Perth Desalination Plant Discharge Modelling: Effects of Desalination Discharges on Dissolved Oxygen

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1. Introduction

1.1 Background

Due to a combination of drying climate and increasing demand, Water Corporation requires additional water supply to meet Perth's (and surrounds) long-term requirements. Water Corporation is proposing to construct and operate a second desalination plant (Perth Seawater Desalination Plant 2 (PSDP2)) adjacent to the existing PSDP1 in Kwinana as an additional source of drinking water to the metropolitan water supply and is seeking environmental approval from the Environmental Protection Authority (EPA) of Western Australia.

PSDP2 will function as a standalone asset independent of PSDP1 and require its own intake and outlet pipelines. The seawater intake will be located in ~10 m water depth around 0.32 km from shore (Figure 1.1). PSDP2 will discharge up to ~70 ML of reject brine per day with a total dissolved solids concentration of up to 65,000 mg/L to Cockburn Sound through a specifically designed diffuser ~0.54 km from shore (Figure 1.1).

One aspect of the desalination process will be the return of desalination discharge water (brine) to Cockburn Sound, which has the potential to induce stratification. Stratification occurs when water with different properties, such as salinity and temperature, form layers that act as barrier for vertical mixing of the water column. Stratification is a natural phenomenon and the strength of the stratification can vary (meaning the energy required to re-mix can vary). Numerous studies have established that Cockburn Sound experiences naturally-occurring episodes of salinity and temperature stratification when the strength of the sea breeze decreases (often in the autumn months), reducing vertical mixing of the water column (D'Adamoo 2002, van Senden & Miller 2005, Okely et al 2007). These natural stratification events can restrict the downward mixing of dissolved oxygen (DO) from the surface, thus DO consumed at the seabed is unable to be replenished, reducing available DO in the bottom waters (D'Adamo 2002).

Discharge of desalination return water has the potential to enhance natural patterns in stratification, which in turn, can promote conditions which can lead to reductions in DO. Water Corporation has operated PSDP1 in Cockburn Sound since 2006 and through numerous investigations, has determined that the return water discharge has had negligible influence on DO concentrations in the Sound (Okely et al 2007, Oceanica 2013, Water Corporation 2013). Despite the low risk, the EPA has long held concerns about the fate and mixing associated with desalination discharges. Furthermore, it is generally accepted that the DO balance in Cockburn Sound remains sensitive to any mechanisms which enhance stratification processes (D'Adamo 2002, van Senden & Miller 2005).

