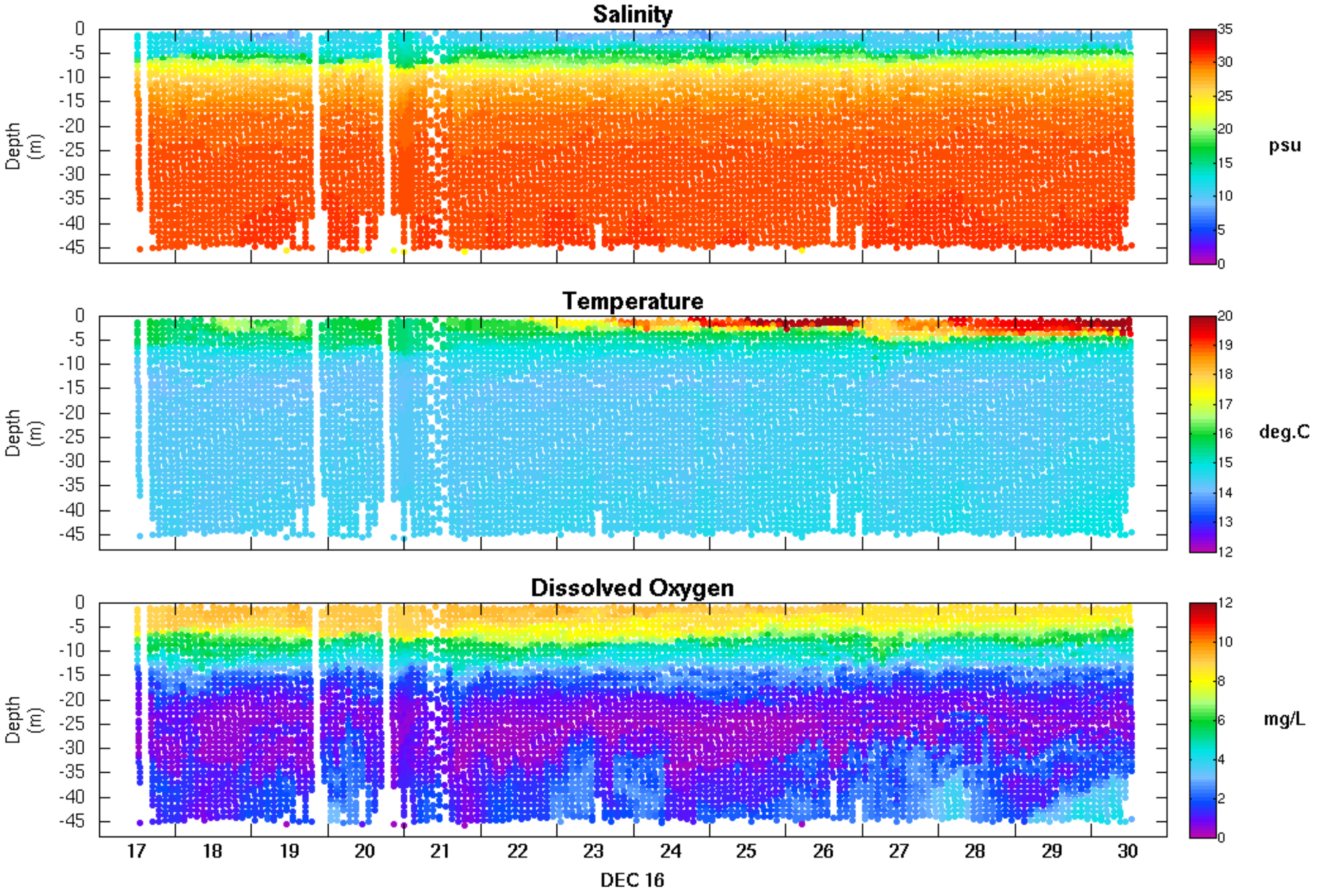

Figure 17 Example observations from the profiling mooring showing temporal change of water column salinity, temperature and dissolved oxygen concentration during 2 weeks in December 2016.

Model assessment

The model has been calibrated and validated by comparing simulations with time-series of observations of sea-level (see Figure 20), temperature, salinity and dissolved oxygen. Both vertical profiles and time-series of salinity, temperature and oxygen tracer concentration from the model are generally in good agreement with those observed at the profiling mooring site (Figure 19Figure 20). In deep water the model employs a constant nominal biological oxygen demand corresponding to benthic-pelagic drawdown. This has proven to superficially account for the complex biological processes associated with detrital sedimentation, remineralization and resuspension. Improved model accuracy and insight into the relative contributions of the various biological processes can only be obtained, from implementation of a fully resolved biogeochemical model.

