Macquarie Harbour Oxygen Project (MHOP): enhancing oxygen levels at depth

Summary

This project was developed to help address an urgent action identified under the updated Conservation Advice for the Maugean Skate to increase the levels of dissolved oxygen in Macquarie Harbour. Both computer modelling and field studies have demonstrated the role that salmonid aquaculture and river flows both play in influencing the dissolved oxygen status of the harbour (MHDOWG 2015; Ross & MacLeod 2017, Wild-Allen et al. 2020). A climate driven increase in bottom water temperatures of 1.5-2°C over the past 30 years in the harbour is also considered to have influenced the observed decline in oxygen through decreased solubility and increased metabolic rates (Ross et al., 2021). Through this FRDC funded project, the salmonid aquaculture industry has committed to helping address this immediate priority to increase oxygen levels to support the conservation efforts for the skate and to help offset the oxygen drawdown of salmonid aquaculture in the harbour. The scientific evaluation program will assess the efficacy and environmental response to the oxygenation. This evaluation will be critical in assessing the feasibility and scalability of the system for either future offsetting and/or remediation of bottom water dissolved oxygen levels.

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Background

Macquarie Harbour on Tasmania's west coast has been a site for salmonid aquaculture since the 1980s, however it wasn't until the early 2000s that standing biomass in the harbour increased beyond 1000 tonnes. Across the following decade biomass increased, peaking at just over 20,000 tonnes in 2014/15 before further increases were halted due to progressive signs of environmental stress in the Harbour. In late 2013 a decline in oxygen levels in the bottom waters of the Harbour was confirmed (MHDOWG 2015), and in spring 2016 a major deterioration in sediment conditions was observed (Ross et al., 2017). To reduce the pressure on the harbour and allow for environmental recovery, the maximum permissible biomass has progressively been lowered by the EPA since early 2017 (https://epa.tas.gov.au/business-industry/regulation/salmon-aquaculture/marinefinfish-farms/macquarie-harbour).

Across this period there has been a major focus on understanding the population status, ecology of the endangered Maugean skate (Zearaja maugeana), and the potential interaction with salmonid aquaculture (Bell et al., 2016; Moreno et al., 2020). Moreno et al., (2020) documented two skate mortality events and the complex relationship with environmental conditions in Macquarie harbour and oxygen depleted waters. The most recent research by Moreno & Semmens (2023) report an estimated decline in relative abundance of the skate in Macquarie Harbour of up to 47% occurred between 2014 and 2021. There is now substantial concern for the species, and this has prioritised the skate for threatened species listing reassessment under the Environmental Protection and Biodiversity Act 1999 (EPBC Act) and the updating of the current Conservation Advice for the Species (DCCEEW 2023a). In July 2023, the National Recovery Team for the Maugean Skate was formed to develop and coordinate the implementation of a conservation plan or program. Membership of the Recovery Team includes representation from all stakeholder groups with an interest in Maugean skate conservation management, including the Australian, State, and local governments, Hydro Tasmania, aquaculture industry, local community, research organisations, natural resource managers, and environmental non-government organisations.

The updated Conservation Advice for the skate has identified several key urgent actions for implementation prior to summer 2023, including ‘Increasing the levels of dissolved oxygen in Macquarie Harbour, via a reduction in aquaculture organic loads and/or utilisation of mechanical/engineering environmental remediation technologies. The Recovery Team convened an Environmental Remediation Feasibility Working Group to assess possible immediate and longer-term options to improve dissolved oxygen levels in Macquarie Harbour. Workshops were help on 31st August and 4th September and considered four remediation options: 1. remove or reduction in salmon biomass, 2. increasing mixing of the water column, 3. increase exchange with the ocean (e.g. pipeline or dredging of the harbour entrance), 4. oxygenation of bottom waters via a pump (DCCEEW 2023b). In summary, for option 1 it was considered that destocking salmon would not likely solve the issues in the short term (6 - 12 months) given the likely lag effect in any oxygen response, option 2 was not considered viable in the short term given uncertainty and risks in relation to the stabilisation of the water column, option 3 was not considered viable based on enormous costs, practical challenges and associated environmental risks. Option 4 whereby oxygenated water (typically super-saturated) is pumped to depth was considered the most viable option for further consideration given the approach and technology has been used successfully overseas and in Australia for environmental remediation (see Larsen et al., 2019; Liu et al., 2020; Stigebrandt & Anderson 2022, US Army Corps 2021). It was agreed to conduct a pilot study to assess the feasibility of this option, and to address the various concerns that have been identified. It was also agreed that a pilot study should be initiated prior to summer if possible.

Several subsequent meetings between scientists and the aquaculture industry led to the development of the pilot oxygen trial and associated research described here. The project concept, design and plan was also presented to government agencies and to the National Recovery Team for the Maugean Skate. The end users and beneficiaries of this research and its potential application at scale are wide ranging. The application at scale has the potential to make a significant contribution to the improvement of oxygen levels in the harbour and the conservation of the skate. At an industry level, the ability to help offset the oxygen drawdown due to salmon aquaculture will greatly benefit the sustainability of their operations in Macquarie Harbour. This will then extend to the associated economic and social benefits for local communities. Further innovation in the methodology and implementation of oxygenation have a wide range of other applications for environmental enhancement and remediations.

The Project

The project centres around three packages of work: 1. engineering and the operation of the oxygenation plant and how the oxygen is delivered into the water column, 2. measuring the ecosystem response to the oxygenation across nutrient concentrations, metal availability, microbial activity, and sedimentary and mobile fauna and 3. computer modelling to predict the diffusion of the oxygen plume and spread both locally and at broad scales. Importantly, the pilot trial will be run in a staged approach whereby the volume, duration and method of injection will be progressively scaled based on the model predictions and detailed water quality and ecosystem observations to ensure that the oxygen is delivered and retained in the bottom waters with no or minimal adverse ecological effects.

Progress

Oxygenation plant and delivery system

Commissioning of the 'Wombat' barge

The ex-navy bunker barge named Wombat, operated by Salmon Tasmania, is fitted with a large oxygen generator and seawater pumps (Figure 1). The oxygen generator, housed within a weatherproof shipping container, can generate 4840kg/day of oxygen. The system is set up so the pumps bring seawater up from 20m deep in Macquarie Harbour. Once on board the barge, this water is injected with highly concentrated micro and nano bubbles of oxygen, before this oxygenated water is released back into the Harbour at depth (30-40m).