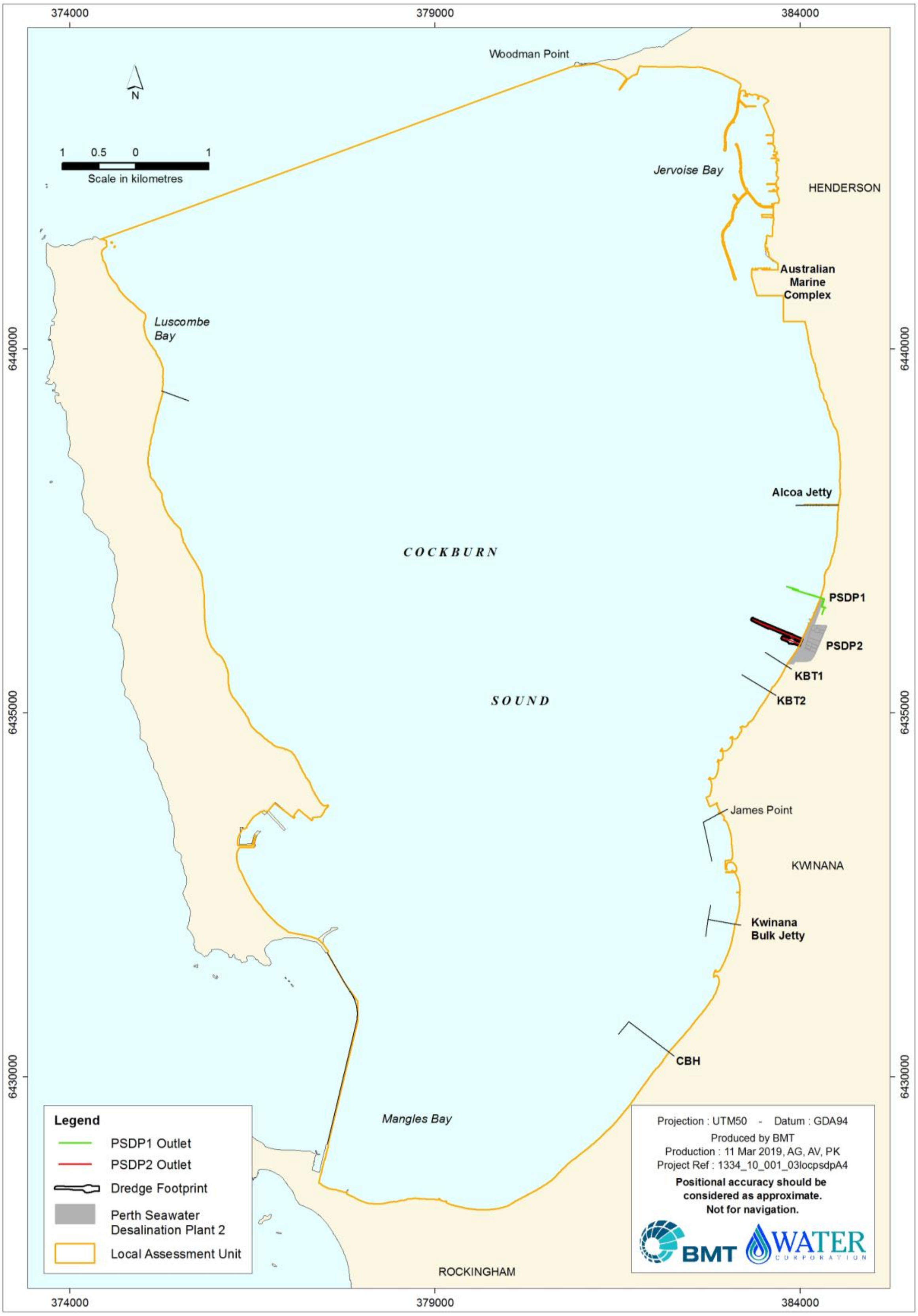


Figure 1.1 Location map

1.2 Research objectives

To address issues raised above, and to inform the environmental impact assessment of the PSDP2 Proposal, Water Corporation has commissioned BMT to develop a hydrodynamic and water quality numerical model of Cockburn Sound and its surrounds, to provide a platform by which the assessment of the fate and transport of return waters from the existing and proposed PSDP2 plant can be undertaken.

The objectives of this investigation are to:

i. advance our understanding of hydrographic mechanisms that impact patterns in DO concentration in the deep basin of Cockburn Sound, including:

- natural patterns in stratification and DO
- mechanisms driving those patterns, and
- the relative influence of desalination discharges associated with PSDP2 on those patterns.

ii. determine potential ecological risks to marine biota, as a consequence of any changes to DO resulting from the PSDP2 proposal

iii. meet EPA regulatory requirements for assessing impacts of the PSDP2 proposal on marine quality.

1.3 This report

This report summarises the outcomes of hydrodynamic and water quality modelling, focusing on key outcomes with respect to DO. The setup and validation of the numerical modelling tool developed for assessment of desalination plant return water discharges to Cockburn Sound are described in full in BMT 2018 and 2019.

2. Mechanisms Driving Stratification and Dissolved Oxygen Concentrations in Cockburn Sound

2.1 General conceptual model of Cockburn Sound

The exchange of water between the deep areas of Cockburn Sound and the adjacent waters - including shallower margins of the Sound and shelf waters - is driven by complex interactions of a range of physical processes (D'Adamoo 2002). However, according to D'Adamoo (2002) *wind* and *density gradients* are the primary influences in the mean basin-scale hydrodynamic behaviour of Cockburn Sound and its adjacent waters through-out the year.

The role of the wind is twofold. Firstly, wind directly exerts stress on the water surface and therefore drives surface water motion within the Sound. Secondly, wind impacts heat exchange at the atmosphere-ocean surface which in turn influences evaporation and therefore temperature and salinity fields within the Sound waters. Wind also imparts energy that can be used for water column mixing, both in terms of wind stirring and wind shear.