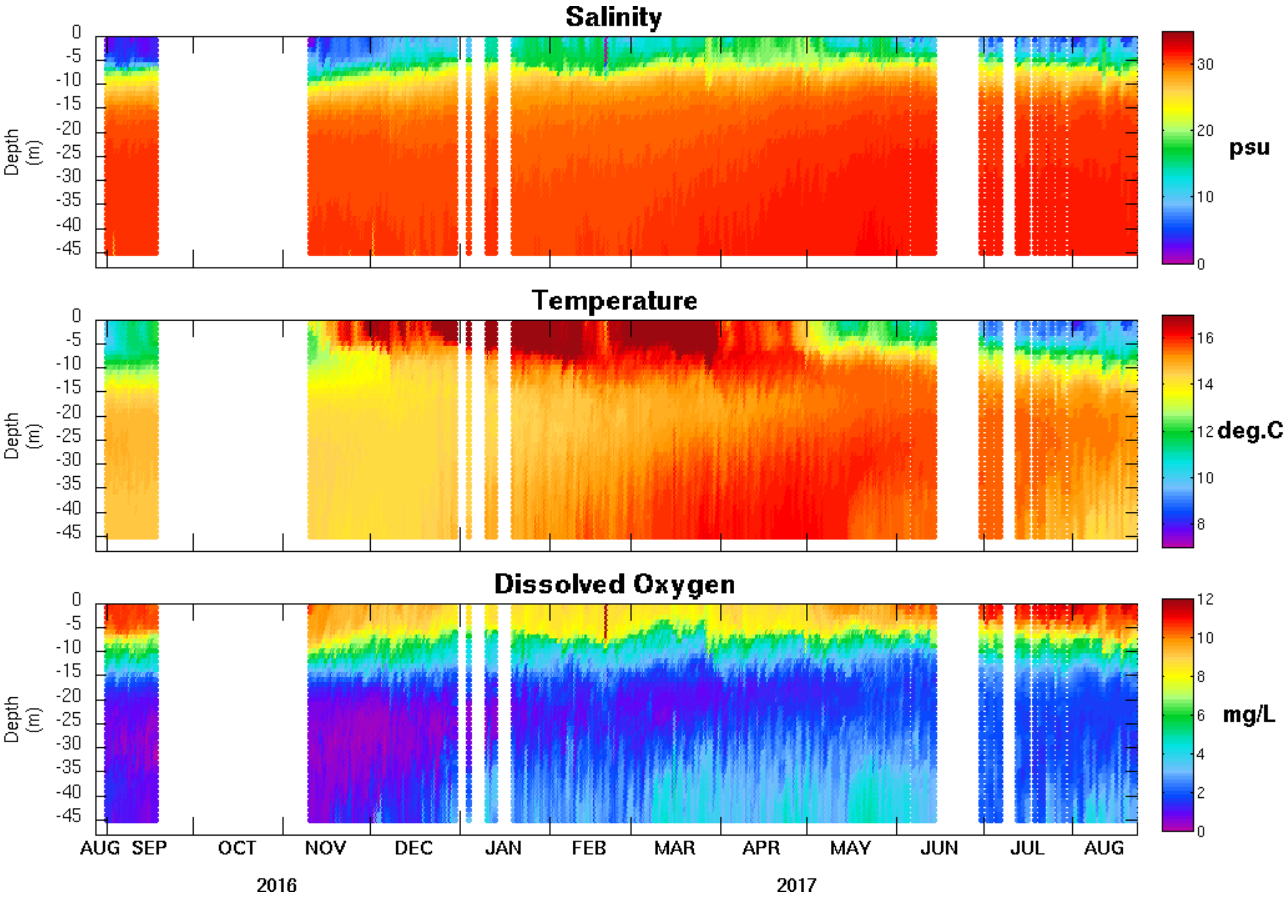

Figure 18 Observations from the profiling mooring showing temporal change of water column salinity, temperature and dissolved oxygen concentration for the full deployment. Profiling operations were suspended (i.e. the gaps in the figure) during very rough weather to avoid entanglement, and on a few occasions to enable platform maintenance.