The barge is moored on the edge of a Huon Aquaculture farming lease (North-East of Double Cove marine farming zone) and is approximately 0.7 km to the northeast of the lease boundary (Figure 2).

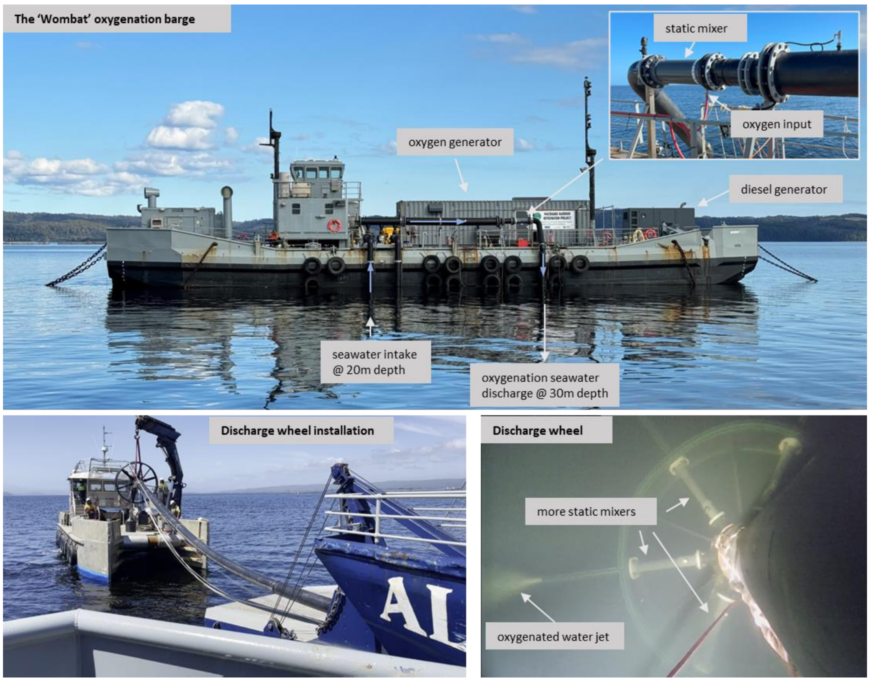

Figure 1 Pictures of the 'Wombat' barge moored in location, the oxygen generator, diesel generator, the pipework and discharge wheel. The static mixer in the pipework on the barge is where the oxygen is injected and dissolved into the seawater that has been drawn from depth. There are additional mixers in the discharge wheel (bottom right) to further break up any remaining microbubbles. The picture on the bottom left is from the installation of the discharge pipe and wheel.

Measuring the environment

Real time sensors

Measuring how effective the oxygenation injection system is at improving oxygen levels in the surrounding water column is achieved through a spatial array of underwater wireless oxygen, salinity and temperature sensors[1], that have been deployed at multiple distances and depths to the northeast

[1] see innovasea.com for a description of the sensors and platform

and southwest of the injection point[2] (**Error! Reference source not found.**). These sensors communicate with a hydrophone and acoustic hub mounted on the barge which then provides the data in realtime via satellite (Starlink) to the Realfish Pro dashboard for viewing via their app. The dashboard is already currently accessed by researchers, growers, and regulators at three existing environmental monitoring strings situated throughout Macquarie Harbour (Figure 2). This sensor network data will be supplemented with manual profiles of the water column during the trials and other existing and planned deployments of water quality sensors through the harbour more broadly. A key purpose of the sensor array near the discharge point will be to ensure that the area of supersaturated water is minimised and consistent with modelling predictions (see below).

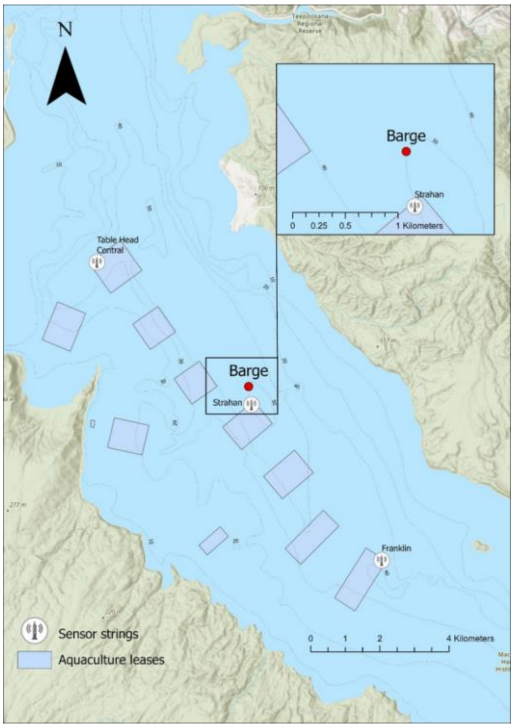

Figure 2 Map showing leases in the harbour, the location of the barge (see outlet pipe) and the 3 environmental strings that have been operational since 2015.

Visual monitoring

The presence and activity of mobile fauna (e.g. fish) in response to oxygen activity will be monitored and analysed using a combination of fixed and portable cameras.

A fixed camera with a live feed is in place on the oxygen system facing the ejection nozzles. This camera is key to ensuring bubble formation is minimal (formation of excessive bubbles can lead to upwelling, potentially creating issues for animals above the halocline) and that any animal interactions with the oxygenated plume are monitored. Two additional cameras are deployed on a frame that is located below the discharge wheel, facing upwards and in different directions to ensure multiple points of view. All cameras have lights and video feeds are viewable in real time on the AXIS dashboard (Figure 4).

[2] the distances and depths will vary between trials, but typically span 0 - 250m from the discharge point in each direction and across depths from 20 - 40m.

Remotely operated vehicle (ROV) surveys will also be conducted before, during and after the oxygenation trials. These will provide another source of information for assessing any potential impacts on wildlife or larger fauna. ROV surveys will involve dropping a weighted shot line on a predetermined GPS location, deploying the ROV down this line to the seafloor and then travelling for a set duration along a compass bearing. This transect will be repeated at the proposed depth of the oxygenation outlet. This repeatability will allow comparisons in time to assess any impact of the oxygenation system.