The density signatures of the Sound are influenced by both saline and thermal gradients (D'Adamoo 2002). Regional scale changes in water density are associated with oceanic phenomena, such as the Leeuwin current and south-eastern Indian Ocean circulation. Both salinity and temperature change seasonally, but at different rates in the Sound compared to the adjacent ocean. As such, density gradients develop both horizontally and vertically between the two water bodies. Local changes in water density arise in response to heating and cooling cycles, evaporation, spatially variable winds, and freshwater inputs from the Swan river and local groundwater sources. Water currents induced by density gradients are generally very small (less than a few centimetres), but when sustained over long periods (e.g. weeks) can lead to significant water and transport exchange (Van Senden 2005).

During mid-winter and spring, Cockburn Sound is regularly exposed to strong winds associated with the passage of low pressure frontal systems, originating between 40 and 50 degrees latitude, that cause complete vertical mixing within the Sound (D'Adamo 2002). In the calmer periods between the passage of the fronts, deep water renewal occurs as relatively calmer ocean waters plunge to the Sound via the sill openings of the northern and southern entrances. Surface cooling during these colder months also contributes to the vertical mixing while the Swan River inflow provides a source of relatively fresh water that contributes to the longitudinal and vertical density gradients within the Sound.

In contrast, during late summer and autumn, evaporative processes lead to strong vertical salinity gradients in the Sound and the strong wind events are not as regular, resulting in less frequent full depth mixing (D'Adamo 2002). According to D'Adamo (2002), on average, wind events of sufficient strength and duration to fully mix the Sound occur on average four to five times per month during this period. Extended periods of low winds may also occur resulting in complete vertical mixing not taking place, in some cases, for up to 20 days. The waters of the Sound are generally heavier than the adjacent ocean, and hence the flushing of the Sound is less regular than at other times. The culmination of these conditions can promote stratification.

In summer, the weaker density gradients and seabreeze cycle generally results in regular complete mixing of the water column (D'Adamo) typically preventing the onset of stratification.

2.2 Mechanisms driving DO concentrations

There is a long history of episodes of low DO levels near the seabed in the deep waters of Cockburn Sound (BMT 2018). Natural, seasonal changes in weather and marine climate trigger these episodes, however managers and regulators are also concerned where projects may have impacts which act to increase the frequency or duration of low DO events.

DO concentrations in the water column are modulated through the mechanisms of surface re-aeration (turbulent diffusion across the air-water interface), production (from photosynthesis), uptake (respiration by living organisms), fluxes across the sediment-water interface and exchange with oxygen sources (e.g. adjacent waters, rivers, etc.). While DO in bottom waters is both consumed and produced by benthic biota, the dominant process is consumption, mainly by bacteria present in the sediments. This net depletion of DO at the sediment water interface is referred herein as the process of sediment oxygen demand (SOD). If water column mixing is limited and oxygen is not transported through external sources to replenish the oxygen consumed by SOD, benthic concentrations of DO can drop under the influence of this demand to levels that can be harmful to marine life (ANZECC/ARMCANZ 2000). The two most common mechanisms to transport oxygen are:

i. vertical and downwards transport from the surface due to mixing driven by the wind and/or penetrative convection (i.e. movement of cooler and denser water from the surface to the bottom)
ii. horizontal advection (sideways currents).

One mechanism that has been identified as inhibiting this oxygen transport is vertical density stratification. Stratification is a natural phenomenon and may arise via many factors, for example: daily heating and cooling of surface waters, inflows of less dense water (rivers, groundwater, less saline and warmer oceanic waters), inflows of denser water (more saline and colder waters), and periods of prolonged light winds and high temperatures (that therefore promote surface water warming and reduced wind mixing conditions). Strong winds blowing for long enough will generally mix most naturally occurring stratifications and increase the rate of surface re-aeration. In doing so such conditions therefore promote increased oxygenation across the water column.