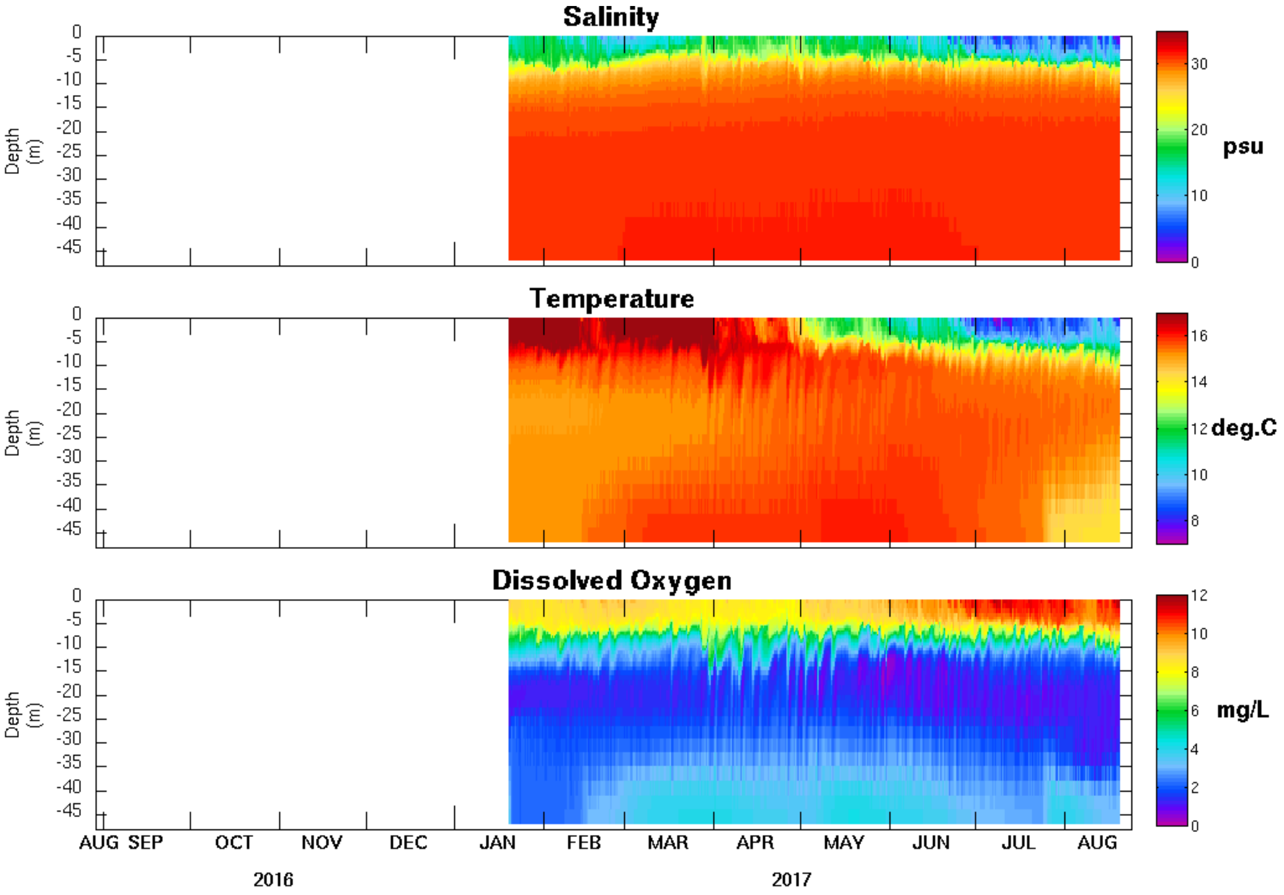

Figure 19 Simulated salinity, temperature and dissolved oxygen tracer time series at the mooring site (scale similar to Figure 18).

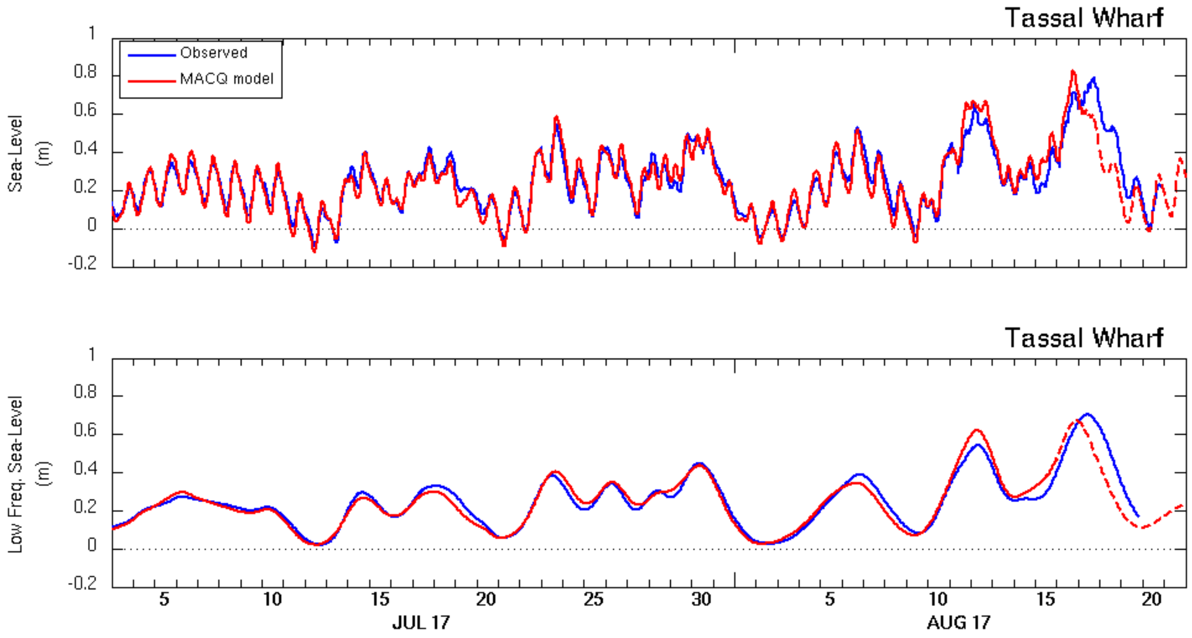

Figure 20 Comparison of simulated sea surface elevation with observed tides (upper panel), and comparison of low-frequency sea-level variation (lower panel).

