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Department of **Primary Industries and Regional Development**

Oxygenating the Vasse estuary exit channel

The results of a two year trial 2015 - 2017

Revitalising Geographe Waterways

VASSE taskFORCE

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The results of a two year trial 2015 - 2017

Securing Western Australia’s water future

Department of Water and Environmental Regulation

Water Science Technical Series

Report no. 83

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Cover photograph: Aerial photograph of the surge barrier and the Vasse exit channel showing the two oxygenation pumps, taken by Ashley Ramsey, Department of Water and Environmental Regulation.

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Summary

The Vasse estuary is the most nutrient-enriched estuary in south-west Western Australia. Symptoms of eutrophication are particularly evident in the Vasse estuary exit channel where low oxygen conditions have led to large fish kills.

Low oxygen concentrations result from an imbalance between the rate of oxygen consumption and the natural processes of replenishment. Resetting the balance is challenging. While broad-scale actions – such as the reduction of nutrient loading from the catchment – are underway, water resource managers may look to engineered means to supplement oxygen levels. Artificial oxygenation, while not commonly applied to shallow estuaries, has been extremely effective at improving oxygen conditions in the Swan and Canning Rivers, Perth.

In the summer and autumn of 2015-16 (year 1) and 2016-17 (year 2) the Department of Water and Environmental Regulation undertook a trial to assess if artificially oxygenating the Vasse exit channel upstream of the surge barrier was a viable option for improving water quality. The trial was in response to the poor water quality exhibited in the Vasse exit channel over summer and the risk of fish kills due to low oxygen concentrations. It used the proven concepts of oxygenation, but employed more flexible and less permanent technology than that used by the plants on the Swan and Canning Rivers.

The primary objectives of the oxygenation trial were to:

1. **Show proof of concept** - successfully install, operate and monitor a small artificial oxygenation plant upstream of the surge barrier.
2. **Determine plant capability** - assess the ability of the plant to maintain dissolved oxygen at concentrations above that which may limit ecological function, defined here as 4 milligrams per litre (mg/L).
3. **Determine the impact on the likelihood of a fish kill** - assess the ability of the plant to reduce the likelihood of a fish kill by minimising the occurrence of hypoxic oxygen concentrations, defined here as 2 mg/L, below which concentrations may result in fish mortalities.

There are numerous benefits of a well-oxygenated water body and the provision of an aerobic sediment-water interface. The release of reduced chemical species such as ammonia and phosphorus from the sediment into the overlying water column is limited, as is the production of hydrogen sulphide and other odorous and potentially toxic gases. In addition, the oxidisation component of the nitrogen cycle (oxidation of ammonium to nitrate and subsequent denitrification of nitrate to inert nitrogen gas) and the aerobic breakdown of organic matter in the sediment is facilitated.

The trial utilised new BOC Solvox drop-in oxygenation technology to add high concentrations of oxygen *in-situ*. A fenced compound on the eastern bank adjacent to the surge barrier housed a liquid oxygen vessel, a vaporiser to convert liquid to gaseous oxygen, a phase convertor to supply three-phase power and a control panel. Oxygen and electrical supply lines ran from the compound to two compact and

efficient BOC Solvox drop-in units; one located near the surge barrier (20 m upstream in year 1 and 115 m upstream in year 2) and a second further upstream (210 m upstream in year 1 and 345 m upstream in year 2). The units drew water at a rate of 20 L/s, adding oxygen under high pressure at a rate of 1 – 6 kg/hr, prior to discharging back into the channel. They operated most commonly in dissolved oxygen control (DO control) mode, turning on and off in response to triggers when the real-time measured dissolved oxygen concentration reached defined oxygen thresholds.

Measuring the impact of the plant was challenging as oxygen concentrations are influenced by an array of physical, biological and chemical variables which cannot be controlled in a real-world trial. To meet objective 1; proof of concept, we undertook short, intensive periods of monitoring (effectiveness testing), measuring dissolved oxygen and a range of other physical and chemical variables under different operating regimes. Background environmental variability was minimised by the short temporal scale and data limitations were carefully considered when drawing conclusions. The aim of effectiveness testing was to determine whether dissolved oxygen increased when the plant was operating and decreased when it was switched off.

Once the ability of the plant to add oxygen was established, it was assessed for its ability to maintain oxygen concentrations above the critical thresholds of 4 mg/L and 2 mg/L, measures of its performance relative to objective 2; plant capability and objective 3; impact on the likelihood of a fish kill. Dissolved oxygen, salinity, pH, turbidity and water temperature were measured through the water column at seven sites upstream of the surge barrier in year 1 and 11 sites in year 2. Field observations and samples to be analysed for total nitrogen, dissolved inorganic nitrogen, dissolved oxidised nitrogen, ammonium, total phosphorus, chlorophyll *a, b, c* and phaeo-pigments and phytoplankton density were also collected. While weekly changes in the transect data gives an indication of trends in water quality, and potential relationships between variables, it is very difficult to disentangle the impact of plant operation on oxygen concentrations from the highly variable background concentrations. As such, when measuring ‘plant success’ we looked at the percentage of time that each pump was operating and oxygen concentration measured at the respective monitoring buoy were above the 4 mg/L and 2 mg/L thresholds.

Major findings from the trial were:

Objective 1: Show proof of concept

- The BOC Solvox drop-in oxygenation units are suitable to the shallow and estuarine Vasse exit channel, working best where operation was automatically triggered when oxygen concentrations dropped below 4 mg/L. Losses of oxygen to the atmosphere appeared to be minimal.
- In year 1 pumps ran for a total of 1243 hours, adding 1515 kg of oxygen while in year 2 pumps ran for a total of 2085 hours adding 6145 kg of oxygen.

- The oxygenation plant improved dissolved oxygen concentrations in the trial area (470 m upstream of the surge barrier) and each pump influenced a stretch of approximately 250 m.
- Effectiveness testing showed that the plant was able to substantially increase dissolved oxygen concentrations, however, the magnitude of its impact was highly dependent on internal oxygen demand which was strongly driven by phytoplankton dynamics.

Objective 2: Determine plant capability

- For much of the trial period, the plant was able to maintain adequate oxygen levels. However, the plant could not maintain critical oxygen concentrations during the respiration phase of a large algal bloom, where rapid drawdown of oxygen exceeded the capacity of the plant.
- Plant capability was quantified by the percentage of time that the plant was operating and able to maintain dissolved oxygen above 4 mg/L; 62% of the time in year 1 and 45% in year 2. Without the operation of the plant, the system would have exhibited low oxygen concentrations or hypoxia during these times.

Objective 3: Determine the impact on the likelihood of a fish kill

- The ability of the plant to mitigate the likelihood of a fish kill was quantified by the percentage of time that the plant was operating and able to maintain dissolved oxygen concentrations above the hypoxic threshold of 2 mg/L; 82% of the time in year 1 and 67% in year 2. Without the operation of the plant, the system would have been hypoxic during these times.

Seasonality and other factors influencing oxygenation success

Understanding the seasonality and daily demand for supplementing oxygen is an important outcome of the trial. While fish kills are more likely to occur in the warm summer months of December, January and February, extensive low oxygen conditions measured in May and June in year 1 of the trial suggest that fish kills are also a risk at other times of the year. The demand for plant operation is likely to be at its highest in the morning, but when operating in DO control, operation was triggered at all times of the day.

Stratification, due to layers of differing salinity or temperature, has the potential to exacerbate low oxygen concentrations in bottom waters, as well as prevent the mixing of artificially oxygenated water through the water column.

Oxygenation may increase oxygen demand by stimulating aerobic decomposition and as such, abruptly ceasing plant operation may lead to a deoxygenation event, a phenomenon that may have contributed to very low oxygen concentrations exhibited in June in year 1 of the trial.

Recommendations

Artificial oxygenation was found to be a viable method of responding to low oxygen concentrations in the Vasse exit channel. An oxygenation facility should be considered as part of the larger remediation strategy that includes a suite of management tools such as the manipulation of flows at the surge barrier. Alternative management actions that limit extreme algal blooms, and the subsequent rate of respiration-driven oxygen drawdown would reduce the size of the plant required to prevent hypoxia.

1 Introduction

1.1 Why is there an oxygen problem in the Vasse estuary?

The Vasse Estuary is the most nutrient-enriched estuary of south west Western Australia, due to intensive land use within its catchment, poor nutrient-retaining soils and an extensive artificial drainage network (McAlpine et al. 1989; Hugues-dit-Ciles et al. 2012). It periodically displays the symptoms typical of a eutrophic system including: macro and micro algal blooms, foul odours, low visual amenity and fish deaths. These symptoms are particularly evident in the Vasse estuary exit channel, the stretch of estuary directly upstream of the surge barrier.

A key water quality parameter contributing to these symptoms is dissolved oxygen. Hypoxic oxygen concentrations (defined here as less than 2 mg/L) in coastal environments are increasing throughout the world (Conley et al. 2009; Wu 2002) and arise from an imbalance between the supply of oxygen by atmospheric exchange and photosynthesis and consumption of oxygen by processes such as decomposing organic matter or respiring organisms. While periods of hypoxia may occur naturally within estuaries, eutrophication of the water body as a result of increased nutrient loading from anthropogenic sources has increased the severity and longevity of such periods (Harris et al. 2015; Middelburg & Levin 2009). One of the most evident consequences of sudden reductions in dissolved oxygen is fish kills.

Resetting the balance between oxygen replenishment and consumption is a challenging task for estuaries with heavily modified catchments. While broad scale approaches such as the reduction of nutrient loading are underway, water resource managers may look to engineered means, such as artificial oxygenation, to assist in maintaining aerobic conditions.

1.2 The history and function of the Vasse estuary surge barrier

The Vasse estuary surge barrier was first installed in 1908 to prevent seawater inundation of agricultural land over summer and to protect the township of Busselton from storm surges. The surge barrier has several mechanical components that can be manipulated to control flow. A series of floodgates allow outflow from the channel when water levels are higher than in Wonnerup Inlet but prevent seawater inflow, thereby mitigating flood risk from storm surges. Check boards are installed at the end of winter and removed in autumn to retain water and provide higher summer water levels in the estuary. A fish gate can be opened in summer to facilitate the passage of fish and allow some seawater to pass into the estuary to maintain minimum water levels at approximately -0.1 mAHD. Marine water may also be added as a means of mitigating poor water quality upstream. A propped gate can be opened to allow small volumes of water to flow from the estuary into the Wonnerup Inlet when the check boards are in place. This has been used to flush algae out of the estuary in the past.

The guidelines for the management of the fish gate and the Wonnerup Inlet sand bar were established in 1990 and are currently being reviewed (Lane et al. 1997).

1.3 Low dissolved oxygen and fish kills

Fish kills have been recorded in the Vasse Wonnerup wetlands system since 1905, with the most frequent events occurring during spring, summer, and autumn. In the last decade, most of the recorded fish deaths have occurred either in the Vasse estuary exit channel or between the floodgates and the sand bar in the Wonnerup inlet. Low dissolved oxygen has been implicated in the majority of fish kills, frequently combined with other stressors related to poor water quality such the clogging of gills and exposure to toxins released by decaying algae and macrophytes (Lane et al. 1997).

1.4 Trialling ‘mobile, drop-in’ oxygenation technology

In order to mitigate periods of low dissolved oxygen, a trial of a temporary oxygenation plant was undertaken in the Vasse estuary exit channel. The trial was a component of the broader project, *Revitalising Geographe Waterways*, and formed part of the “Vasse Surge Barrier Actions” which aim to improve water quality conditions in the Vasse estuary, upstream of the surge barrier.

The trial spread over two operating seasons, the first from January to June 2016 (year 1) and the second from November 2016 to June 2017 (year 2). The plant added oxygen to two locations directly upstream of the Vasse surge barrier, the details of which are discussed in Section 2.

The primary objectives of the oxygenation trial were:

1. **Show proof of concept** - successfully install, operate and monitor a small artificial oxygenation plant upstream of the surge barrier.
2. **Determine plant capability** - assess the ability of the plant to maintain dissolved oxygen at concentrations above that which may limit ecological function, defined here as 4 mg/L.
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There are numerous benefits of a well-oxygenated water body and the provision of an aerobic sediment-water interface. The release of reduced chemical species such as ammonia and phosphorus from the sediment (Beutel 2006) into the overlying water column is limited, as is the production of hydrogen sulphide and other odorous gases. In addition, the oxidation component of the nitrogen cycle (oxidation of ammonium to nitrate and subsequent denitrification to inert nitrogen gas) and the aerobic breakdown of organic matter in the sediment is facilitated.

The challenge of undertaking such a trial is isolating the impacts of plant operation from the large background variability exhibited by the system (Section 3). As such, the effectiveness of the plant was accessed in two ways (Section 4). Firstly, did the technology work in this application; specifically, was there an increase in oxygen when the plant was operating and a decrease in oxygen when it was switched off? To achieve this, effectiveness testing was carried out in each operating season over a one or two week period to measure the rate of increase and decrease in dissolved oxygen when the plant was switched on and off. While oxygen concentrations still incorporated background variability, the short temporal scale made it possible to identify patterns associated with plant operation.

Secondly, if the plant is able to add dissolved oxygen to the system, can it do so at a rate that maintains oxygen concentrations above the critical thresholds of 4 and 2 mg/L over the operating season, the latter being particularly important in reducing the likelihood of a fish kill? This second measure is more challenging to disentangle from the highly variable background fluctuations in dissolved oxygen. Analysis was undertaken of both seasonal patterns in oxygen concentration over the operating season, as well as the performance of each pump to maintain oxygen concentrations above the low oxygen and hypoxic threshold at its respective monitoring buoys.

Practical considerations for undertaking oxygenation in the medium-term are outlined in Section 5 and a discussion of the trial in the context of its greater implications is included in Section 6. Findings are summarised in Section 7 and general recommendations are given in Section 8.