Due to Cockburn Sound being a semi-enclosed embayment (with much of the embayment a distance from the ocean) it has generally been assumed that oxygen levels near the seabed of the deep basin (around 20m depth) are dominated by vertical stratification and wind mixing rather than sideways advection and much of the data collected for Cockburn Sound is consistent with this wind mixing hypothesis. Notwithstanding, this wind mixing (and therefore the vertical transport of oxygen) is ineffective when winds are light and/or the water is stratified (layers of less dense water overlie layers of denser water).

According to the Ministerial Condition 832 (EPA 2010), a low dissolved oxygen event is defined as:

"… declines in dissolved oxygen of bottom waters, defined as less than or equal to 0.5 metres above the seabed, to 60% saturation (24 hour running median) or less in the high and/or moderate protection areas of Cockburn Sound as defined by the SEP ".

Low DO events emerge when oxygen transfer via surface re-aeration is reduced as the wind intensity diminishes. At the same time, the density differences between the Sound and adjacent waters under the action of coastal shelf waves combine to strengthen vertical stratification of the water column, which in turn limits vertical mixing and transfer of DO to lower portions of the water column. As wind transfer is reduced and vertical stratification sets in, DO demand, particularly in the sediment, cannot be met by oxygen transfer at the surface, so DO concentrations become progressively lower until a meteorological and/or other event is sufficiently energetic so as to drive full water column mixing and therefore reaeration. For example, D'Adamoo (2002) showed that, for full water column mixing in autumn, wind action alone is generally insufficient and penetrative convection from surface cooling is needed to provide the additional energy required to de-stratify the water column. For typical stratification strengths in autumn, a wind of 7.5 m/s combined with a surface heat loss of 300 W/m^2 requires approximately 13 hours to mix the entire water column (D'Adamoo 2002).

3. Regulatory Considerations for EIA

Because of uncertainties around links between desalination discharge and low DO events in Cockburn Sound, EPA has required Water Corporation adopt a precautionary approach to modelling and monitoring and management of DO in Cockburn Sound over a long period of time. It is useful to examine the marine environmental approvals and monitoring history of PSDP1, so that lessons learnt can be used to inform the environmental impact assessment and condition setting process for PSDP2.

3.1 State Environmental (Cockburn Sound) Policy 2015

An important priority for the state government is to ensure that Cockburn Sound continues to support the multiple values for which it is renowned. The Cockburn Sound SEP was first introduced by government in 2005 (updated in 2015) as a mechanism to ensure that the values and uses of Cockburn Sound are protected and fully considered in decision-making about ongoing and new uses of the Sound.

The overall objective of the policy is to ensure that the water quality of the Sound is maintained and, where possible, improved so that there is no further net loss and preferably a net gain in seagrass areas, and that other environmental values and uses are maintained. The management framework established by the policy is based on that recommended by the National Water Quality Management Strategy (ANZECC & ARMCANZ 2000), representing an agreed, Australia-wide approach to protecting water quality and associated environmental values.

As the basis for protecting these values, the Cockburn Sound SEP establishes environmental quality objectives and environmental quality criteria, and an environmental quality management framework (EQMF) for monitoring and reporting against the objectives and criteria. Environmental quality criteria (EQC) are further detailed in Environmental Quality Criteria Reference Document for Cockburn Sound – A supporting document to the State Environmental (Cockburn Sound) Policy 2015 (EPA 2017). Particularly relevant to this review is the EQC for DO that requires:

Table 3.1 Environmental quality criteria for protecting the marine ecosystem from the effects of low DO

Environmental Quality Guideline		Environmental Quality Standard	
High ecological protection areas	Moderate ecological protection area	High ecological protection areas	Moderate ecological protection area
The median DO concentration in bottom waters at a site, calculated over a period of no more than one week, is greater than 90% saturation	The median DO concentration in bottom waters at a site, calculated over a period of no more than one week, is greater than 80% saturation	The median DO concentration in bottom waters at a site, calculated over a period of no more than one week, is greater than 60% saturation	The median DO concentration in bottom waters at a site, calculated over a period of no more than one week, is greater than 60% saturation
		No significant change beyond natural variation in any ecological or biological indicators that are affected by poorly oxygenated water unless that change can be demonstrably linked to a factor other than oxygen concentration.	No persistent (i.e. ≥ 4 weeks) and significant change beyond natural variation in any ecological or biological indicators that are affected by poorly oxygenated water unless that change can be demonstrably linked to a factor other than oxygen concentration.