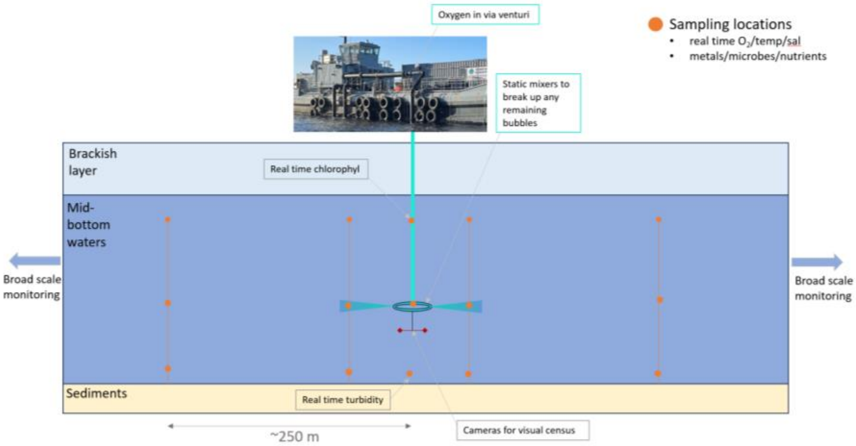

Figure 3 Conceptual diagram showing the location of the real time logger strings relative to the outlet pipe.

Water Column and sediment sampling

To characterise the response of water column conditions (i.e. beyond that of the oxygen/temperature/salinity) to oxygen injection, samples will be collected before, during and after each trial on 2-4 transects radiating out from the point of injection. On each transect sampling will correspond to the depths and distances where the sensors are deployed (note, the distances and depths sampled will depend on the parameter being measured). Samples will be collected to assess the form and concentration of nutrients (organic carbon, inorganic N & P), heavy metals (e.g. dissolved and total copper) and microbial composition and activity.

To characterise the response of sediments in the area of oxygen enrichment, benthic grabs will also be collected at increasing distances on radiating transects. The sediment surveys will occur less frequently than water column measurements, but at minimum will include a baseline survey before the trials start, 1-2 surveys during the trials, and one survey post the trials. Samples will be collected to evaluate condition (sulphide, redox), nutrient and heavy metal content (C &N) and benthic community structure.

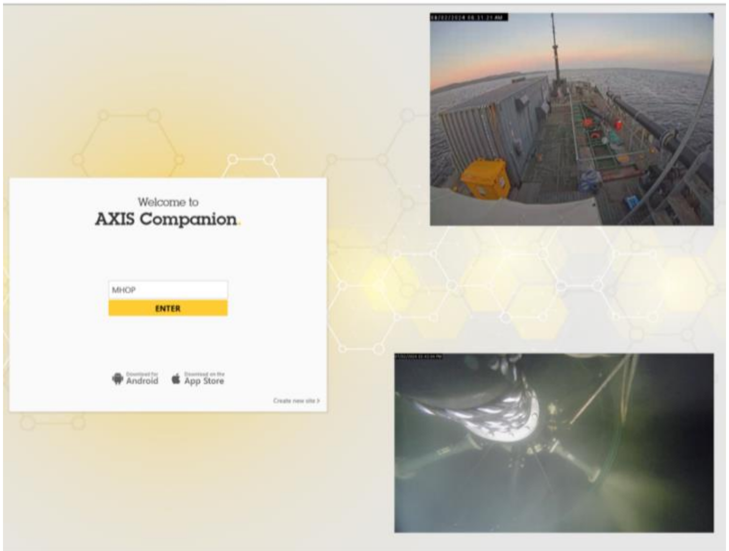

Figure 4 AXIS dashboard for viewing live footage from the deck and cameras deployed underwater

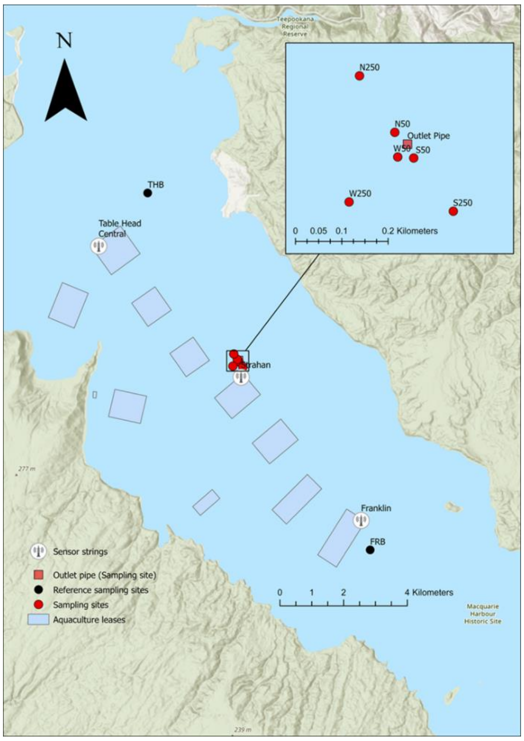

Figure 5 Map showing leases in the harbour, the location of the barge (see outlet pipe) and associated sampling sites. The three environmental strings that have been operational at Table Head Central, Strahan and Franklin since 2015 are also shown.

The role of modelling

The modelling component of the project can be separated into two parts that address different scales and questions. Plume modelling will be used to model the near field environment and the dispersion of oxygen from the point of injection. This modelling will be used to run a range of scenarios to inform injection depth, VSA concentration, and the volume and duration of each pumping trial. The model set up will be informed based on existing profile of the water column and an ADCP current measurements collected at the site. At the broader scale, CSIRO's numerical model of Macquarie Harbour that reproduces the main current and mixing patterns in the harbour will principally be used to assess the feasibility of scaling the trial and the suitability of multiple injection locations.