1.5 Defining critical thresholds

Within this report dissolved oxygen concentrations are considered against two key oxygen concentrations thresholds defined as;

- Low oxygen threshold (<4 mg/L) – below this threshold, various sub-lethal effects may be experienced (e.g. growth and reproductive impairment) and behavioural changes may be exhibited (e.g. avoidance, cessation of foraging) by certain aquatic species. Above this threshold, dissolved oxygen (DO) is not considered to be a limiting factor for species survival and ecological function.
- Hypoxic threshold (<2 mg/L) – Below this threshold, sensitive aquatic species are likely to exhibit signs of acute stress and modified behaviours (e.g. hyperventilation and gulping at the surface), and depending on other variables, death may result.

2 What we did: A description of the trialled technology

The land-based component of the plant was contained within a fenced compound on the road reserve on the eastern side of the Vasse estuary surge barrier. It consisted of an oxygen vessel to store liquid oxygen, a vaporiser to convert liquid to gaseous oxygen, a phase convertor to supply three-phase power and a control panel (Figure 1).

Figure 1 The land-based plant on the eastern side of the Vasse estuary surge barrier

The in-river components of the plant were two BOC Solvox drop-in units; one located near the surge barrier (20 m upstream in year 1 and 115 m upstream in year 2) and a second located further upstream (210 m upstream in year 1 and 345 m upstream in year 2). In year 1 the units were mounted on frames that sat on the estuary bed, while in year 2 they were suspended from two large buoys, which were secured by anchors (Figure 2). The in-river units were connected to the land-based plant by electrical and gaseous oxygen supply lines (Figure 3).

The Solvox drop-in units are new technology which has previously been applied by BOC successfully in the aquaculture industry. They are compact (approximately 1.5 m long and 25 cm in diameter), and contain a submersible pump, an oxygen dissolver and a distribution system. While the two units are commonly referred to as pump 1 and pump 2, it is important to note that the pump itself is just one component of the system. Each unit pumped water at a flow rate of 20 L/s and added oxygen at flow rates ranging from 1 - 6 kg/hr, at high dissolution efficiencies, which is an essential requirement for application to the shallow Vasse estuary exit channel, where short contact times do not facilitate in-river dissolution of oxygen bubbles. The Vasse oxygenation plant utilised different oxygenation technology to the permanent plants that operate on the Swan and Canning rivers in Perth, Western Australia, but was based on similar principles.

Figure 2 (a) A Solvox drop-in unit mounted on a frame in year 1 of the trial, with oxygen (blue) and electricity (black) supply lines (b) Contractors lowering a unit into the estuary to be suspended in the water column by a buoy in year 2 of the trial (c) The Vase1 monitoring buoy, and the two distinct oxygen plumes of pump 1 in year 1 of the trial.

The plant had several modes of operation, including a simple on and off function, timer mode and DO control. DO control was the preferred mode of operation in which the units turned on and off when real-time dissolved oxygen concentrations dropped below or above operator-defined thresholds. The two units operated independently of each other with pump 1 and pump 2 triggered by DO measured at the Vase1 and the

Vase1Ref monitoring buoys respectively (Figure 4). Because of this independence, the timing, duration, and impact of operation may be very different for each of the units across an operational season. Subsequently, the results of the trial are often specifically discussed for each of the units and for each of the monitoring buoys to highlight differences due to location.

While it is possible to modify the DO control triggers, in general, the units switched on when the monitoring buoys measured oxygen concentrations below 4 mg/L and switched off once concentrations had elevated to either 6 or 8 mg/L.

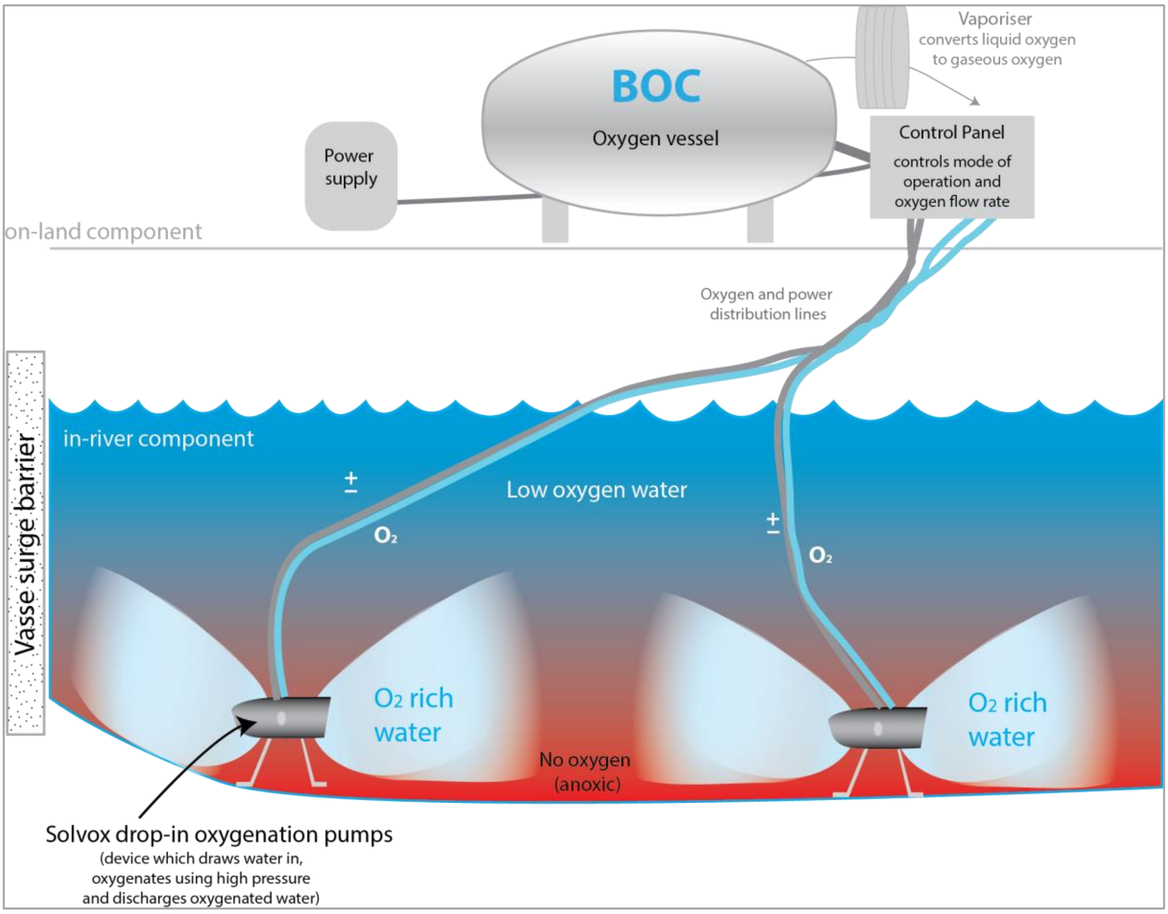

Figure 3 Major on-land and in-river components of the Vasse oxygenation plant

Figure 4 Location of oxygenation plant compound, in-river units and monitoring buoys in both years of the trial

The initial installation of the Vasse oxygenation plant was completed in December 2015, but it was not fully operational until 21 January 2016. In year 1 of the trial, the plant operated from 21 January to 10 June 2016, before being temporarily decommissioned in August 2016. The land-based plant was isolated from power and oxygen, and the in-river Solvox units and associated electrical and oxygen supply lines were disconnected and removed for cleaning and maintenance. The exterior of the Solvox units were heavily bio-fouled, particularly from mussel and barnacle growth, but the interior of the pumps were relatively clean. In November 2016 the Solvox units were reinstated, and year 2 of the trial ran from 16 November 2016 to June 2017, prior to permanently decommissioning the plant infrastructure.

3 Prevailing environmental conditions; two very different testing years

3.1 Weekly water quality monitoring

Water quality monitoring was carried out as part of the Vasse Estuary Seawater Inflow Trial (VASSIT) sampling program. Samples were collected one to three times per week from November to April, and monthly for the rest of the operating season in year 1 and weekly in year 2. The routine sampling included seven sites upstream of the surge barrier in year 1 and 11 sampling sites in year 2 (Appendix A).

At each site along the transect, DO, salinity, pH, turbidity and water temperature were measured at 0.2 m intervals from the water surface down 0.2 m above the river bed using a YSI ProDSS sonde. Additionally, field observations, including light penetration (Secchi) depth, the percentage of cloud cover, wind speed and direction, water colour, and presence of algae and smell were recorded.

Grab water samples were collected from the surface (0.2 m below the surface) and bottom (0.2 m above the sediment) weekly at Vase1 and analysed for total nitrogen, dissolved inorganic nitrogen, dissolved oxidised nitrogen, ammonium, total phosphorus, and filterable reactive phosphorus. Surface samples were also analysed for Chlorophyll *a, b, c* and phaeo-pigments in year 1 and both surface and integrated (integrated over the depth of water column) samples were analysed for Chlorophyll *a, b, c* and phaeo-pigments in year 2. In both trial years integrated samples were analysed for phytoplankton cell density.

3.2 Surge barrier controls and the impact of water levels, temperature and salinity

The management actions and the environmental conditions in the Vasse estuary exit channel were very different across the two years of the oxygenation trial. In year 1, the fish gate of the Vasse surge barrier was opened on 5 January in response to low water levels and poor water quality. As a result of seawater inflow, salinity in the exit channel increased from 13 ppt (brackish) to an average of 37 ppt (saline), and stayed saline for the remainder of Year 1 of the trial (Figure 5). Average midday temperature increased marginally from 25.8°C to 26.5°C following the opening of the fish gate (Figure 5).

In year 2, water levels were higher than in previous years, so as part of the seawater inflow trial the fish and propped gates of the surge barrier were left shut throughout the summer months as the -0.1 m water level threshold for gate opening was not reached until March. Consequently, salinity was much lower in year 2 of the trial until 9 March 2017 when the fish and propped gates were opened to reduce phytoplankton density and to maintain critical water levels (Figure 5). On average, salinity and midday temperature in the exit channel was 8 ppt and 25.3°C respectively in January and February 2017. After the opening of the fish and propped gates, salinity increased to an average of 34 ppt and midday temperature decreased to an average of 20°C.

Actions at the surge barrier can also strongly influence the presence of stratification in the Vasse exit channel. Stratification is the presence of discrete density layers within the water column; the result of differences in surface and bottom water salinity and/or temperature. Stratification inhibits the vertical mixing of the water column, preventing the resupply of oxygen from the naturally oxygenated surface waters to the bottom waters. Stratification may result from the intrusion of marine water upstream with the controlled opening of the surge barrier (e.g. December and January of year 1), from inflows of fresher catchment runoff following rainfall (e.g. mid-January and June year 1), or from uneven warming of the water body due to solar radiation (e.g. late December and early January of year 2). The larger the difference in salinity or temperature across layers, the more inter-mixing will be inhibited. Restricted mixing has consequences for both nutrient release and the impacts of oxygenation. Nutrients released from the sediment due to degradation of organic matter will be concentrated in bottom layers, rather than being diluted through the whole water column. When artificially oxygenating, added oxygen will contained in the density layer of the treated water.

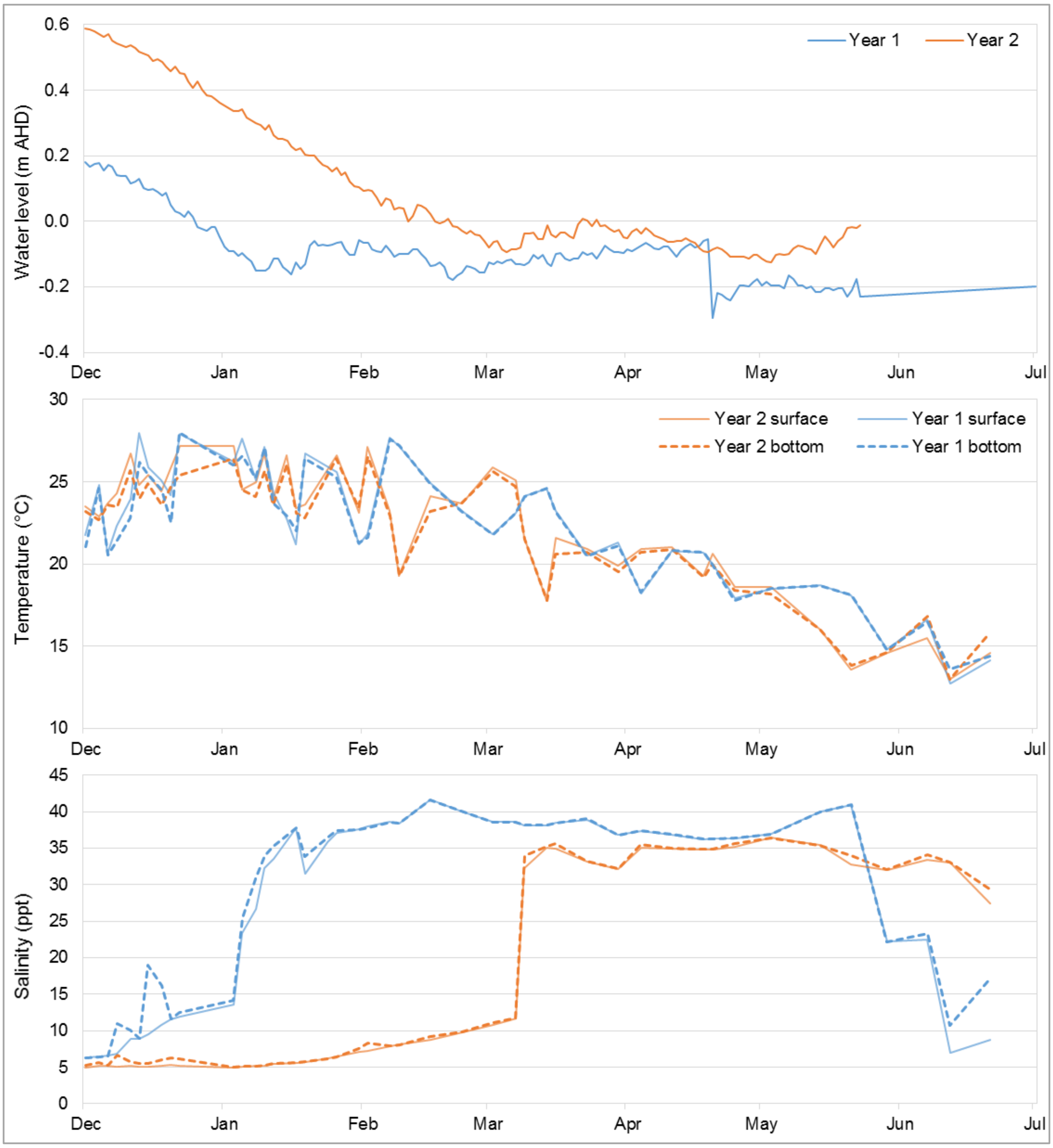

Figure 5 Water levels (m AHD) at the surge barrier and weekly surface and bottom temperatures (°C) and salinity (ppt) in years 1 and 2

3.3 Phytoplankton dynamics

Major differences in salinity and temperature contributed to different phytoplankton populations across the two years of the oxygenation trial. The concentration of photosynthetic green pigment, chlorophyll *a,* gives an estimate of the abundance and relative biomass of phytoplankton and suggests periods of low or high primary productivity. The variability in phytoplankton density (integrated over the water column) and chlorophyll *a* concentrations (surface) are shown in Figure 6. Integrated chlorophyll *a* concentrations have been omitted from this summary report as data were not available for year 1 of the trial, and patterns in integrated samples in year 2 were similar to that of surface samples.