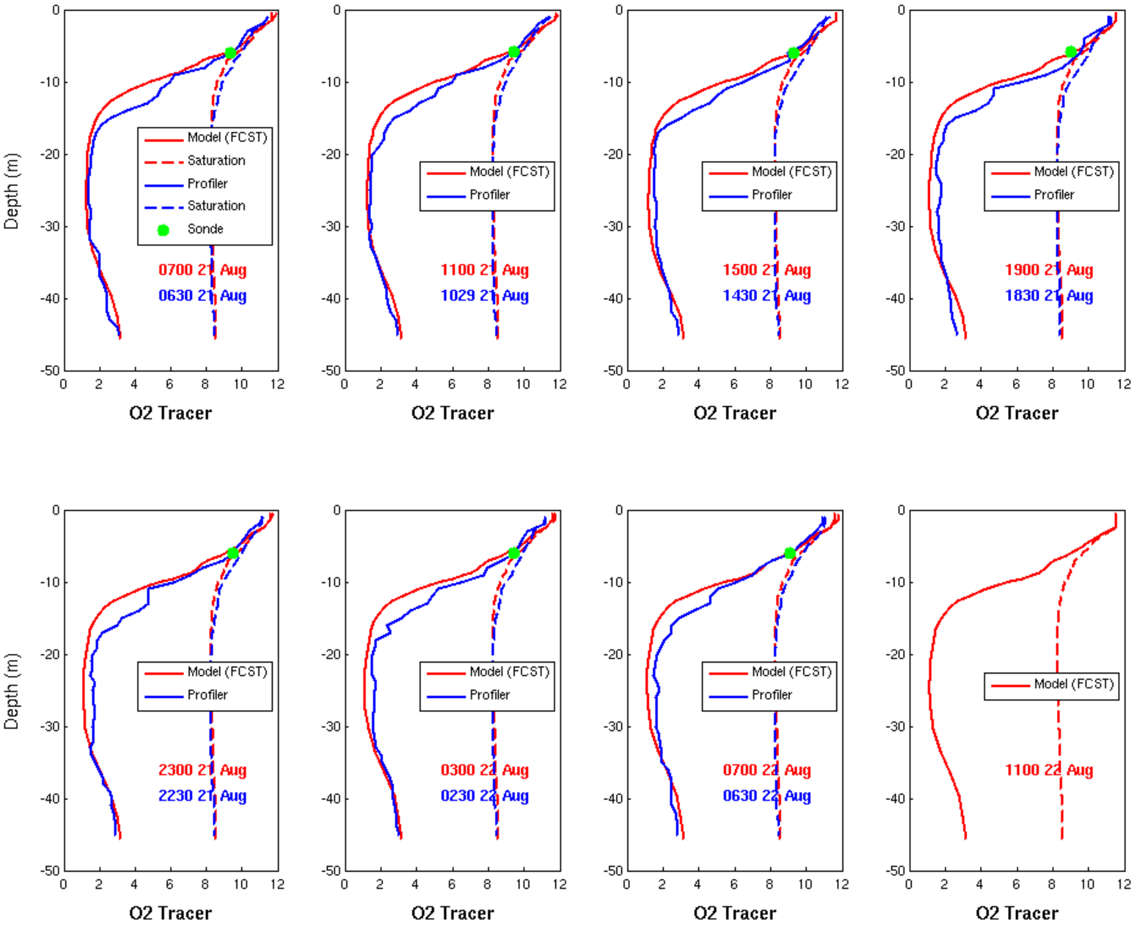

Figure 21 Profile comparison of oxygen between the profiler observations and the model

Model results

The model clearly reproduced the estuarine nature of the harbour with fresh surface water accumulating in the basin due to the narrow marine entrance. This fresher water gives rise to a strong density stratification that limits surface air-sea replenishment of depleted mid-water oxygen concentrations. A well-defined surface layer of approximately 5m persisted throughout the year (2016-17).

In the case of salinity, a fresh layer, which varies in strength according to season and river flow, sits atop the remainder of the water column which remains largely unaltered at 31psu (Figure 22, top panel). In the case of temperature, the profile does tend to show the 3-layer structure observed by Cresswell et al (1989). The surface layer is cool in winter (Figure 22, middle panel), and warm in summer (Figure 23) while the mid-water remains at about 14-15°C throughout the entire year. The bottom water then varies slightly away from this, tending towards the surface temperature (i.e. cooler in winter or warmer in summer). This behaviour suggests that the bottom water is replenished from surface water, and Figures 22 and 23 indicate this is due to density currents flowing down the steep incline at the western end of the harbour.

The oxygen tracer exhibits the most variation and clearly shows a 3-layer structure. It remains near saturation in the surface layer, varying according to replenishment from both the rivers and the ocean, while it has a minimum at mid-depths of 15 to 30m, and then increases again in the bottom layer, but remains far below saturation (Figure 22, bottom panel). The increase in the bottom water appears to be as a result of the same mechanism as described above for temperature.