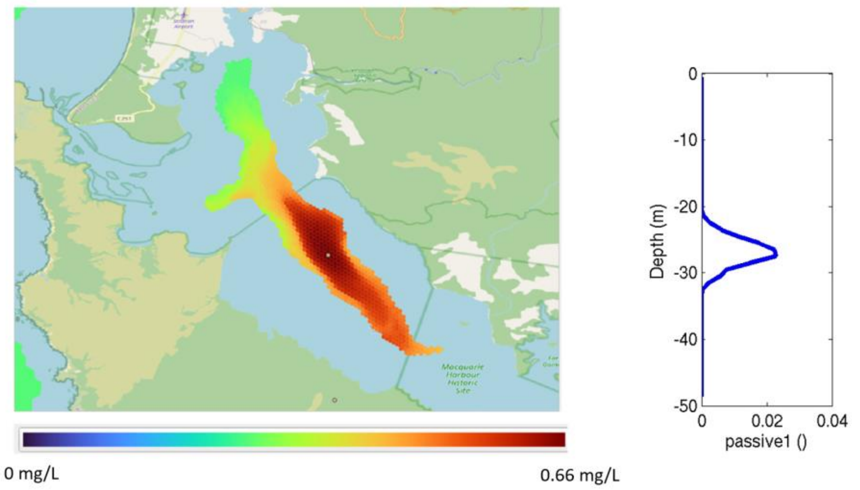

Figure 6 Preliminary model output simulating the release of a passive tracer at the proposed barge location using CSIRO's numerical model of Macquarie Harbour. The output shows the median concentration after one month and a discharge load of 5000 kg oxygen per day; horizontal (left) and vertical (right).

Macquarie Harbour Oxygen Project (MHOP): enhancing oxygen levels at depth

Science Update - Trial #1

March 2024

The “Wombat” barge was successfully fitted out and moored in late January. Before the first trial was initiated, plume modelling was completed to inform the injection depth and load. Based on the design of the discharge wheel, the spread and dilution of the jets from each of the six discharge ports was modelled. Each jet starts with a diameter of 0.076 m and an exit velocity of 5.5 m/s. The jets travel horizontally, entraining seawater so they gradually expand, slow down and show increased dilution with distance (Figure 7). At the ambient current of 4 to 5 cm/s, the jets extend to about 25 m from the rosette before matching the ambient velocity, in the six directions of the ports. Mixing caused by the jets leads to a dilution of 20:1 and a plume width of just over 1.5m at 25m from the rosette. As such the model simulates the spread of oxygenated water over a circle of diameter 50 m and a depth of around 3 -4 m (centred at the depth of discharge). At a discharge concentration of around 40 mg O^2 l^{-1}, the jet dilution will reduce the dissolved oxygen at the end of the spreading jet to around 2 mg O^2 l^{-1}. The jet is likely to extend a bit further at times of weak currents and be diverted and broken up at shorter distance at times of strong currents.

The modelled outputs were further scaled using the CSIRO numerical model of Macquarie Harbour to look at the broader horizontal and vertical dispersion of the predicted plume. The model was used to simulate the release of a passive tracer at the barge location. In Figure 6, the outputs are scaled to show the median concentration after one month and a discharge load of 5000 kg oxygen per day demonstrating the likelihood for significant horizontal spread and dilution throughout the harbour and minimal vertical migration through the water column.

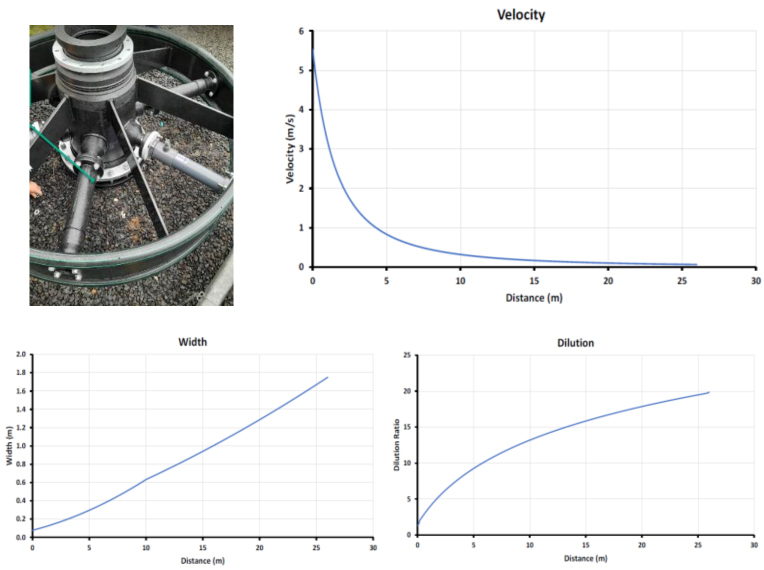

Figure 7 The discharge wheel and radial mixers which terminate as a discharge nozzle. Model results for jet velocity (top right), width (bottom left) and dilution (bottom right) with distance from the discharge nozzle.

The model simulations were then used to inform the survey design and location of environmental sensors, with strings deployed at the barge, 50m and 250m to the north and south (see Figure 3). Sensor strings and the camera system (Figure 4) with live feeds were set up in early February. Baseline sampling of the water column (22/12/2023 & 8/2/2024) and sediments (15/1/2024) was completed in the lead up to the first trial (Figure 5).

On February 20, the first trial commenced, injecting ~ 500kg O_2/day for days 1-3 and 720kg O_2 /day for days 4-7. Extensive water column profiling of dissolved oxygen, salinity and temperature, and grab samples for metals, nutrients and eDNA (microbial community) were collected immediately before, during and after the first trial; see tables 1 and 2 for more detail. From the profiles, the oxygen plume was detectable at 5-10m from the discharge wheel 1 hour after the pumping started, and by day 7, the plume was evident at the 50m sites (Figure 8). There was no evidence of a shift in nutrient concentrations (Figure 9) or metal availability (Figure 10) near, or distant from, the discharge wheel. Whilst there was some evidence of a shift in the microbial community composition in the immediate vicinity (5-10m) of the discharge wheel, the change was small, not observed further away, and within the natural variability observed in the harbour bottom waters.

Table 1 List of the main water quality sites

Sites	Description	** Notes
BN	Barge North	
BS	Barge South	
BW	Barge West	bacteria and 35m only
S50	South 50m	
S250	South 250m	
N50	North 50m	
N250	North 250m	
W50	West 50m	bacteria and 35m only
W250	West 250m	bacteria and 35m only
FRB	Franklin River Basin	
TRB	Table Head Basin	

Table 2 Details of the parameters, sites and depths collected during trail #1.