The primary species present in December and January of year 1 of the trial was the cyanobacteria *Nodularia spumigena* (Figure 7a). There was an increase in surface chlorophyll a concentrations at this time. The primary species present in January and February of year 2 was *Anabaenopsis arnoldii* (Figure 7b). Concentrations of chlorophyll *a* were reported during this bloom that were much higher than the preceding year. For example, in mid-January the chlorophyll *a* concentration was up to 3 times greater in year 2, despite similar cell densities. Very high phytoplankton densities of over 105 cells/ml ceased by February in year 1, but persisted into March in year 2. In both years the high cell counts were not constant over time, and peaks and troughs of phytoplankton density can be identified (Figure 6). These cycles in population density are due to the growing phytoplankton population eventually running out of key resources (such as nutrients, light or some other factor) and suffering a rapid decline in cell numbers. With a re-supply of resources the population recovers only to crash again.

Maximum surface chlorophyll *a* concentrations were measured on 1 June in year 1 of the trial, however, integrated phytoplankton density data is not available for this time due to poor sample preservation. Historically this is not a time of year generally associated with phytoplankton blooms that would elevate chlorophyll *a* concentrations to this extent. Picoplankton blooms have been noted, but are an unlikely explanation for such extremely high concentrations. The period from late December to early March in year 2 of the trial can be identified as the most extensive period of elevated surface chlorophyll *a* concentrations in the trial, with the maximum concentrations measured on 8 March.

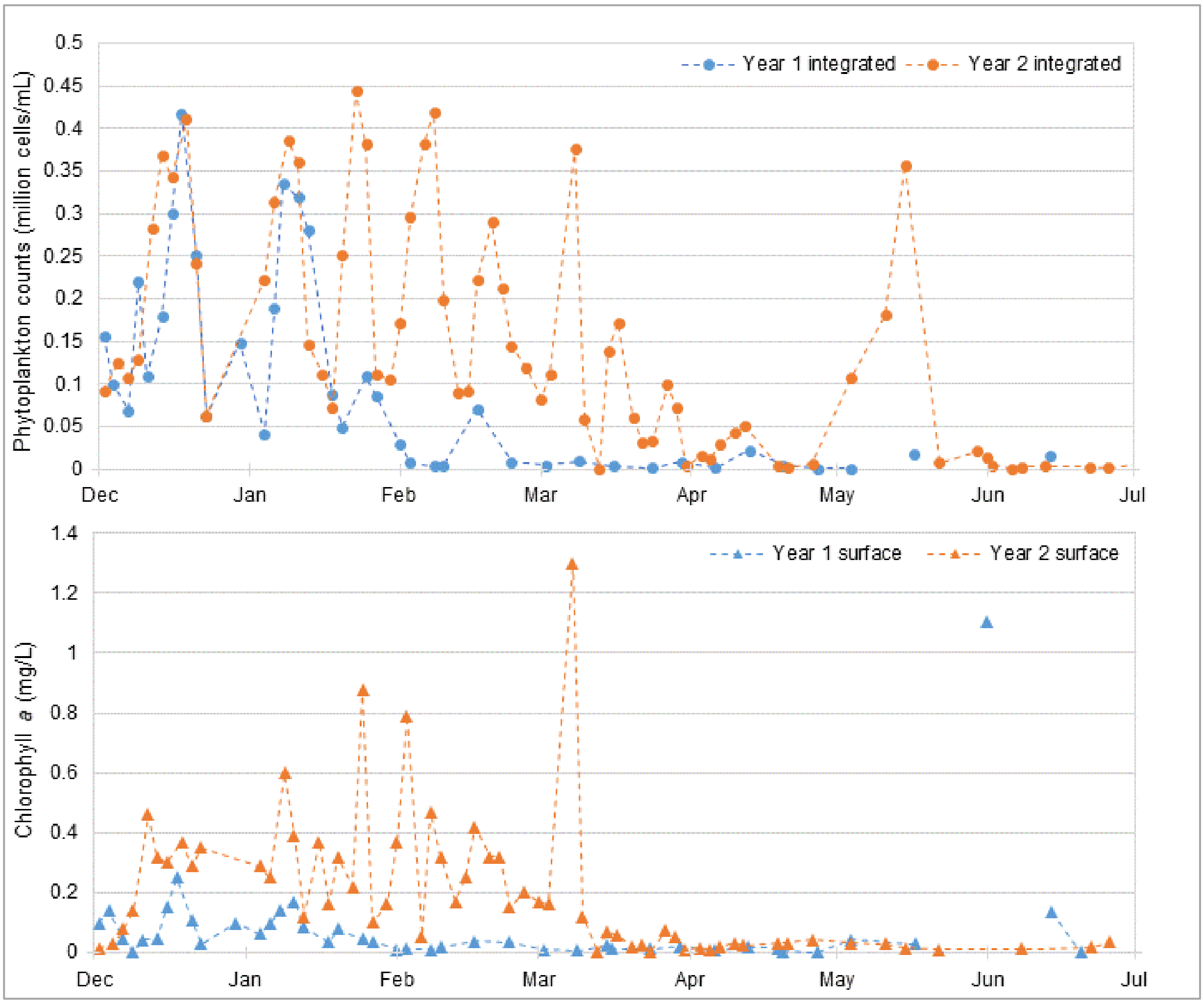

Figure 6 Total phytoplankton counts (million cells/mL) from integrated water samples, and chlorophyll a concentrations (mg/L) from surface water samples from Vase1 in years 1 and 2 of the trial

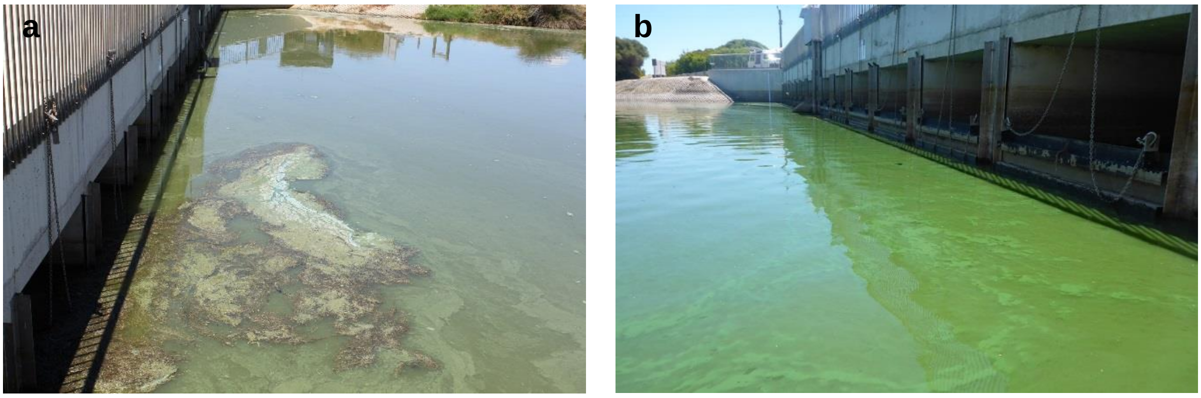

Figure 7 (a) Nodularia spumigena present at the surge barrier in year 1 and (b) Anabaenopsis arnoldii in year 2

4 Effectiveness of the oxygenation plant

4.1 Proof of concept - does the technology work?

Oxygen concentrations are influenced by multiple physical, biological and chemical variables which cannot be controlled in a real-world trial. As the Vasse exit channel is a unique system, there was no control site available to distinguish the effects of the plant from natural variability. To determine how well the technology worked, we undertook short, intensive periods of monitoring (effectiveness testing), measuring dissolved oxygen and a range of other physical and chemical variables under different operating regimes. The challenges of background environmental variability were limited by the short temporal scale, making it possible to draw conclusions on the impact of plant operation on localised DO.

Effectiveness testing – year 1

During the first two weeks of May 2016, we undertook effectiveness testing to assess the extent of plant influence, and the response of the estuary to different oxygen flow rates. While modifications were made to the operation of the plant, water column profiling of DO, salinity, and temperature was undertaken at seven sites from the surge barrier to 350 m upstream (map of transect in Appendix A).

Results from the first week are shown in Figure 8, with a reduction in oxygen concentrations after the plant was switched off. DO declined with depth, and was measured at less than 1 mg/L in bottom waters at the three sites upstream of pump 2, suggesting that the sediment oxygen demand is a significant component of the oxygen drawdown exhibited by the system. This is known to occur in organic-rich estuaries (Higashino et al. 2004). When the plant was switched on at an oxygen flow rate of 5 kg/hr, there was an immediate improvement in DO with progressive increases in oxygen concentration with further operation.

Results of the second week of testing (Appendix B) suggested that the lower oxygen flow rate of 1 kg/hr was able to meet the oxygen demand during the time of sampling and that each unit was able to influence a stretch of the estuary in the order of 250 m.

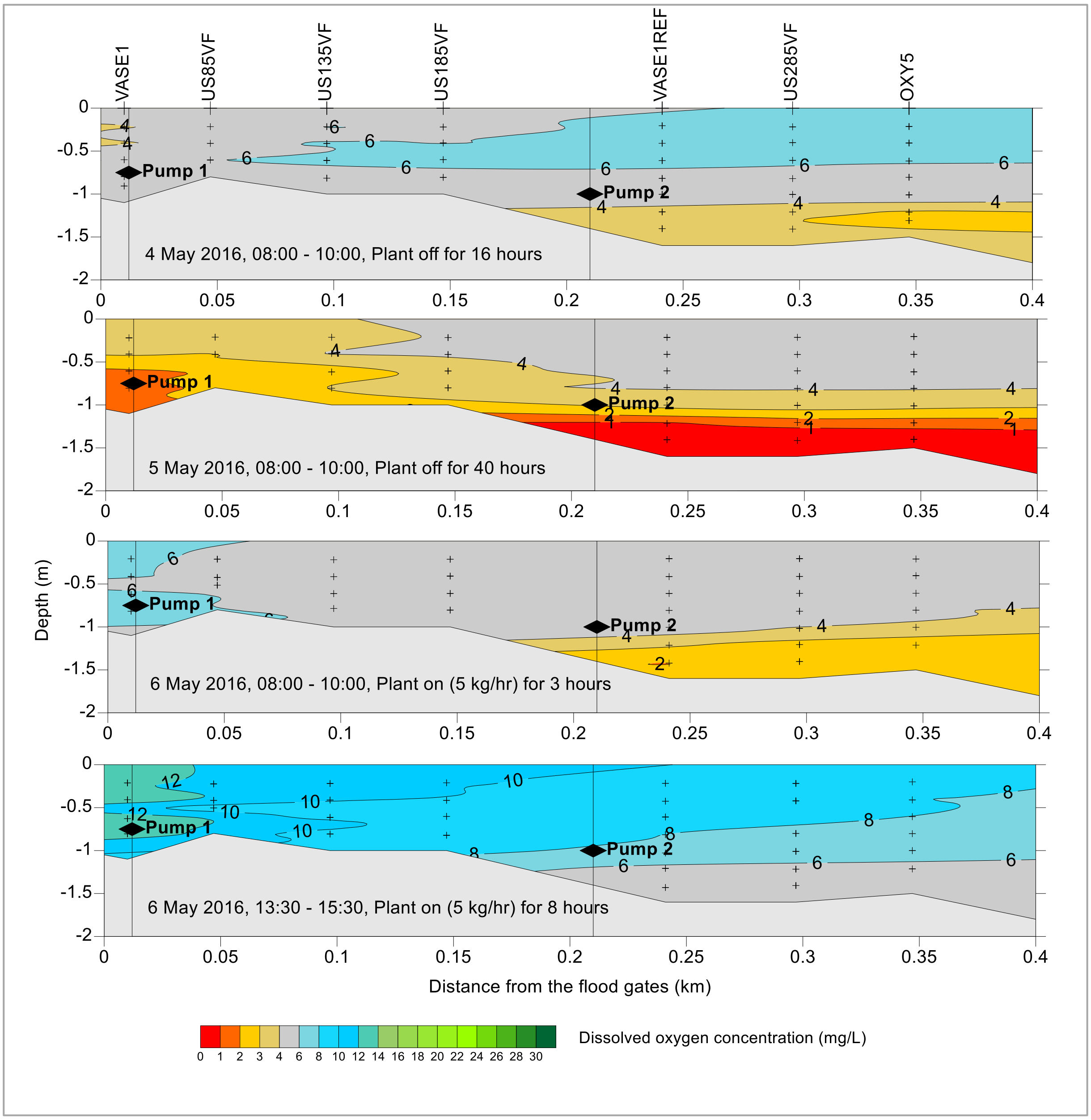

Figure 8 Changes in dissolved oxygen conditions with operation of the oxygenation plant (week 1). See Appendix B for results from the second week.