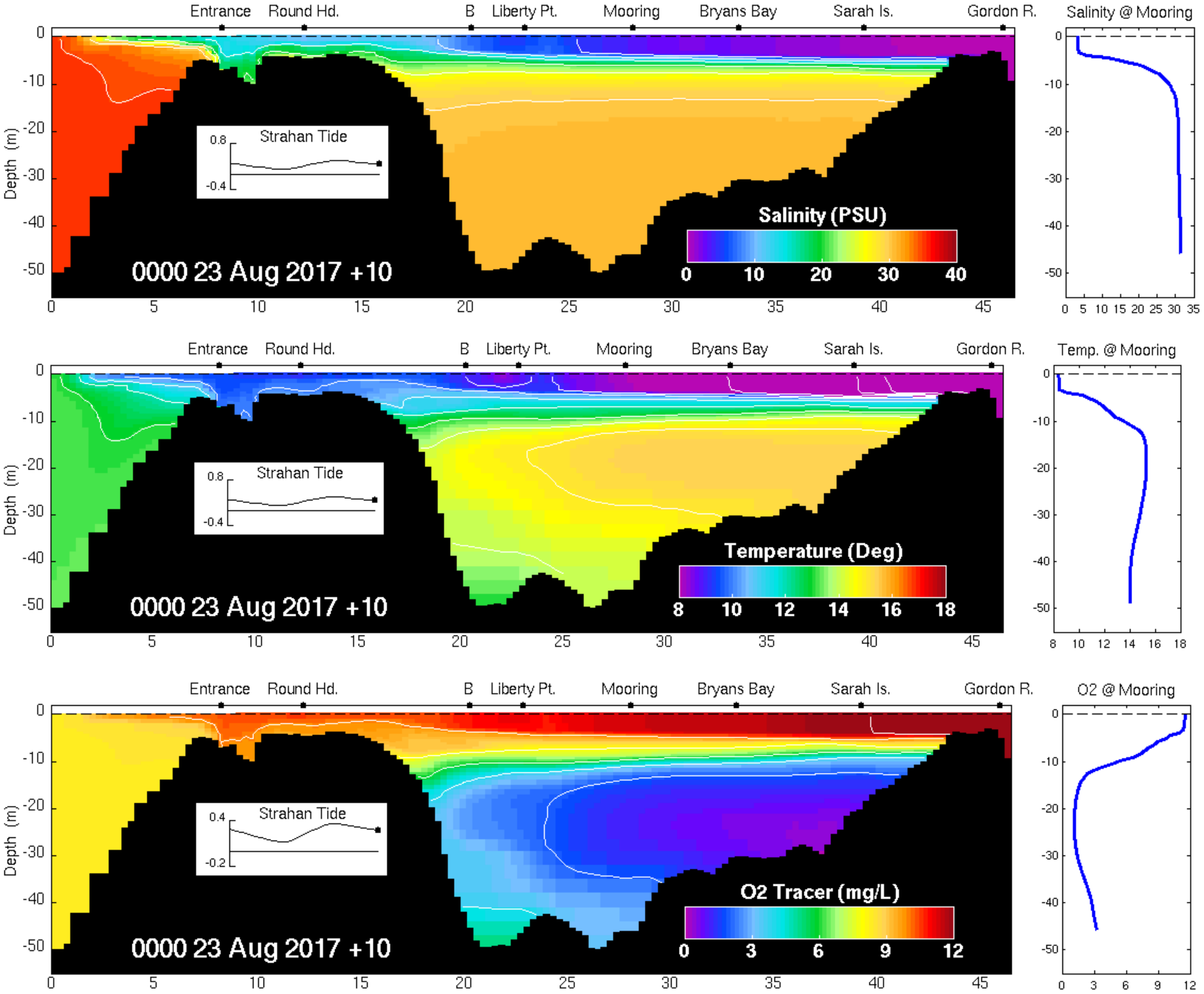

Figure 22 Examples of model cross sections along the long axis of the harbour during winter, showing salinty (upper), temperature (middle) and oxygen tracer (lower).

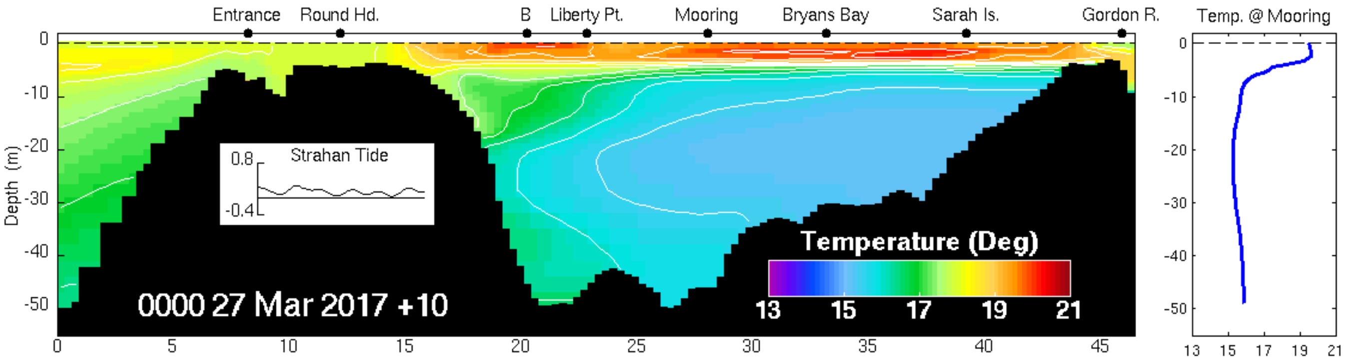

Figure 23 Example of model cross sections of temperature along the long axis of the harbour during autumn

Residence Times

Residence times for the three predominant layers in the harbour were determined by initializing those layers in the model, each with a different tracer. The model was then run for periods of four months, under differing meteorological/river flow conditions (normal river flows versus no river flow), and the time for the tracer concentration to drop by half calculated and compared across layers and the two different flow conditions.