Time		T0	T1	T6	T24	T72	T168	T 192
Sites **		All	All (excl FRB and TRB)	All (excl FRB and TRB)	All	All	All	All
Depths (m)		5, 20, 35, 45	35	35	35	35	5, 20, 35, 45	35
Replicates		1	1	1	1	1	1	1
Drops per site		1	1	1	1	1	1	1
Analytes	WQ profile	√	√	√	√	√	√	√
	Bacteria eDNA	√	√	√	√	√	√	√
	Nutrients (total and dissolved)	√				√	√	
	NPOC	√				√	√	
	Metals (Dissolved & total)	√				√	√	
	Mercury	√				√	√	
	Site and depth summary	9 sites @ 4 depths plus 2 (west) sites @ 1 depth	9 sites @ 1 depth	9 sites @ 1 depth	9 sites @ 1 depth	9 sites @ 1 depth	9 sites @ 4 depths plus 2 (west) sites @ 1 depth	9 sites @ 1 depth

Next steps

Following a review of the results from the first trial, both the science team and technical advisory committee agreed that there were no environmental responses that were a cause for concern, and that we should proceed with the second trial. Scheduled for mid-April, this trial will run for longer (3-4 weeks) and the load added per day will be increased to 1000kg O_2/day and greater. Modifications will also made to the pipework following the first trial. Notably, the mixers on the discharge wheel were all replaced with the better performing Gaia mixers (now 6 in total), the outlet pipe raised from 35 to 30m depth and external nozzles will be fitted on the diffusers to increase the velocity and spread of the discharge jets.

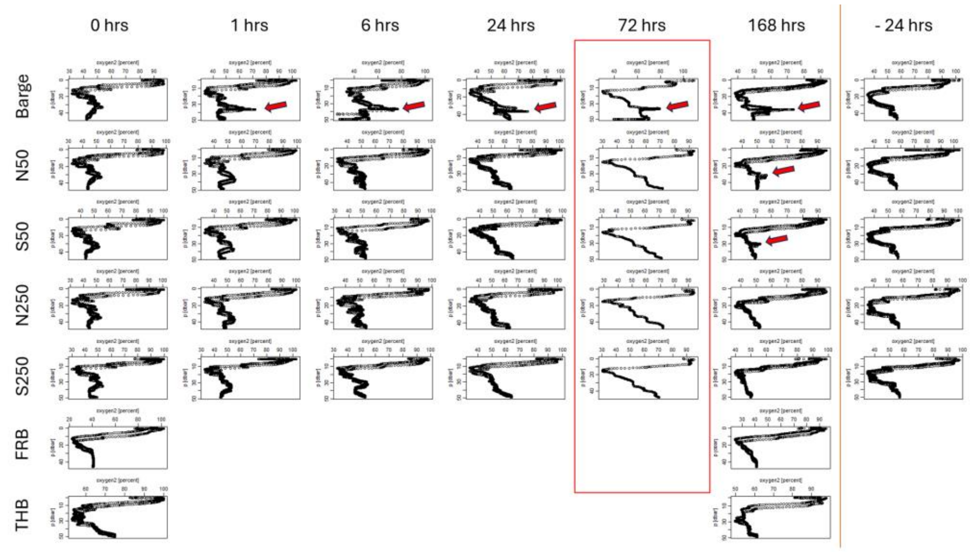

Figure 8 Oxygen profiles across the water quality sites before, during and after the first oxygenation trial. The red arrows identify the oxygen plume.

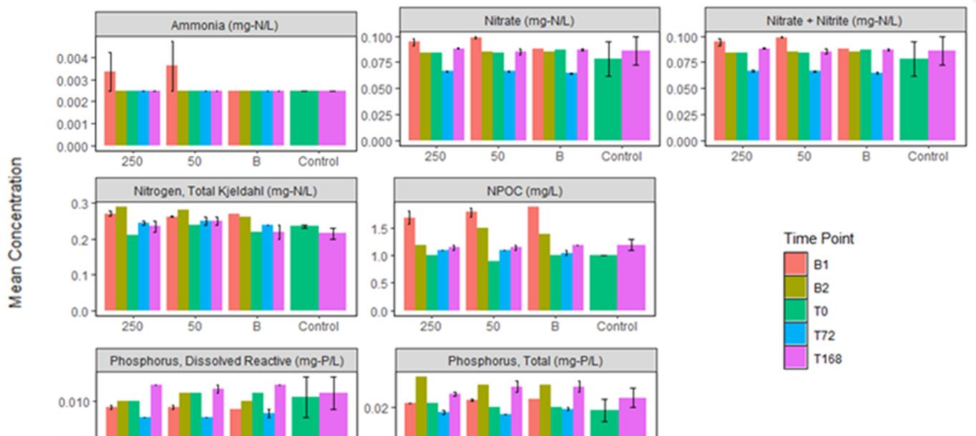

Figure 9 Nutrient concentrations at the water quality sites during the baseline (B1, B2), just prior to the start of the first trial (T0) and at 3 and 7 days during the oxygenation.

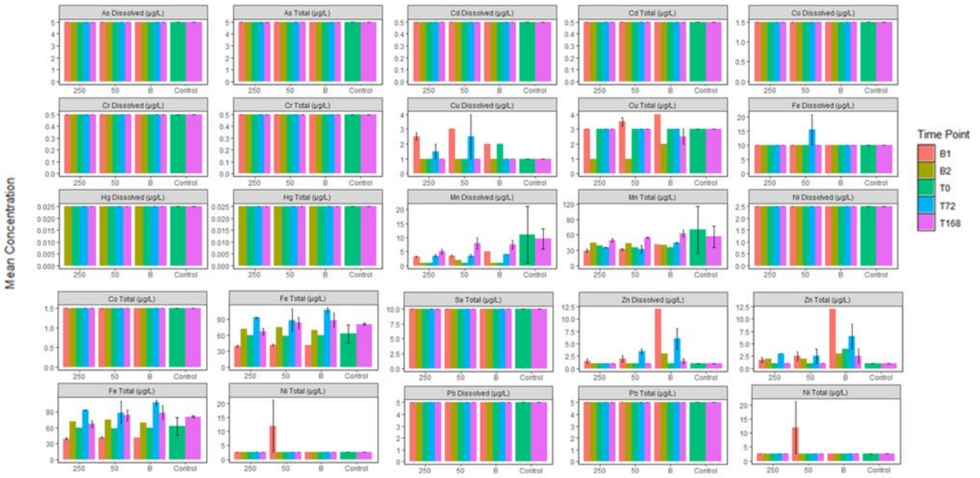

Figure 10 Metal concentrations at the water quality sites during the baseline (B1, B2), just prior to the start of the first trial (T0) and at 3 and 7 days during the oxygenation.