Effectiveness testing – year 2

In year 2, effectiveness testing was undertaken at the end of February to examine the impact of the plant in late summer; a period historically associated with poor water quality. The sampling transect was extended to include 11 water column profiling sites measuring DO, salinity and temperature extending from the surge barrier to 470 m upstream (map of transect in Appendix A). Diurnal dissolved oxygen fluctuations were extremely large during this time, and consequently, oxygen contour plots are compared across either mornings or afternoons to minimise diurnal variability.

Results from the morning sampling are shown in Figure 9, with an increase in low oxygen and hypoxic conditions when the plant was switched off (results from the afternoons are included in Appendix B). As observed in year 1, oxygen concentrations declined with depth and were less than 1 mg/L in bottom waters from Vase1Ref to Oxy7 after 45 hours without operation. When the oxygenation plant was switched back on at an oxygen flow rate of 2 kg/hr, oxygen concentrations steadily improved however, in comparison to effectiveness testing from year 1, the rate of increase was slower. Even after 45 hours of continuous plant operation, there was still evidence of low dissolved oxygen concentrations in the deeper parts of the water column, suggesting further operation or a higher oxygen flow rate was required to adequately meet the oxygen demand at the time.

Loss of oxygen gas to the atmosphere

In very shallow systems like the Vasse exit channel, there is not much contact time for gaseous oxygen to be dissolved in the water column. Any oxygen added in the form of a gaseous bubble will have the tendency to rise to the water surface and be lost to the atmosphere. This can be considered as an efficiency loss. As a result, it is important that the percentage of oxygen gas dissolved in water prior to discharge to the receiving water body is maximised.

In the oxygenation trial, dissolution of oxygen occurred under pressure within the submersible oxygenation units. The oxygenated plumes discharged by the units appeared ‘milky’, and bubbles were not visible to the eye. Calculations of oxygen transfer efficiency suggested losses of oxygen gas to the atmosphere were very low.

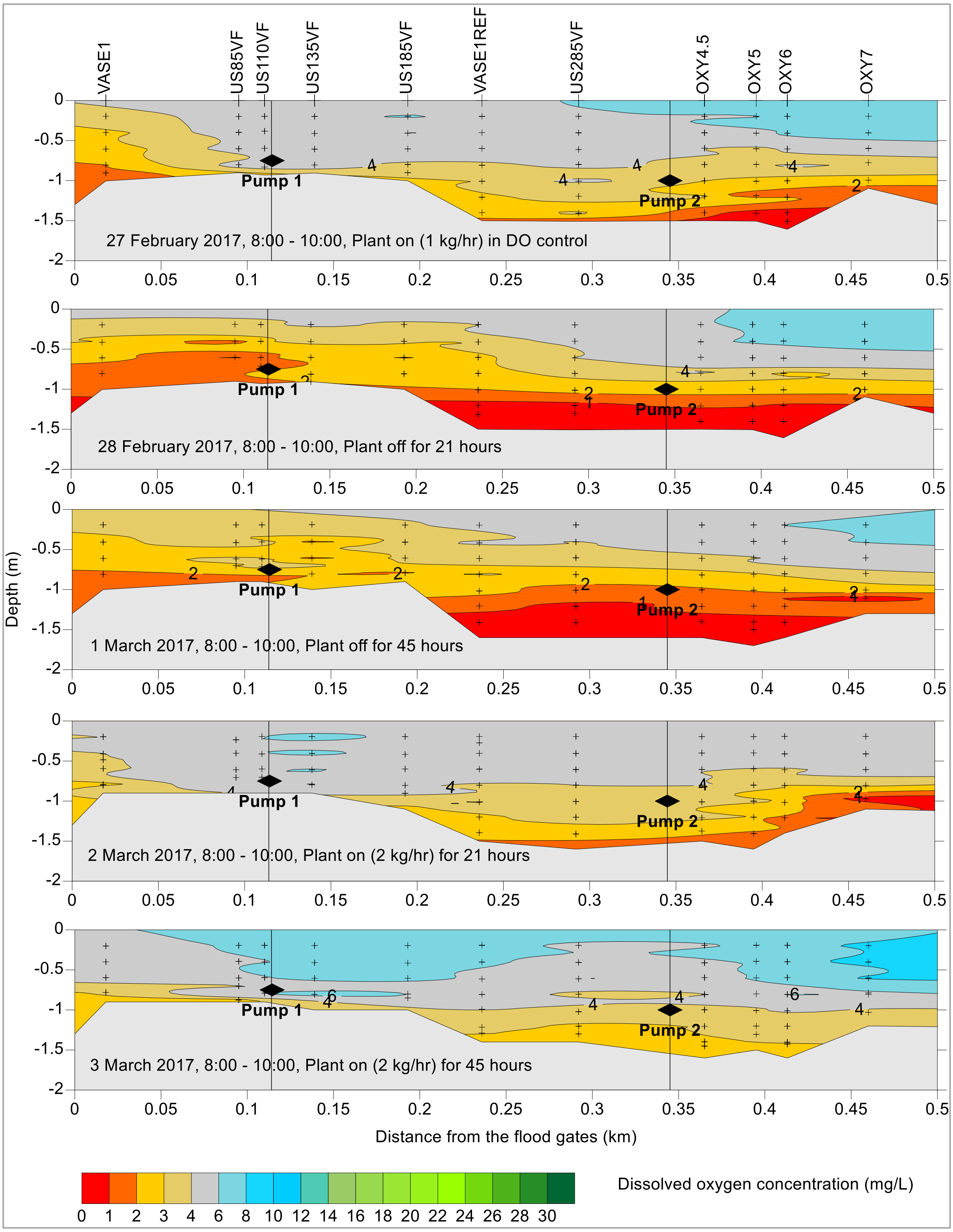

Figure 9 Changes in dissolved oxygen with operation of the oxygenation plant (mornings). See Appendix B for results from the afternoon.

4.2 How did the plant operate over each season?

Mode, operational hours and the addition of oxygen

In both years, the plant mostly operated in DO control mode (98% of the time in year 1 and 94% in year 2). As a result, the total run hours is primarily a reflection of the amount of time that there was a measured deficit in oxygen within the system (Table 1). Comparing the percentage of the time that at least one pump was running each month highlights the large seasonal and annual variability of oxygen demand.

In year 1 of the trial, plant operation was most frequent in the months of March, May and June, whereas in year 2 of the trial, plant operation was most frequent in January, February and March. January 2017 was by far the most intense period of operation in the trial, with at least one unit supplementing oxygen 66% of the time. This coincided with the period of observed high phytoplankton biomass in the Vasse exit channel, and elevated concentrations of chlorophyll *a*.

In years 1 and 2 pumps ran for a total of 1243 and 2085 hours respectively. It is important to note that the operating season was substantially longer in year 2. The total oxygen added is dependent upon the oxygen flow rate which is set by the plant operator. In year 2, the oxygen flow rate was often higher, as the capacity of the plant to meet elevated oxygen demands was tested. As a result, the total oxygen added in year 1 was 1515 kg, while in year 2 it was 6575 kg.

Table 1 Summary of operating hours, percentage of the time operating and quantity of added oxygen in years 1 and 2 of the trial (operated for only 10 days in June of year 1)

		December	January	February	March	April	May	June
Year 1	Pump 1 operation (hours)		29	107	234	43	78	59
	Pump 1 addition of oxygen (kg)		29	107	233	43	118	59
	Pump 2 operation (hours)		13	19	114	19	348	182
	Pump 2 addition of oxygen (kg)		13	19	114	19	580	182
	Percentage of the month at least one pump was operating		5%	17%	35%	8%	49%	32%
	Total oxygen added (kg)		42	125	347	62	698	241
Year 2	Pump 1 operation (hours)	104	428	215	66	62	16	39
	Pump 1 addition of oxygen (kg)	222	1874	581	136	124	32	77
	Pump 2 operation (hours)	118	433	276	247	57	0	24
	Pump 2 addition of oxygen (kg)	208	1867	792	498	114	1	48
	Percentage of the month at least one pump was operating	21%	66%	46%	34%	15%	2%	0%
	Total oxygen added (kg)	430	3741	1374	634	238	33	126

Figure 10 and Figure 11 summarise the operation and oxygen flow rate of pumps 1 and 2 and the corresponding DO concentration measured at the Vase1 and Vase1Ref monitoring buoys in years 1 and 2. It is evident from these figures that the conditions during the two years of the trial were very different. In year 2, the plant operated at much higher oxygen flow rates, particularly through January and February but DO observed at the monitoring buoys during this time was frequently below the 2 mg/L and 4 mg/L thresholds. In year 1 the rapid decline in dissolved oxygen at Vase1 is evident when the plant was decommissioned in June.

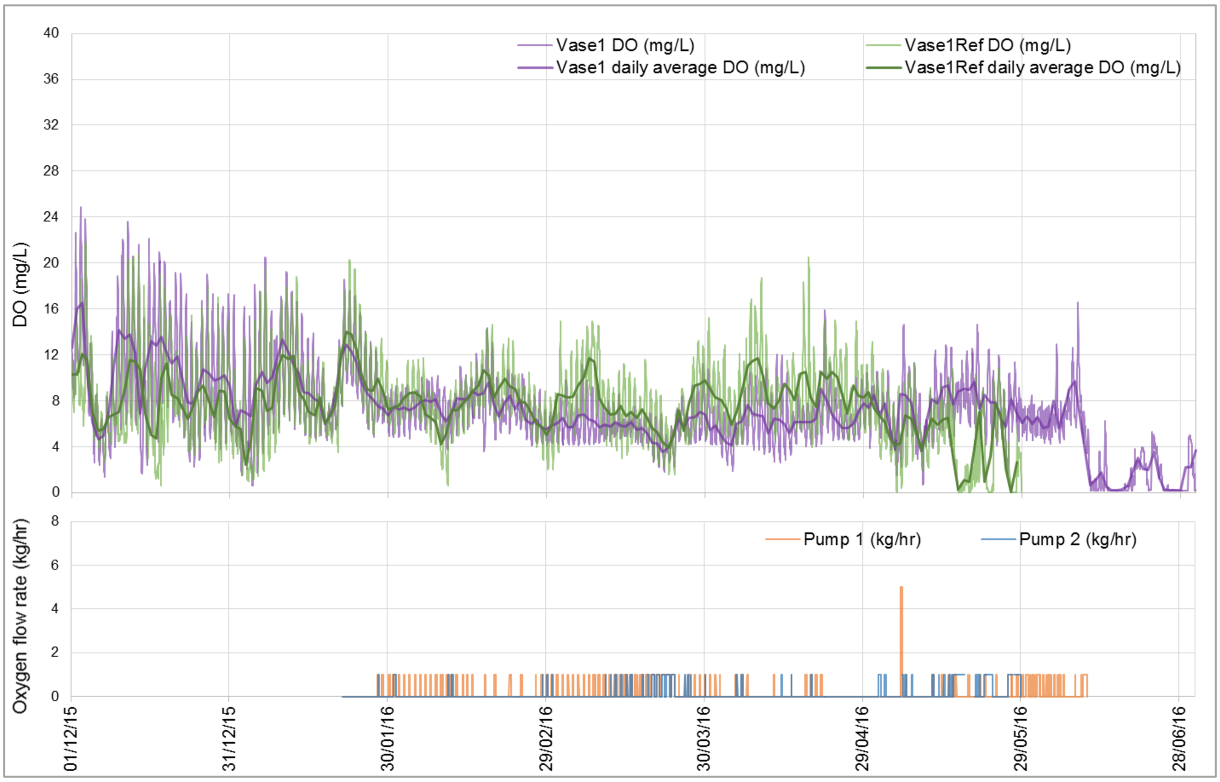

Figure 10 DO concentrations at Vase1 and Vase1Ref, and oxygen flow rates at pump 1 and pump 2 in year 1 of the trial

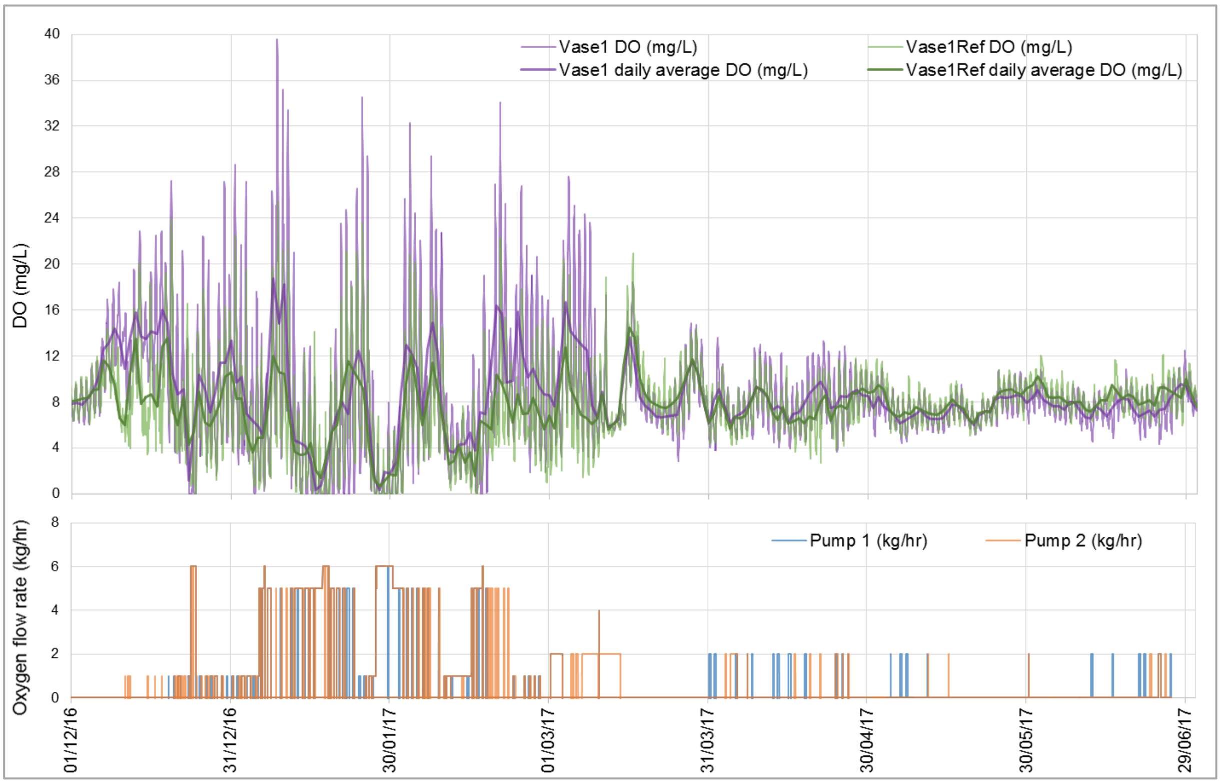

Figure 11 DO concentrations at Vase1 and Vase1Ref and oxygen flow rate at pumps 1 and 2 in year 2 of the trial

What times of the day did the pumps operate most frequently?