In the top layer, the time for concentration to drop by half is approximately 40 days under normal flows, and this extends to approximately 70 days when there is no river flow. For the middle layer, these times are considerably longer and the trend is reversed. For normal river flow the decay time is approximately 110 days, and for zero flow it reduces to 65 days. For the bottom layer, residence times are shorter than the middle layer, and are approximately 70 days for normal flows, and 50 days for zero flow (Table 6). Thus, there are distinct differences between residence times for different flow conditions, and for the different water layers. For the surface, as expected, residence times are longer for low flow conditions, whereas for the deeper layers, residence times are longer under higher flow conditions. And the residence times of the middle water layer are generally longer than those for the bottom layer.

Layer	**Normal River flow**	**Zero River Flow**
Top	40 days	70 days
Middle	110 days	65 days
Bottom	70 days	50 days

Table 6 Times for passive concentration to reduce by half, in 3 layers of the water column under different flow conditions.

Oxygen Recharge

To investigate environmental events which may be conducive to oxygen recharge, concurrent time-series of wind, atmospheric pressure, sea-level, river flow, observed salinity and dissolved oxygen, were assembled for the year the profile mooring has been operating from August 2016 to August 2017 (Figure 24). These data suggest that oxygen concentration in the deeper water, below 20m, is strongly tied to salinity at the surface, and hence to river flow. From August to November 2016 river flow was high, salinities at 1m depth were below 5psu, and oxygen levels at 40m were approximately 1 mgL^{-1}. Throughout the following summer and autumn, river flow reduced and surface salinity increased to a maximum of 20psu in May, while oxygen at 40m increased to a peak of 5 mgL^{-1}, also in May. From June to August 2017, river flow increased again, salinities dropped, as did oxygen levels - however August 2017 levels were not as low as in 2016. This may be because total river flows for June-August 2017 were considerably lower than those for the same period in 2016.

Within the above seasonal variation, there are shorter time-scale oxygen recharges which are more difficult to correlate with known events. For example, oxygen at 40m jumps sharply in early March and early May – while although there are corresponding increases in salinity, there are no significant changes in river flow (or at least the estimated river flow).

On even shorter time-scales of hours and days, small recharges occur at 40m (Figure 18) which again don't appear to align with changes in other factors. One possibility, is that these events are due to horizontal movement of benthic water masses past the mooring. Spatial measurements scheduled to occur throughout the harbour in October 2017, may be able to confirm this.