Macquarie Harbour Oxygen Project (MHOP): enhancing oxygen levels at depth

Science Update - Trial #2

July 2024

For the second trial modifications were made to the discharge wheel with the better performing Gaia mixers (now 6 in total) installed on all 6 outlets ports, and external nozzles were also fitted on the end of the mixers to increase the velocity and spread of the discharge jets (Figure 11). The discharge wheel was also raised from 35 to 30m depth to make it more accessible by divers if required. To increase the depth resolution of the *in situ* real time sensors at the depth of the plume at each location (i.e. sensor string), the sensors were redeployed at 2.5m depth increments between 25 and 35m. For this trial the strings were deployed at 100m and 250m to the north and south of the discharge point, with additional sensors deployed at the discharge point (i.e. 0m) at 20m and just above the bottom at 45m depth. At 45m there is a turbidity sensor to ensure that we are not disturbing the sediments, and the sensor at 20m, just below the halocline is to ensure we are not creating an uplift of water and disturbing the halocline.

Figure 11 Discharge wheel in the first (left) and second trial (right) following the modifications to increase the velocity and spread of the discharge jets

On April 17, the second trial commenced, with the oxygen load progressively increased based on performance over a six-week period (see timeline in

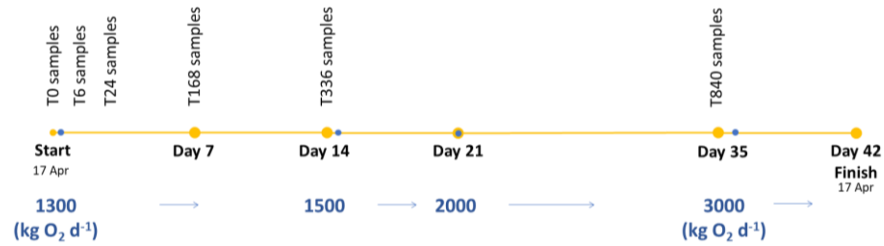

Figure 12). From days 1-14 ~ 1300kg O2/day was injected, 1500kg O2 /day for days 14-21, 2000kg O2 /day for days 21-35 and for the last week the oxygenation system was again increased, injecting to ~ 3000kg O2 /day. During the trial, the CSIRO model was run in forecast mode, simulating the movement and dilution of the injected oxygen as a passive tracer released from the discharge location and subject to local and regional hydrodynamics (Figure 13).

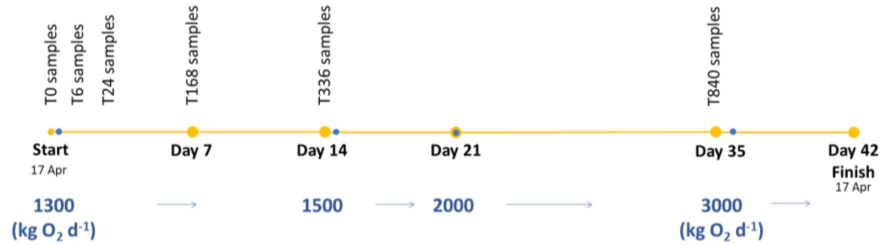

Figure 12 Timeline for trial #2 with the yellow dots representing when environmental samples were taken and the blue dots when the oxygen delivery was started and increased

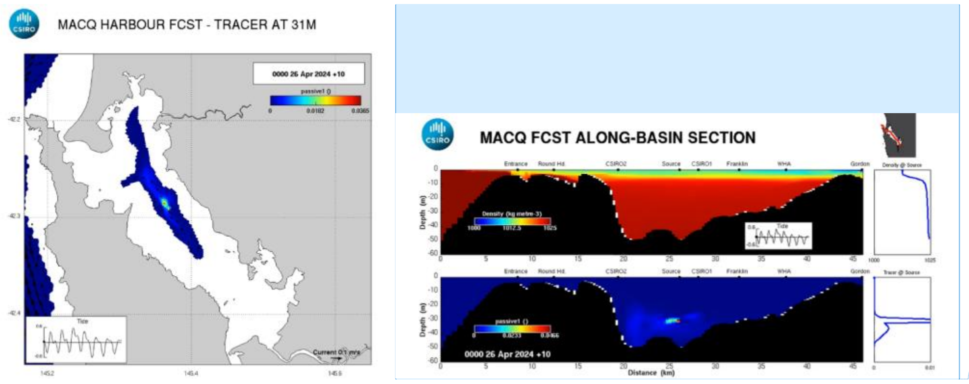

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Figure 13 Model output for trial #2 simulating the release of a passive tracer at the barge location using CSIRO's numerical model of Macquarie Harbour including the cross harbour view on the right (Storm Bay Modelling & Information System (csiro.au)).

Water column profiling of dissolved oxygen, salinity and temperature, and grab samples for metals, nutrients and eDNA (microbial community) were collected immediately before, during and after the second trial; see table 3 for more detail. Not surprisingly, when considering the dynamics of the plume and its variation in extent and direction demonstrated in the model, clear detection in both the profiles and fixed position environmental strings proved challenging. For the profiles taken at the water quality and string sites, the plume was clear in the immediate vicinity (5-10m) of the discharge wheel at the

Table 3 Details of the parameters, sites and depths collected during trail #2.