When operating in DO control it would be expected that the plants would operate most frequently at times when oxygen concentrations are typically at their lowest, for example overnight when respiration is high and photosynthesis is not occurring. Figure 12 shows the percentage of time in each hourly block that the two pumps were running between the first and final operation of each season (28/1/2016 – 10/6/2016 in year 1, and 11/12/2016 – 26/6/2017 in year 2).

In year 1, it is evident that the location of the paired monitoring buoy dictated the extent of operation, with quite different patterns of operation between pump 1 and pump 2. The operating times of pump 1 tended to align more strongly with a diurnal trend, operating more than 30% of the time in the hours between 3:00 and 7:00 and less than 5% of the time in the late afternoon between the hours of 14:00 and 20:00. Pump 2 operated much more consistently throughout the day, operating more than 30% of the time at hours between 6:00 and 10:00 and a minimum of 16% of the time at hours between 17:00 and 19:00.

In year 2, with the pumps positioned in their new locations, the patterns in operation were more consistent between pump 1 and pump 2, but the times of peak operation shifted to later in the morning. Pump 1 operated more than 30% of the time at hours between 7:00 and 12:00, and less than 7% of the time at hours between 18:00 and 20:00. Pump 2 operated more than 30% of the time at hours between 7:00 and 14:00 and between 14% and 15% of the time between the hours of 19:00 and 23:00.

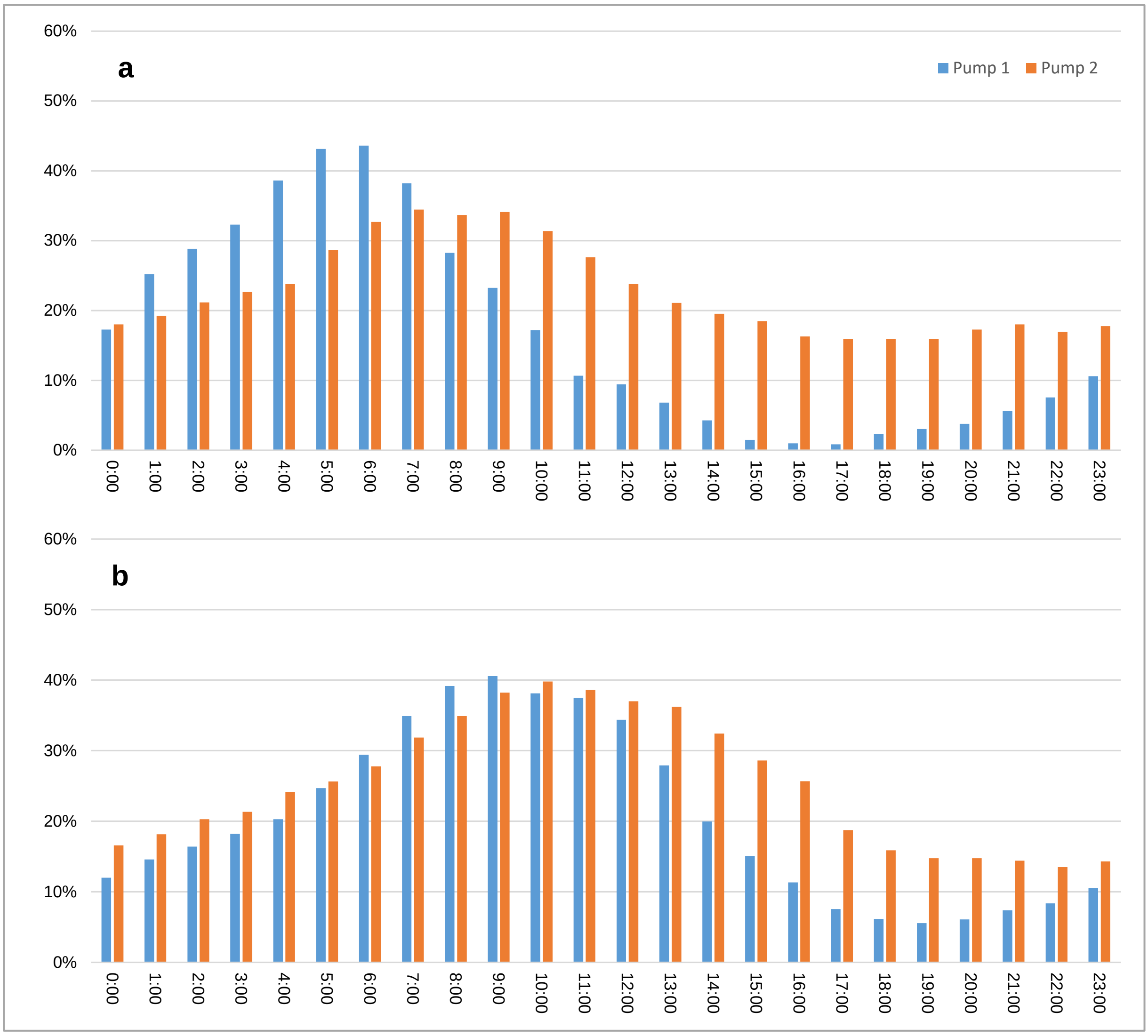

Figure 12 Percentage of time pumps operated in hourly blocks for years 1 (a) and 2 (b)

4.3 Seasonal oxygen conditions relative to the critical thresholds of 2 and 4 mg/L

To examine if the plant effectively maintained critical DO concentrations, oxygen conditions over the season were summarised by determining the percentage of DO readings from the two monitoring buoys that fall into the following key categories;

- < 2mg/L
- ≥ 2 mg/L and < 4 mg/L
- ≥ 4 mg/L.

It is important to highlight that these percentages incorporate the impact of plant operation as well as all other background processes that influence oxygen concentration, including phytoplankton respiration and photosynthesis. Therefore, DO readings above 4 mg/L are not solely the result of plant operation. Isolating and quantifying the impact of the plant has been investigated in Section 4.4. The following summary statistics summarise oxygen conditions over the operating season and enable comparison between year 1 (Figure 13) and year 2 (Figure 14) of the trial.

In year 1, DO was greater than or equal to 4 mg/L at least 90% of the time, in all months except June at Vase1 and May at Vase1Ref. This is an interesting result, as May and June are not months that are historically associated with low dissolved oxygen. In May 2016, 26% of data points measured at Vase1Ref were less than 2 mg/L and a further 19% were less than 4 mg/L (but greater than or equal to 2 mg/L). Pump 2 operated extensively during the low DO periods of May 2016 but the oxygen flow rate of 1 kg/hr was insufficient at meeting the oxygen demand at this time. In June 2016, 49% of data points measured at Vase1 were less than 2 mg/L and a further 14% of data points were less than 4 mg/L (but greater than or equal to 2 mg/L). From the 10 June onwards, the oxygen vessel was empty and the decision was made not to refill so late in the operating season. As a result, it was not possible for the plant to mitigate the subsequent low DO evident at Vase1 (Figure 9). The extensive low DO in June, coincides with the highest concentration of surface chlorophyll *a* measured in year 1 of the trial. Phytoplankton density data is not available at this time (Figure 6). In addition, manipulation of the surge barrier on 13 June 2016 led to intrusion of marine water upstream, and stratification of the water column of the Vasse exit channel. Under these conditions, bottom waters will be unable to mix with the surface waters in contact with atmospheric oxygen, which will exacerbate low oxygen conditions in the bottom waters.

Low DO in the second half of June may also be the result of an ‘induced oxygen demand’ that can occur when artificial oxygenation is abruptly stopped (Bryant et al. 2011, Gantzer et al. 2009). Aerobic processes, such as those involved in the breakdown of organic material in the sediment, can be intensified by the presence of DO from plant operation, which in itself may be a positive impact of artificial oxygenation. However, if the artificial supply of oxygen is abruptly ceased, consumption rates will continue, rapidly drawing down oxygen until the system is anoxic. This suggests it is prudent to keep the plant operational until the oxygen demand tapers off through natural processes such as declining water temperature in winter.

Monthly trends were different in year 2, with DO greater than or equal to 4 mg/L at least 90% of the time in all months except January and February at both Vase1 and Vase1Ref. In January, 35% and 31% of data points were less than 2 mg/L at Vase1 and Vase1Ref respectively, and a further 13% and 16% were less than 4 mg/L (but greater than or equal to 2 mg/L). During this month, both pumps operated more than 57% of the time at an oxygen flow rate of 5 or 6 kg/hr, adding a total of 3.7 tonnes of oxygen.

In February, 10% and 12% of data points were less than 2 mg/L at Vase1 and Vase1Ref respectively, with a further 13% and 16% less than 4 mg/L (but greater than or equal to 2 mg/L). Again the plant operated extensively during this time (32% for pump 1 and 41% for pump 2), adding 1.4 tonnes of oxygen to the Vasse estuary exit channel. The prevalence of low dissolved oxygen and hypoxic conditions in

January and February 2017, despite the extensive operation of the plant, suggests capacity was insufficient to meet the oxygen demand. During these months, the monitoring buoys measured extreme diurnal fluctuations in DO (ranging from 0 to 35 mg/L), the product of phytoplankton cycles of photosynthesis and respiration. Integrated phytoplankton densities were also elevated, with numbers fluctuating with population dynamics. In addition, surface chlorophyll *a* concentrations were very high, indicating photosynthetic activity was responsible for the large diurnal fluctuations in oxygen.

Interestingly, comparing the integrated phytoplankton densities, surface chlorophyll *a* concentrations and oxygen dynamics in January of year 1 to year 2 highlights that integrated algal cell density alone does not predict the magnitude of oxygen drawdown due to respiration. While integrated algal density was similar in both years, surface chlorophyll *a* concentrations were substantially higher in year 2, as was the frequency of low dissolved oxygen and hypoxic conditions. Differences in oxygen drawdown in January of the two trial years appears to reflect differences in phytoplankton species and other environmental parameters such as wind strength and direction.