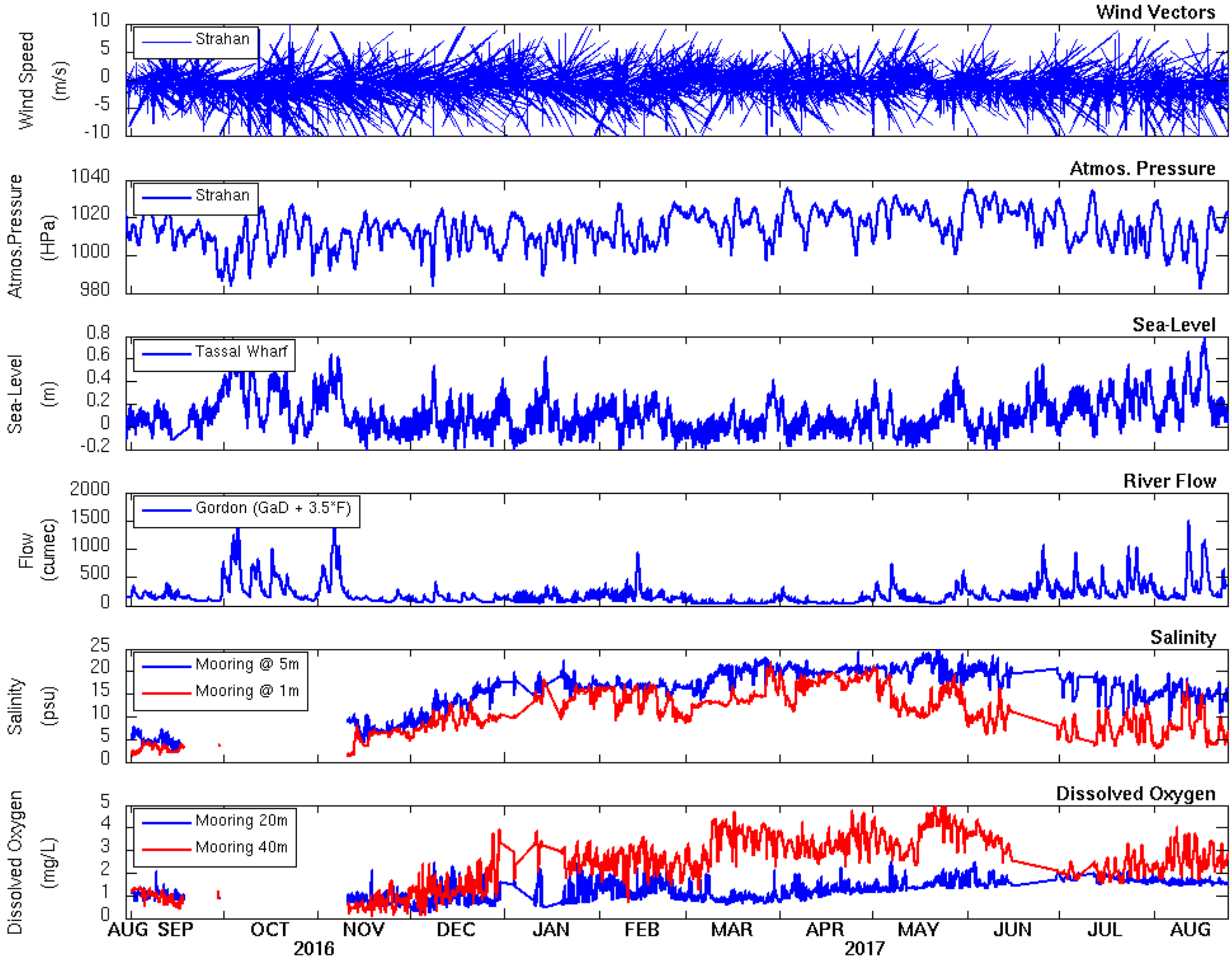

Figure 24 Time-series of concurrent environmental phenomena which may suggest favourable conditions for oxygen recharge.

The primary mechanism for recharge of oxygen in the lower water column appears to be oceanic water flowing in over the sill, mixing with resident fresher water, but remaining at an increased density to descend the slope into the deeper basins. This behaviour has been investigated by including tracers in the model i.e. to track the movement of the water coming in from the ocean a tracer was added outside the entrance, and to track the water coming down the rivers a tracer was added to the Gordon River. The model was then run through the months of June to August, 2017 with normal (strong) river flows, and then a second time with zero river flow. Cross-sections of the ocean tracer near the beginning and ends of these runs are given in Figure 25. In the case of normal river flow, much of the incoming ocean water appears to mix and then 'slide' in under the fresh surface layer at about 10m depth. In the case of no river flow the incoming ocean water mixes less, and is able to descend further (bottom, left panel of Figure 25). After 3 months, the ocean tracer is considerably more dispersed throughout the harbour when there is no river flow, while in the normal flow case, there is a dearth of tracer at mid-depths, which decreases along the harbour away from the entrance. This is consistent with recent measurements of dissolved oxygen and demonstrates that oxygen recharge in the (deeper) harbour is likely to occur more strongly when river flows are low.

It also seems feasible that the highly oxygenated water from the rivers, which are part of the mixing process inside the entrance, could also contribute to the oxygen recharge process. Cross-sections of the river tracer were analysed, and examples from the normal river flow model run are given in Figure 26. The plot from the end of the run indicates that indeed some river tracer is entrained into the downwelling, and hence some river oxygen is likely to refresh the deeper water, however concentrations are much lower than those originating from the ocean.