								POST PUMPING
Time		T0	T6	T24	T168 (1 week)	T336 (2 weeks)	T504 (3 weeks)	T840 (5 weeks)	P0 (6 weeks)
Sites		All	BN, BS, BW	BN, BS, BW	All	All	Oxygen plume Vertical and lateral profiles (~30 m)	All	All & oxygen plume Vertical and lateral profiles (~30 m)
Depths (m)		5, 20, 30, 45	30	30	5, 20, 30, 45	5, 20, 30, 45		5, 20, 30, 45	
Analytes	Bacterial eDNA	✓			✓	✓		✓	
	Bacterial eRNA	✓ (30 m barge only)	✓ (30 m barge only)	✓ (30 m barge only)	✓ (30 m barge only)	✓ (30 m barge only)		✓ (30 m barge only)	
	Water nutrients and metals	✓			✓	✓		✓	
	CTD profile	✓	✓	✓	✓	✓	✓	✓	✓
	ROV	✓			✓	✓		✓	

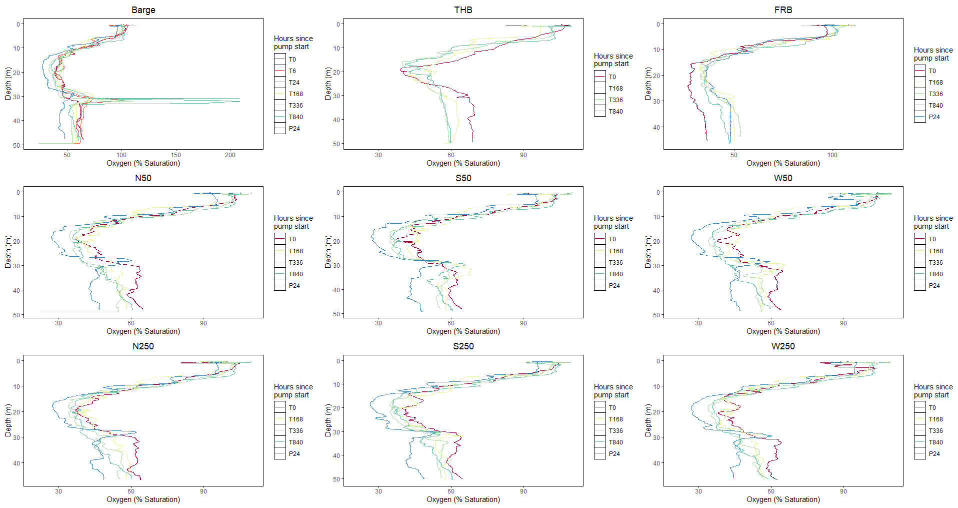

Figure 14 Oxygen profiles across the water quality sites before (T0), during (T168, T336, T840) and after (P24) the first oxygenation trial.

barge (Figure 14). At one week and two weeks into the trial, concentrations just over 100% were detected and at 5 weeks concentrations exceeded 200% saturation in the immediate vicinity of the discharge wheel. These concentrations are consistent with expectations based on the oxygen load added and dilution. The detection of the plume at the more distant stations was more variable. At 50m, the plume was more evident to the south and west at the time of profiling, with increases of 10-15% oxygen saturation typical. Notably, concentrations remained elevated, with an increase of 10-20%, in the profiles taken a day after the pumping was ended, but following a period where the oxygen load was ~ 3000kg O2 /day. At the 250m stations there was also evidence of the plume in each direction depending on the date of sampling, with increases of 10-15% saturation observed. At the real time strings 100 and 250m to the south and north it is difficult to see any shift in oxygen concentrations against a highly variable background in the first few weeks of the trial, but after 2-3 weeks when the oxygen load approached ~ 2000kg O2 /day, there was a noticeable increase in variation and maximum concentrations observed. Concentrations of over 70% became regular and this wasn't seen at comparable depths at the nearby Strahan (~700m away) or more distant long term string locations.

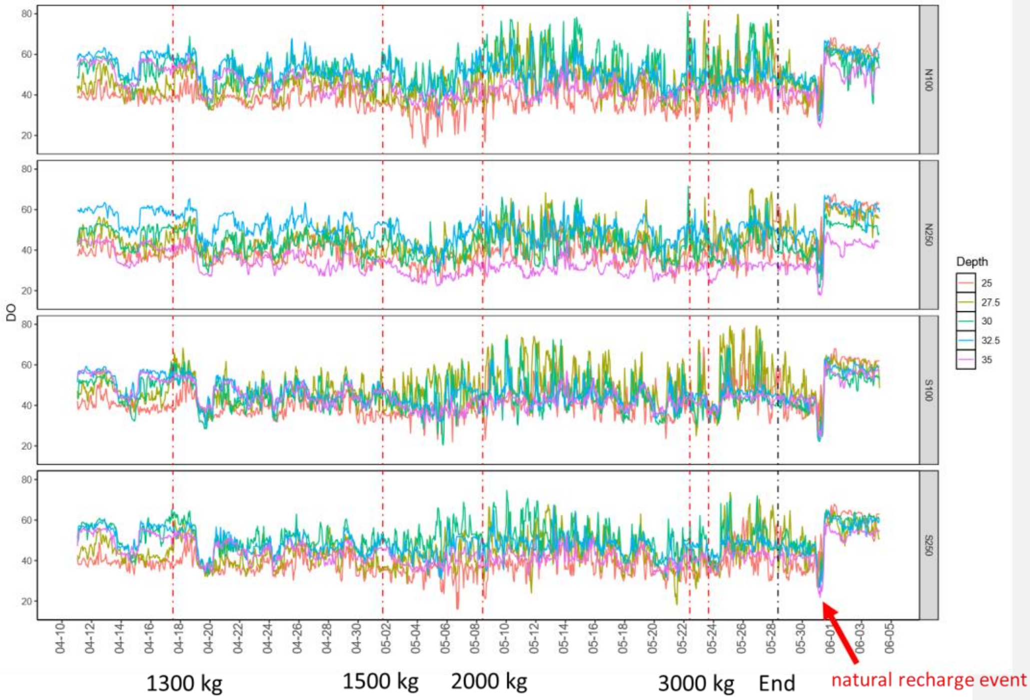

Figure 15 Oxygen concentrations measured in real time at the sensor strings to the north and south of the discharge location before, during and after the trial #2 oxygenation. Notably, 3 days after the trial finished there was a recharge and overturning event following a period of very strong NW winds.

To provide a more detailed picture of the plume, we trialled a method to map the plume one day after the pumping finished by profiling up and down through the plume depth whilst gradually moving along a transect from the outlet. The picture this produced indicated a plume of elevated (↑ 5-10% saturation) oxygen approximately 800m long and 5-10m thick. This method will be developed further and mapping the plume in greater resolution will be a major focus of the next trial.