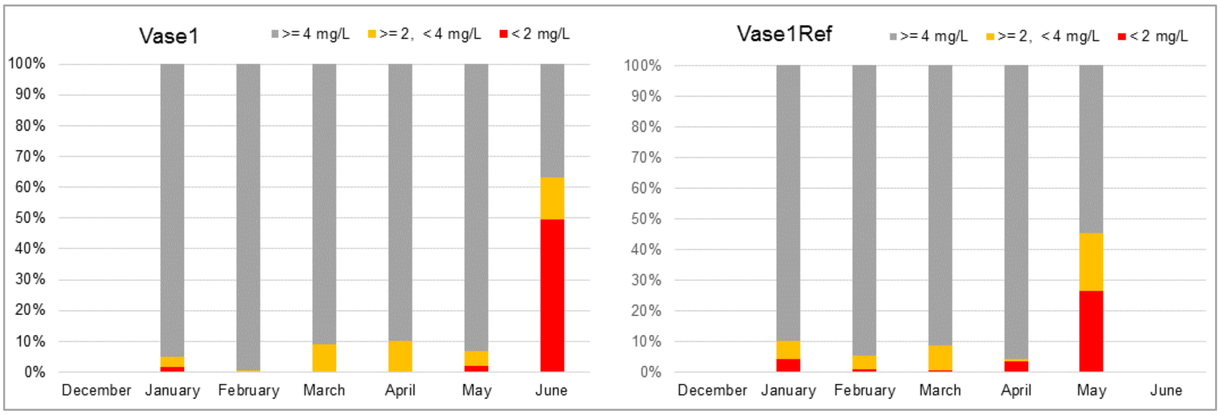

Figure 13 Percentage of dissolved oxygen concentrations less than 2 mg/L and 4 mg/L at Vase1 and Vase1Ref in year 1 of the trial

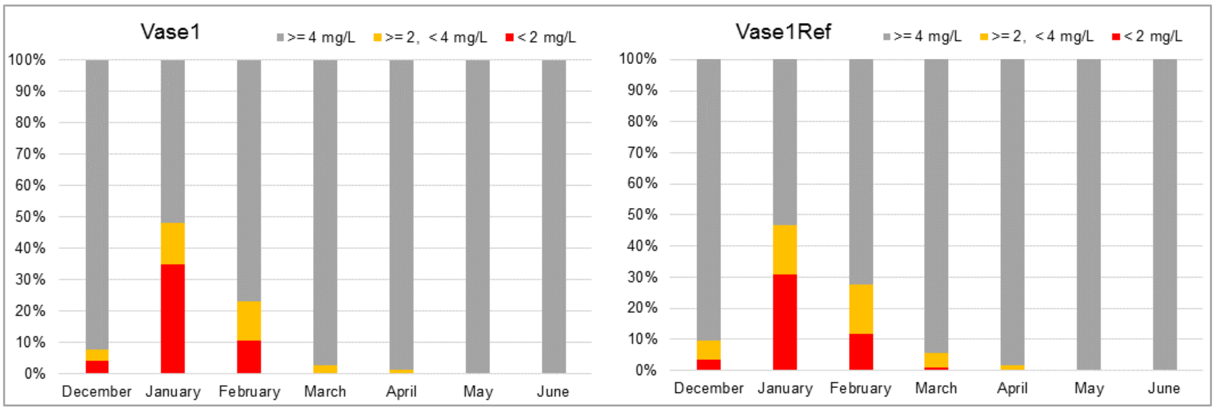

Figure 14 Percentage of dissolved oxygen concentrations less than 2 mg/L and 4 mg/L at Vase1 and Vase1Ref in year 2 of the trial

4.4 Was the plant able to prevent hypoxia?

Effectiveness testing showed that the oxygenation plant was able to add measurable amounts of dissolved oxygen to the water column (Section 4.1). To quantify the ability of the plant to prevent hypoxic (<2 mg/L) or low (<4 mg/L) oxygen concentrations we looked at the percentage of time that, when either pump was operating, the DO measured at the respective measuring buoy fell into the following categories;

- DO <2 mg/L - the percentage of the time that each pump was operating, but its respective monitoring buoy was less than 2 mg/L, can be considered as the proportion of time in which the plant was unable to prevent hypoxia and mitigate the risk of a fish kill.
- DO >= 2 mg/L and <4 mg/L – the percentage of the time that each pump was operating but its monitoring buoy was less than 4 mg/L (but greater than or equal to 2 mg/L) can be considered as the proportion of the time that the plant was unable to prevent low oxygen conditions, limiting ecological function.
- DO >= 4 mg/L – the percentage of the time that each pump was operating and the DO measured at the monitoring buoys was above the low DO threshold of 4 mg/L but below the threshold for ceasing pump operation (defined by the plant operator, either 6 or 8 mg/L) is the proportion of the time that the pump succeeded in elevating the DO to adequate concentrations in addition to the times that other processes, such as photosynthesis were increasing DO.

As each pump operated independently when in DO control mode, their individual performance was assessed, and also combined into an overall measure of plant performance for years 1 and (Figure 15 and Figure 16). It is important to note that the percentages shown in these figures are a proportion of the time the plant was operating, not the proportion of the entire season. Without artificially oxygenating, oxygen concentrations would have been low or hypoxic during these periods - the entire pie chart would be orange or red. The ability to prevent low oxygen conditions and hypoxia was limited by the maximum oxygen flow rate of the trial plant.

In year 1 of the trial, pump 1 appeared to be far more successful at preventing hypoxia and low DO than pump 2 (Figure 15). This is likely due to the close positioning of the Vase 1 monitoring buoy to pump 1, rather than inherently lower oxygen demands at Vase 1 compared to Vase1Ref. In year 2, when pump 1 was moved further away from the surge barrier and the Vase1 monitoring buoy, and pump 2 was moved further upstream, the ability of each pump to elevate the oxygen concentrations of its respective monitoring buoy were much more closely matched (Figure 16).

Overall, in year 1 of the trial, the plant;

- prevented low oxygen conditions 62% of the time

- averted hypoxia and the risk of the fish kill 82% of the time
- was unable to mitigate the risk of a fish kill while operating 18% of the time.

In year 2, the plant;

- prevented low oxygen conditions 45% of the time
- averted hypoxia and the risk of the fish kill 67% of the time
- was unable to mitigate the risk of a fish kill while operating 33% of the time.

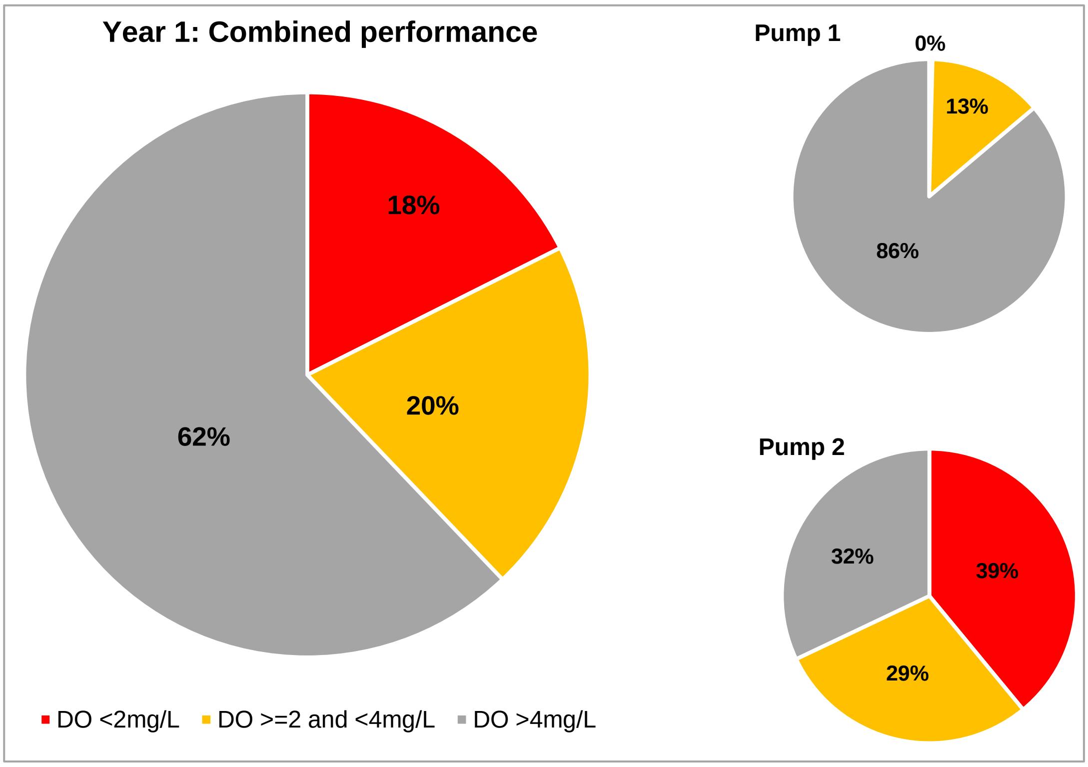

Figure 15 Ability of the plant to prevent hypoxia (<2 mg/L) and low oxygen concentrations (<4 mg/L) in year 1 of the trial

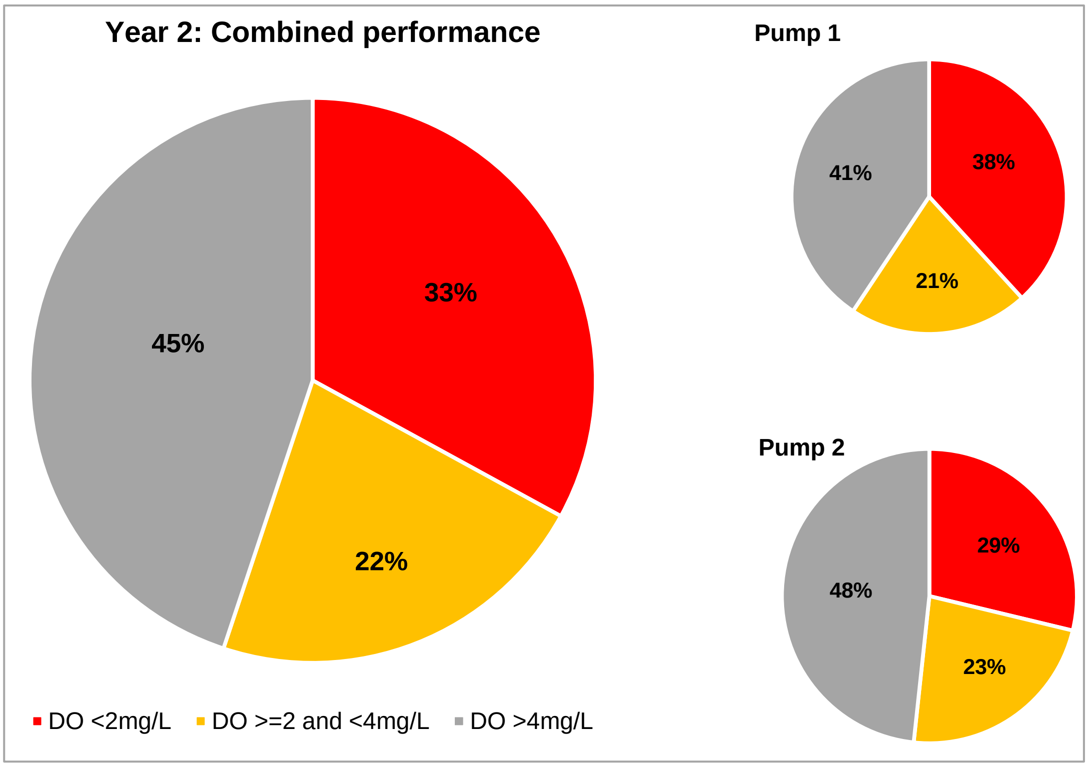

Figure 16 Ability of the plant to prevent hypoxia (<2 mg/L) and low oxygen concentrations (<4 mg/L) in year 2 of the trial

Required oxygen supply rate to prevent hypoxia under periods of extreme oxygen demand

We determined how much additional oxygen is needed by the estuary during periods of extreme oxygen demand. To do this we calculated the rate of decline in oxygen concentration from 4 mg/L to the minimum concentration associated with each ‘drawdown event’ and multiplied by the volume of the trial treatment area at that time.

In general, the largest drawdown events occurred in summer and were likely to be the result of oxygen consuming chemical reactions associated the respiration of the large phytoplankton population. It should be noted that these are short periods (several hours) of very rapid declines in oxygen, which would require very high oxygen flow rates to compensate. The rest of the time, much lower oxygen flow rates would suffice. However, ideally an artificial oxygenation plant would be designed to prevent hypoxia under all conditions.

Indicative values of maximum oxygen demand were calculated for periods when the plant was not operating. On 2 - 5 January 2016, prior to plant commissioning, the calculated oxygen drawdown was 16 – 21 mg/L/day (required oxygen flow rate of 9 – 13 kg/hr). On 12 – 13 June 2016, post year 1 decommissioning, oxygen drawdown was 9 – 31 mg/L/day (required oxygen flow rate of 8 – 26 kg/hr). On 28 February – 1 March 2017, during effectiveness testing, the oxygen drawdown was 17 – 30 mg/L/day (required oxygen flow rate of 11 – 19 kg/hr).

If oxygenation was to be undertaken in the medium-term a thorough analysis of the design oxygen flow rate should be undertaken. However based on the conditions observed during the two year trial, there were short periods when an oxygen flow rate up to 26 kg/hr was required to prevent hypoxia, which could not be met by the 12 kg/hr maximum oxygen flow rate of the trial plant.

Effect on inorganic nutrients

The build-up of organic matter in the sediment is a common symptom of eutrophic estuaries, requiring large quantities of oxygen for decomposition, and contributing to the imbalance between natural processes of oxygen supply and consumption. In addition to improving oxygen concentrations in the water column, oxygenation can also maintain an aerobic sediment-water interface. This enhances aerobic respiration in the sediments and helps to reduce the stores of organic carbon over time.

An aerobic sediment-water interface is also important because the nutrient chemistry in the sediment changes when oxygen is absent. Phosphate and ammonium released during the breakdown of organic carbon are much more likely to reach the water column under anoxic conditions, where there become available to stimulate phytoplankton growth. In aerobic sediments the phosphate is generally trapped by minerals in the sediment, but in anoxic sediments these minerals are not stable and phosphate is released. Anoxia also shuts down natural processes that act to remove bioavailable nitrogen from the system. If oxygen is present, ammonium is oxidised to nitrate, where it is available to microorganisms and is transformed via a series of steps to inert nitrogen gas. In the absence of oxygen the nitrogen remains as bioavailable ammonium in the aquatic system. Providing an aerobic sediment-water interface limits this nutrient release from sediments, potentially reducing the strength of positive feedback mechanisms.

The oxygenation trial did not measure the impact of plant operation on oxygen concentrations at the sediment-water interface. As such, it is not possible to conclude whether the plant was able to control nutrient release. However, by increasing oxygen concentrations within the water column, anoxia is less likely at the sediment-water interface. Weekly water quality sampling at Vase1 in year 1 (Figure 17) showed notable increases in ammonium when oxygen concentrations dropped to hypoxic levels in December and early January, before the plant was operating. Another factor which may have played a role in the increase in ammonium in December and January was temperature and salinity stratification which can trap nutrients released from sediments in the bottom layer (Figure 5).

In year 1 phosphate concentrations were generally low. In year 2 (Figure 18) very high concentrations of ammonium were evident from mid-December through to mid-March, coinciding with the prevalence of hypoxia within the water column. There was some temperature stratification in late December and early January of year 2 which is likely to have exacerbated the low dissolved oxygen conditions. Phosphate concentrations increased during periods when the water column DO was essentially zero, with notable peaks in late December, January and early February 2017. In both years significant concentrations of nutrients typically only occurred when the oxygen concentrations were less than 4 mg/L some time during the past day, demonstrating the value of maintaining an oxygenated water column to restrict nutrient release.