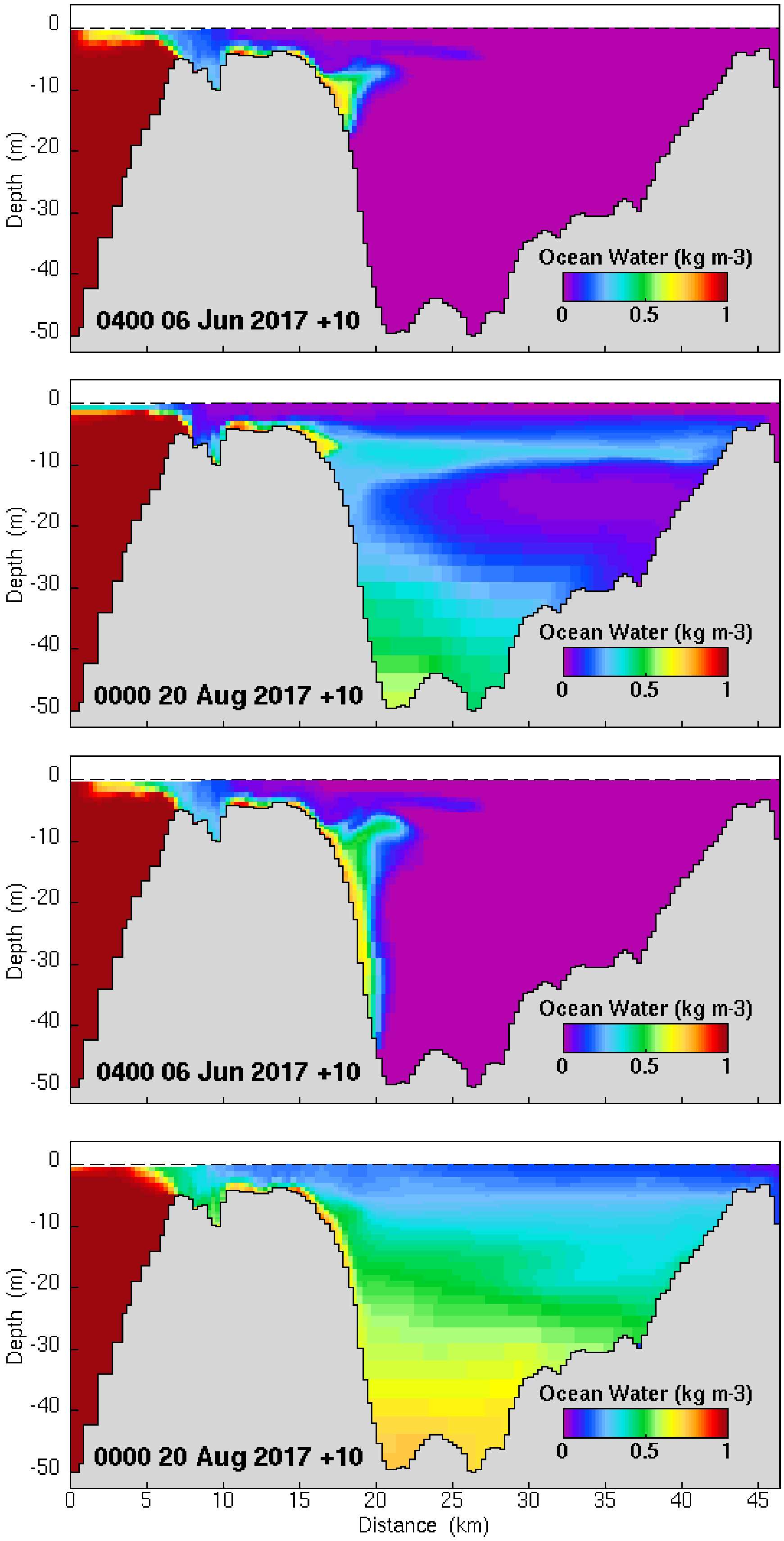

Figure 25 Evolution of an ocean water tracer during a 3 month model run with normal river flow (top 2 panels), and with no river flow (bottom 2 panels),

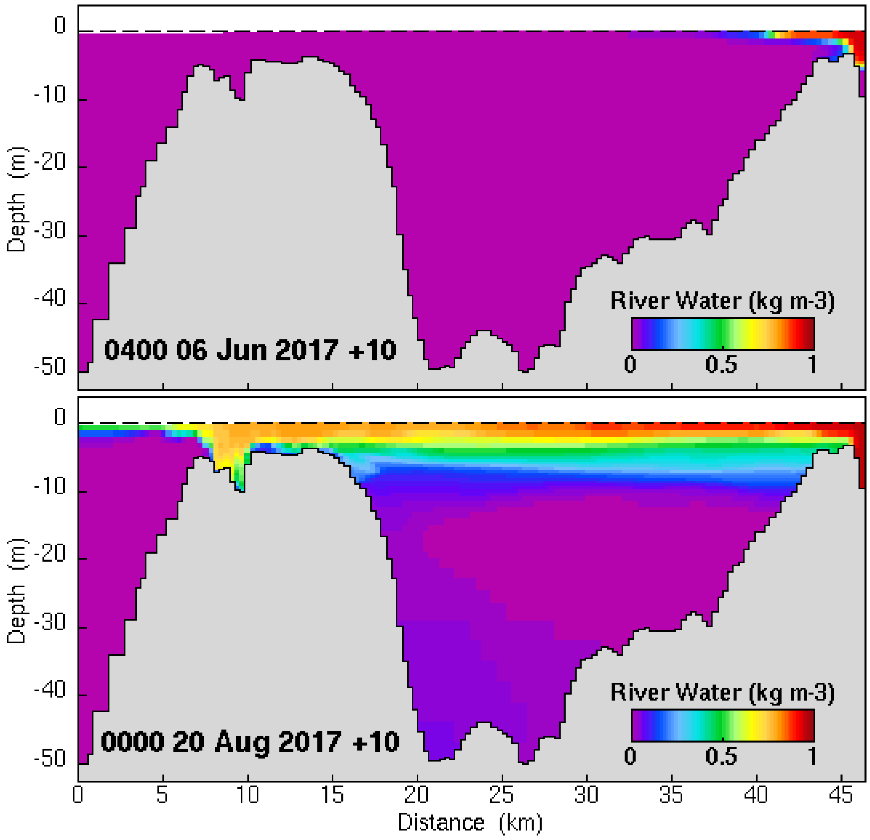

Figure 26 Evolution of a river water tracer during a 3 month model run with normal river flow.

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