Particularly noteworthy is the natural recharge event captured on the string sensors 4 days after the pumping was stopped. This reflected a period of stormy weather and strong NW winds down the harbour which drove intense vertical mixing of the water column. Oxygen levels at the string depths first went down before increasing and stabilising. This reflects the lower oxygen water that resides immediately above (~15-20m) the sensor depths (25-35m), first mixing downwards and then followed by the shallower more oxygenated waters.

Consistent with trial#1 was no evidence of a shift in nutrient concentrations (Figure 9) or metal availability (Figure 10) near, or distant from, the discharge wheel. For some parameters, concentrations changed throughout the trial, but there were no patterns with proximity to the discharge wheel. Similarly, there was clear evidence of a shift in the microbial community composition in time, but there was no evidence of a change in composition with proximity to the discharge wheel.

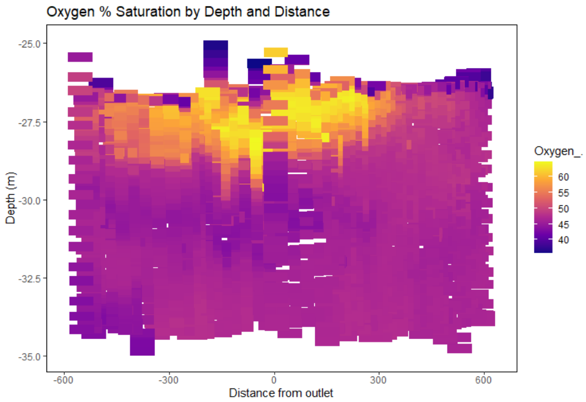

Figure 16 Oxygen concentration at depth and distance from the outlet based on profile mapping of the plume one day after the pumping was stopped.

Next steps

A third trial will commence mid-August with loads to be progressively increased beyond 3000kg O2/day. It is likely that we are approaching the maximum load capacity for the discharge wheel, beyond which we will start to see oxygen come out of solution and form larger bubbles, at which stage we will install a second discharge wheel. The aim with be to approach the maximum capacity of the oxygen generator (5000kg O2/day) by utilising two discharge wheels. A focus of the environmental monitoring for this trial will be more focused profiling and mapping of the oxygen plume. This may also include the use of the inert fluorescent dye rhodamine as a tracer of the injected water and oxygen.

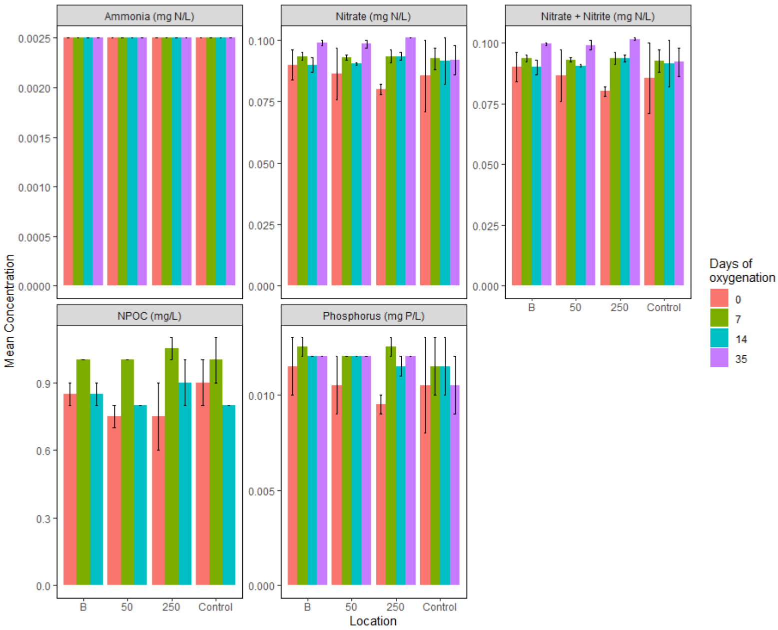

Figure 17 Nutrient concentrations at the water quality sites just prior to the start of the second trial (T0) and at 1, 2 and 5 weeks during the oxygenation

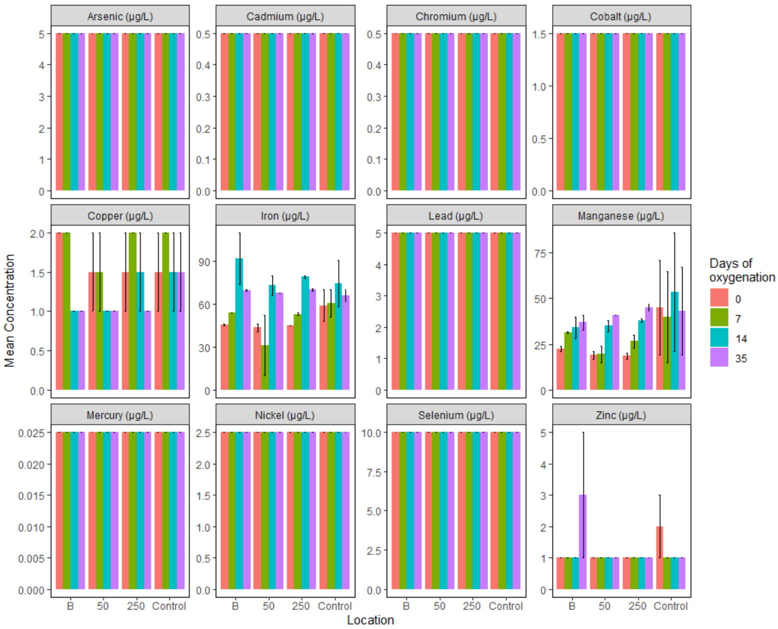

Figure 18 Total metal concentrations at the water quality sites just prior to the start of the second trial (T0) and at 1, 2 and 5 weeks during the oxygenation

FRDC: FRDC is a co-funded partnership between the Australian Government and fishing and aquaculture. As statutory corporation, FRDC plans, invests in and manages R&D for fishing, aquaculture and the wider community and encourages adoption of the resulting knowledge and innovation for impact.

IMAS: The Institute for Marine and Antarctic Studies (IMAS) is an internationally recognised centre of excellence at the University of Tasmania whose mission is to improve understanding of temperate marine, Southern Ocean and Antarctic environments, their resources, and their roles in the global climate system through research, education and outreach.

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