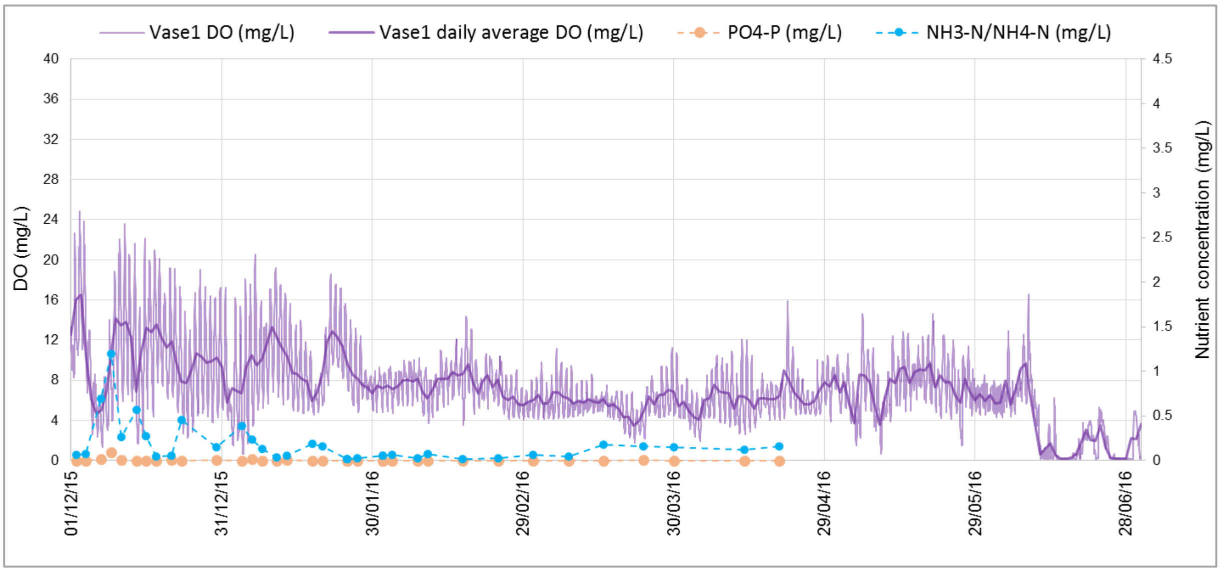

Figure 17 Dissolved oxygen (DO) at the Vase1 monitoring buoy shown against weekly concentrations of filterable reactive phosphorus (PO4-P) and ammonium

(NH3-N/NH4-N) in year 1. Concentrations of nitrite/nitrate were also measured but were always below 0.1 mg/L

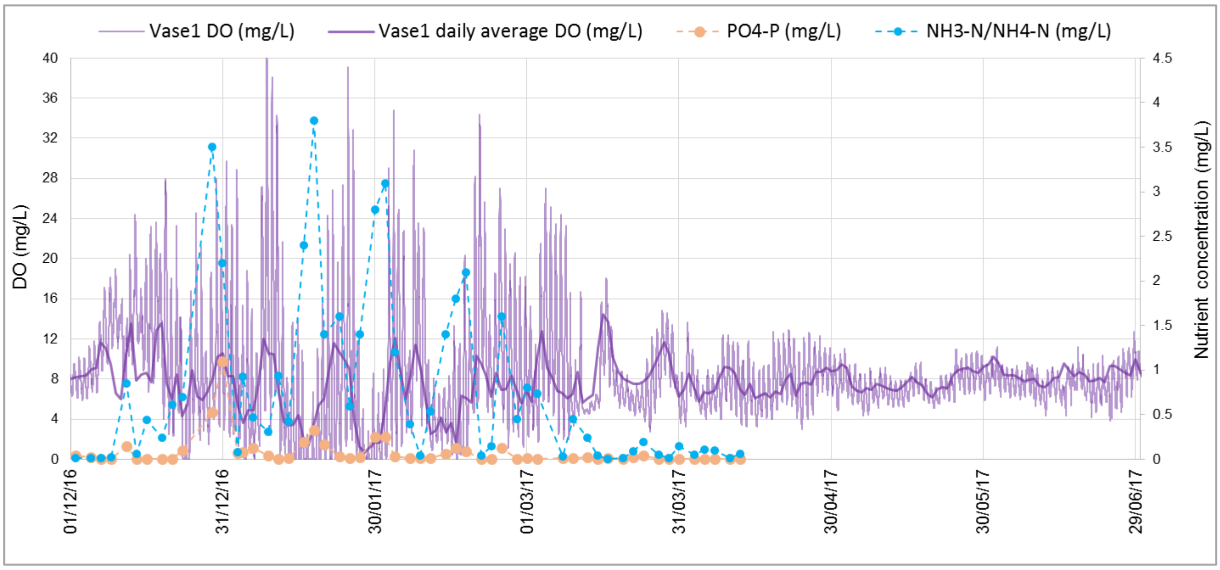

Figure 18 Dissolved oxygen (DO) at Vase1 monitoring buoy shown against weekly concentrations of filterable reactive phosphorus (PO4-P) and ammonium (NH3-N/NH4-N) in year 2. Concentrations of nitrite/nitrate were also measured but were always below 0.1 mg/L

5 Practical considerations for a medium-term oxygenation system in the Vasse

5.1 Site selection

Site options in the vicinity of the Vasse exit channel are extremely limited as much of the land adjacent to this stretch of the river is privately owned. For the trial, the land-based component of the oxygenation plant was positioned in the road reserve on the eastern side of the Vasse estuary surge barrier.

If a medium-term oxygenation solution is committed to, a thorough site selection process should be undertaken, considering the following factors;

- access to power; ideally three-phase with consideration to direct mains connection and alternative supplies such as solar and LNG gas turbines as well as battery storage
- close vicinity to the Vasse exit channel
- community and local resident support
- minimising the length of the oxygen and power supply lines and ensuring they are less than the limitations of the technology.

5.2 Required plant capacity

The maximum oxygen flow rate should optimise the trade-off between capital expenditure and the ability of the plant to meet periods of extreme oxygen demand, such as that exhibited in January and February of year 2 of the trial.

Estimates of the maximum required oxygen flow rate under these conditions are 13 – 26 kg/hr applied over the oxygen trial treatment area (from the floodgates to 470 m upstream), in comparison to the maximum flow rate of 12 kg/hr that was applied during the trial.

If the exit channel was to be artificially oxygenated in the future, the length of the channel that exhibits low oxygen conditions should be investigated with consideration given to the extension of the treatment area. Based on measurements taken during the trial, to meet extreme oxygen demands in the entire exit channel (from the floodgates to 830 m upstream), a maximum flow rate of 30 – 50 kg/hr would be required.

If the intensity, frequency, and duration of large phytoplankton blooms can be reduced through additional management actions (for example, strategic salt water inflows at the surge barrier), the rate of diurnal oxygen drawdown and the maximum oxygen flow rate could be substantially reduced. An oxygen flow rate of 10 kg/hr for the oxygen trial treatment area or 20 kg/hr for the whole exit channel may be adequate. A more in-depth analysis of oxygen drawdown events would improve estimates of required plant capacity. It may also be beneficial to improve the understanding of the sediment oxygen demand through measurement with benthic chambers or an autonomous sediment profiler.

Before designing an oxygenation plant for the medium-term, the following objectives should be agreed on;

- What is the target oxygenation zone? Is it the previous trial area (470 m upstream of the surge barrier), the extent of the exit channel (830 m upstream of the surge barrier), or something different all together?
- Under what conditions is the plant going to operate? All year round, or only during particular months?
- What are desired outcomes of the plant? Is it the prevention of low oxygen (less than 4 mg/L) or hypoxic (less than 2 mg/L) conditions?
- Is the sole aim of the plant to provide an oxygenated refuge for fish, or will it also be used in the greater context of a remediation technique for oxygenating the sediment-water interface?

5.3 Selecting appropriate oxygenation technology

When undertaking artificial oxygenation in the medium-term, consideration should be given to the most efficient technology. If the BOC Solvox drop-in units are to be used again, extra units may be added to the system to increase the total oxygen flow rate. The benefit of the Solvox drop-in units is they have limited permanent infrastructure in-river, and the location of the pumps can be altered relatively simply. In addition, the upfront cost is less than alternatives, and the efficiency of oxygen transfer is reasonable (estimated to be around 70%).

An alternative plant design, similar to the permanent installations on the Canning River, Perth, should also be considered. Here, river water is pumped to the dissolver on the bank, then returned to the exit channel via a distribution pipe and a series of nozzles at strategic locations to disperse the highly oxygenated water. This type of plant has a higher dissolution efficiency (in the order of 95%), but also a higher upfront cost, with less flexibility after installation to modify the locations where oxygenated water is added to the river.

On-going costs associated with electricity, oxygen, and maintenance must also be factored into a cost-benefit analysis of alternative oxygenation technologies.

5.4 Operating guidelines

The most intense period of operation is likely to occur in summer and early autumn when oxygen demand is at its highest. However, it is advisable that a medium-term oxygenation plant be designed so it can be operated all year round, except for a period during winter when essential annual maintenance is undertaken.

Artificial oxygenation should not be abruptly stopped, but rather operations should taper off in response to the reduced demand naturally associated with cooler months, in order to prevent a deoxygenation event due to the ‘induced oxygen demand’ associated with operation.

When controlling flows at the surge barrier, consideration should be given to preventing stratified conditions in the Vasse exit channel, where density differences may prevent mixing of the water column. Under stratified conditions, naturally aerated surface waters are unable to mix with oxygen depleted bottom waters. In addition if artificially oxygenating, oxygenated waters cannot freely mix throughout the water column.

6 Discussion

Hypoxia and anoxia are common symptoms of eutrophic estuaries, with an array of detrimental consequences to the ecosystem. In water bodies with low oxygen, the removal of nitrogen via denitrification will be inhibited, and phosphorus will be less strongly bound to minerals in the sediment and may be released in bioavailable form to the water column. In addition, organic matter cannot be broken down via aerobic processes, which is more energetically efficient than anoxic degradation and gases such as hydrogen sulphide will be generated and released into the atmosphere. Aquatic ecosystems deficient in oxygen are limiting for biota and there is an elevated likelihood of a fish kill.

While artificial oxygenation has been successfully applied to the Swan and Canning rivers for the past two decades, the concept has never been applied to smaller water bodies in regional areas of Western Australia. As such, the first aim of the trial was to undertake a ‘proof of concept’ to confirm the applied technology was appropriate to the shallow and warm waters of the Vasse exit channel. This was an exciting trial of newly developed technology to a very different environment than previous industry applications.

Artificial oxygenation, while designed to improve oxygen concentrations in the water column, can be considered a whole of system remediation technique. If adequately sized, it can also prevent the occurrence of low oxygen conditions at the sediment-water interface, facilitating the aerobic breakdown of carbon and reducing the release of nutrients from sediments. Over an extended period of time, it is possible that this will result in a reduction in the quantity of organic matter in the sediment. This in turn will reduce the sediment-oxygen demand, which is likely to be a significant component of oxygen drawdown in organic-rich estuaries like the Vasse (Higashino et al. 2004). Reducing the sediment oxygen demand has the potential to shift the system back towards a balance between oxygen replenishment and consumption, particularly if the intensity of phytoplankton blooms can be reduced via complementary management actions.

The two-year trial demonstrated that the BOC Solvox drop-in units could improve oxygen concentrations in the Vasse exit channel. The pumps ran effectively in DO control mode, generally programmed to come on when dissolved oxygen concentrations dropped below 4 mg/L and turn off when it exceeded 6 or 8 mg/L. The system demonstrated efficient oxygen transfer and minimal losses to the atmosphere, despite the extremely shallow depth and the warm temperatures of the receiving water body. The plant added substantial quantities of oxygen to the Vasse exit channel in both years (1515 kg in year 1 and 6145 kg in year 2). This helped meet the excessive oxygen demands of the system associated with the large organic loading at the sediment as well as the rapid drawdown of oxygen through respiration by phytoplankton blooms.

Plant capability was quantified by the percentage of time that the plant was operating and able to maintain DO above 4 mg/L; 62% of the time in year 1 and 45% in year 2.

Without the operation of the plant, the system would have exhibited low oxygen concentrations or been hypoxic during these times.

Fish kills, are a highly visible sign of an imbalance within an ecosystem, and are often a consequence of a combination of factors, including low oxygen, toxicity, and blocking of the gills. Maintaining oxygen concentrations above 2 mg/L will reduce the likelihood of a fish kill, and as such we used this threshold as an indication of the plant's success in fish kill prevention. When the plant was triggered to operate, it was able to maintain oxygen concentrations above 2 mg/L 82% of the time in year 1 and 67% of the time in year 2, thereby substantially reducing the likelihood of a fish kill.

In both years the role of phytoplankton in influencing the water column concentrations was evident as diurnal fluctuations in oxygen concentration. During the day phytoplankton photosynthesise and produce oxygen gas, with a subsequent increase in oxygen concentrations. At night time photosynthesis stops and respiration dominates, and consequently oxygen concentrations decline. The magnitude of the diurnal fluctuation in year 2 was considerably greater than in year 1. The stronger phytoplankton imprint on oxygen concentrations in year 2 is consistent with higher chlorophyll *a* concentrations and a more vigorous phytoplankton community.

A very large population of the cyanobacteria, *Anabaenopsis arnoldii*, found in much of January and February in year 2, was associated with extraordinarily high rates of oxygen consumption (daily maximum oxygen drawdown estimated in the order of 17 - 30 mg/L/hr). This was a contributing factor to the lower success rate of the plant in preventing hypoxia in that year. There was a peak in chlorophyll *a* concentrations (a measure of the photosynthetic green pigment), at this time, which may be a good indicator of the magnitude of primary productivity and the potential for elevated rates of oxygen drawdown through respiration.

There was also a large bloom of another cyanobacteria, *Nodularia spumigena,* in December and January of year 1. However, rates of oxygen consumption were lower (daily oxygen drawdown estimated in the order of 16 - 21 mg/L/hr). The magnitude of chlorophyll *a* concentrations while still high, were significantly less than the bloom the following year. *Anabaenopsis* has a slightly larger biovolume than *Nodularia* but all species of algae will vary in photosynthetic activity (Boulton & Brock 1999). So while large phytoplankton blooms have the potential to control oxygen dynamics in the Vasse exit channel, the relationship between phytoplankton density, chlorophyll *a* and oxygen is not straight forward, and will be species dependent and strongly influenced by confounding environmental variables. As a result, an artificial oxygenation plant for the Vasse exit channel should be considered in combination with complementary management actions, such as the strategic management of seawater inflows at the surge barrier to reduce the intensity of phytoplankton blooms.

This study did not specifically measure nutrient release from the sediment under variable bottom water oxygen conditions, so it is not possible to attribute plant operation to reductions in bioavailable nutrients. There were periods of time where increases in water column ammonium and filterable reactive phosphorus coincided with water column DO approaching zero (e.g. December and January of year 2).

When water column DO approached zero, it is likely that oxygen concentrations at the sediment-water interface were also anoxic, which is likely to have prevented the aerobic process of nitrification, potentially leading to a build-up of ammonium and the release of phosphorus previously bound to iron in the sediment. The presence of stratified conditions, due to density differences associated with either temperature or salinity, is also likely to be an influential factor in the increase in nutrient concentrations within the water column. Even small density differences between surface and bottom water layers will substantially reduce mixing within the system and keep any nutrients released from the sediment concentrated in the bottom layer. In a system where water column nutrients are limiting, preventing nutrient release from the sediment can restrain phytoplankton growth. The extremely high concentrations of nutrients in the runoff from the catchments of the Vasse estuary would suggest that sediment nutrient release is not a controlling factor at all times, however in the summer of year 2, filterable reactive phosphorus concentrations are reduced to zero every time the phytoplankton numbers peak, suggesting the bloom is potentially becoming phosphorus limited. If this is the case, the application of a phosphorus binding clay to the sediments of the Vasse exit channel should also be considered as an appropriate management tool.

Hypoxic and anoxic oxygen concentrations in coastal environments are increasing throughout the world (Conley et al. 2009), and are frequently linked to eutrophication of the water body as a result of increased nutrient loading from anthropogenic sources (Harris et al. 2015, Middelburg & Levin 2009). Artificial oxygenation may be considered as an effective remediation technique, while broader scale efforts to reduce nutrient loading from the catchment are undertaken. The 2015-17 trial of BOC drop-in oxygenation technology successfully showed that smaller, shallow estuaries can be effectively treated, but oxygenation plants needed to be sized carefully in order to mitigate extreme drawdown events associated with larger phytoplankton blooms.

7 Major findings

Objective 1: Show proof of concept

- The BOC Solvox drop-in oxygenation devices are suitable to the shallow and estuarine Vasse exit channel, working best in DO control where operation was triggered when oxygen concentrations dropped below 4mg/L. Losses of oxygen to the atmosphere appeared to be minimal.
- In year 1 both pumps ran for a total of 1243 hours, adding 1515 kg of oxygen while in year 2 both pumps ran for a total of 2085 hours adding 6145 kg of oxygen.
- The oxygenation plant improved DO concentrations in the trial area (470 m upstream of the surge barrier) and each pump influenced a stretch of approximately 250 m.
- Effectiveness testing showed that the plant was able to substantially increase dissolved oxygen concentrations, however, the magnitude of its impact was highly dependent on internal oxygen demand which was strongly driven by phytoplankton dynamics.

Objective 2: Determine plant capability

- For much of the trial period, the plant was able to maintain adequate oxygen concentrations, however, the plant could not maintain critical DO levels during the respiration phase of a major algal bloom, where rapid drawdown of oxygen exceeded the capacity of the plant.
- Plant capability was quantified by the percentage of time that the plant was operating and able to maintain DO above 4 mg/L; 62 % of the time in year 1 and 45% in year 2. Without the operation of the plant, the system would have exhibited low oxygen concentrations or been hypoxic during these times.

Objective 3: Determine the impact on the likelihood of a fish kill

- The ability of the plant to mitigate the likelihood of a fish kill was quantified by the percentage of time that the plant was operating and able to maintain the DO above the hypoxic threshold of 2 mg/L; 82% of the time in year 1 and 67% in year 2. Without the operation of the plant, the system would have been hypoxic during these times.

Seasonality and other factors influencing oxygenation success

- Understanding the seasonality and daily demand for supplementing oxygen is an important outcome of the trial, and while historically fish kills are more likely to occur in the warm summer months of December, January and February, extensive low DO measured in May and June in year 1 of the trial suggests that fish kills are a risk at other times of the year as well. The demand for plant operation is likely to be at its highest in the early morning, but when operating in DO control, operation was triggered at all times of the day.

- Stratification (due to layers of differing salinity or temperature) has the potential to exacerbate low oxygen concentrations in bottom waters, as well as prevent the mixing of artificially oxygenated water through the water column.
- Oxygenation may increase oxygen demand by stimulating aerobic decomposition and as such, abruptly ceasing oxygenation may lead to a deoxygenation event, a phenomenon that may have contributed to very low oxygen concentrations exhibited in June in year 1 of the trial.

8 Recommendations

Key recommendations from the trial are;

- Artificial oxygenation should be considered as a viable method of responding to low oxygen concentrations in the Vasse exit channel.
- An oxygenation facility should be a component of a larger remediation strategy which includes a suite of other management tools, such as the manipulation of flows at the surge barrier.
- Alternative management actions designed to limit extreme algal blooms and reduce the rate of oxygen drawdown associated with phytoplankton respiration would complement an oxygenation facility and reduce the size of the plant required to prevent hypoxia and meet design objectives.

Appendix A — Transect sampling sites

Appendix B — Effectiveness testing, additional results

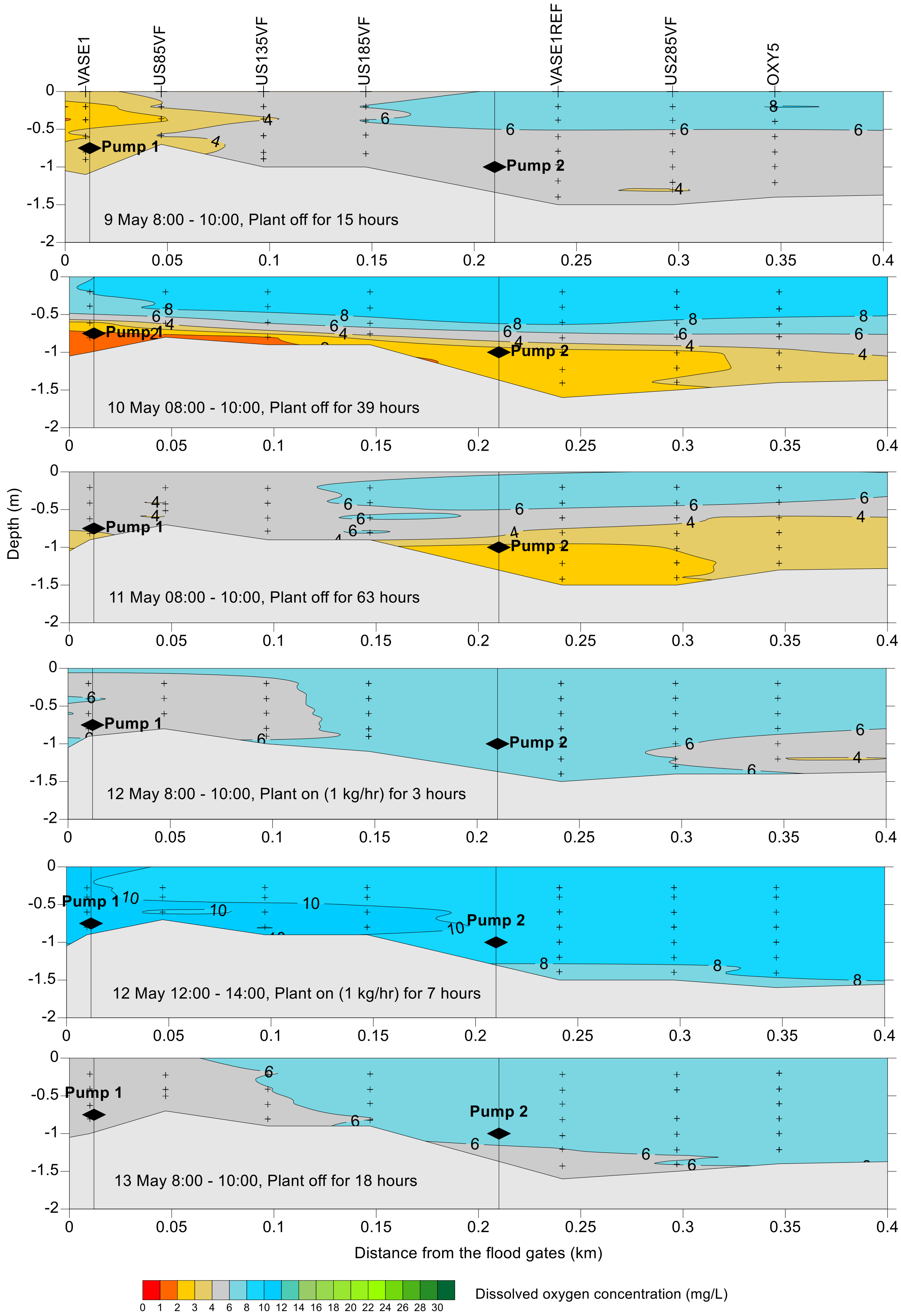

Figure B1 Dissolved oxygen conditions, week 2 of effectiveness testing in year 1 of trial

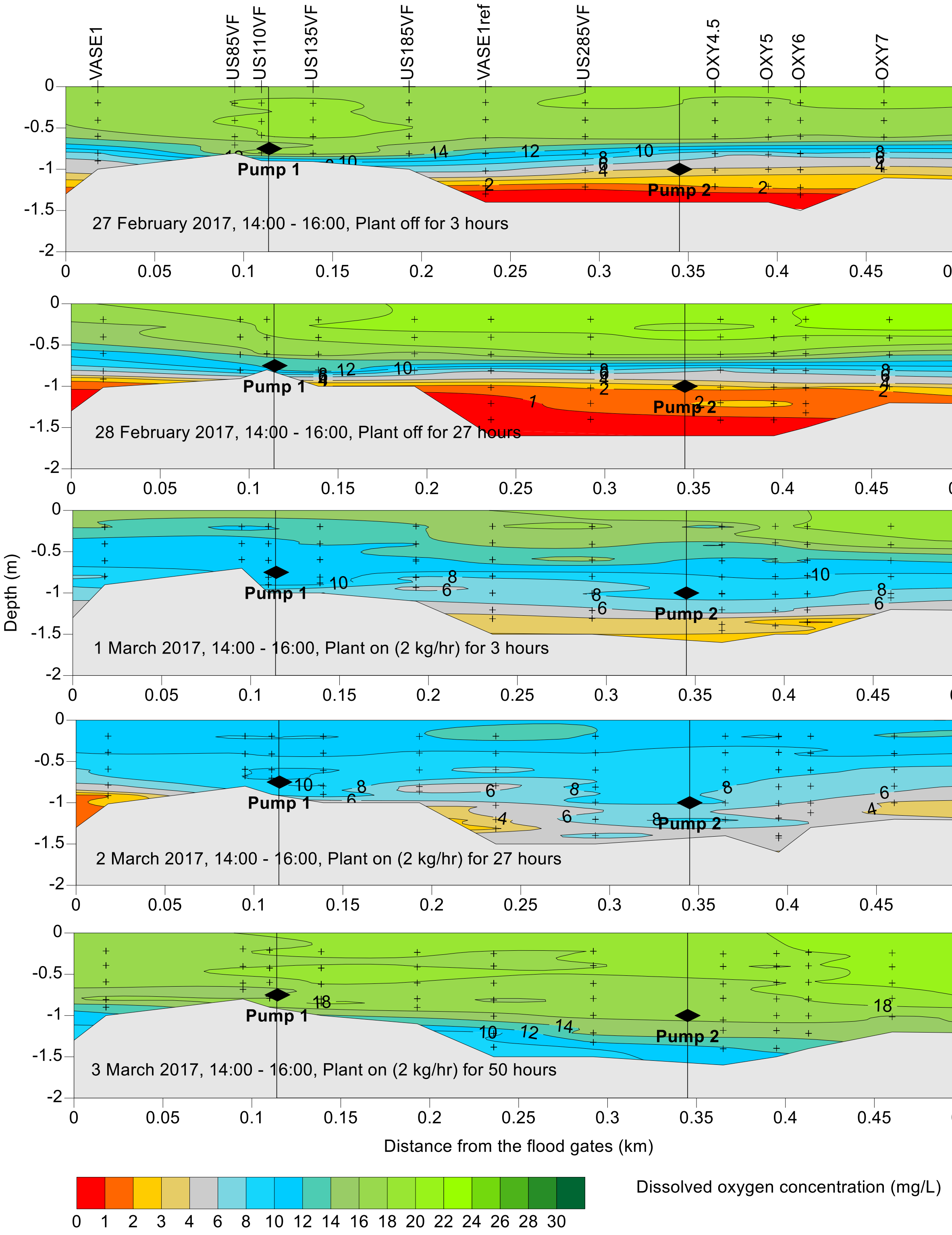

Figure B2 Dissolved oxygen conditions in the afternoons of effectiveness testing in year 2 of trial

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