		No deaths of marine organisms resulting from deoxygenation.	No deaths of marine organisms resulting from deoxygenation.

3.2 PSDP1 Ministerial conditions and monitoring requirements

The DO monitoring and management decision scheme for the PSDP1 is regulated under Part V of the EP Act (i.e. administered via licence conditions). These licence conditions have been the subject of several independent reviews, commissioned both by Water Corporation (CWR) and the EPA (Hart & Church 2006, NIWA 2008), and have been significantly modified and added to, since the plant originally commenced operation.

In July 2005, the Minister for Environment requested that the Office of the Environmental Protection Authority (OEPA) consider and provide advice under Section 46 of the Environmental Protection Act 1986 on Water Corporation's licence associated with the Perth Seawater Desalination Plant. The Section 46 Report was submitted to the Department of Environment & Conservation (DEC) on 14 November 2007. On behalf of the EPA, the DEC then commissioned a second peer review of the Section 46 report by Dr Robert Spiegel of the National Institute of Water & Atmospheric Research. In December 2008, the Water Corporation produced a Response to Public Comments document addressing issues raised during the public comment period and in the NIWA review.

On 25 May 2009, the OEPA issued a report to the Minister for Environment in response to the Section 46 Report with advice and recommendations on the key environmental considerations, conditions and procedures for the operation of the desalination plant. On 28 June 2010, Ministerial Statement 832 was issued in addition to the existing Statement 655. Statement 832 included a condition (Condition 8), to ensure that the marine water quality of Cockburn Sound is not adversely impacted by the operation of the Perth Seawater Desalination Plant (DWER Licence L8108/2004/4). Condition 8 required the development and implementation of a marine monitoring plan and management response to declines in dissolved oxygen in the bottom waters of Cockburn Sound for a continuous period extending over at least two autumn periods to provide the basis for the Minister for Environment and the Minister for Water to review the requirement for further monitoring and management.

3.3 Compliance monitoring outcomes

In accordance with DWER Licence L8108/2004/4 and Ministerial Statements 655 and 832, seawater discharge from PSDP1 has been subject to extensive post-commissioning monitoring, including real time monitoring of temperature, salinity, and DO, and during low DO events, manual plume tracking monitoring and an interim management response. Benthic surveys have also been commissioned by Water Corporation in 2006, 2008 and 2013 to ascertain the condition of sediment, flora and fauna, as well as Rhodamine dye tests and modelling on the brine discharge to track its movements and dispersal patterns.

This monitoring covered a period of unprecedented low DO in April 2013, where DO saturation remained below trigger levels for 15 days in Cockburn Sounds deep basin (Water Corporation 2013). Except for 26 April, on each day during the low DO event, salinity measured from within the anticipated plume foot print (D arc) was less than the salinity at the control sites, suggesting that the plume had dispersed as it moved through the Sound (Water Corporation 2013). Furthermore, the data showed that the DO saturation at the Stirling Channel monitoring sites never dropped below 67% saturation, also indicating that the plume had no local impact on the environment in terms of causing anoxic conditions at the seabed. It was therefore concluded that the operation of PSDP1 was unlikely to be affecting or exacerbating naturally-occurring low DO events in Cockburn Sound (Water Corporation 2013).

This monitoring confirmed that episodic depressions in DO concentrations, when they occur, are likely being driven by large scale natural processes rather than stratification influenced by the PSDP1 discharge. As a result, also supported by external peer review by GHD (2013), Water Corporation (2013) concluded the low DO event in 2013 was unrelated to the PSDP1 discharge, but the result of the operation of other natural processes within Cockburn Sound. The Office of the EPA (OEPA; now DWER) concluded that the monitoring had adequately demonstrated that the risk of low-DO events associated with PSDP1 was low and that the real-time monitoring required under condition 8-1 of Statement 832 was no longer required (N.B. N.B. while Ministerial Conditions were amended, Water Corporation continues to maintain routine water-quality monitoring in locations around Cockburn Sound, including of physico-chemical properties, bacteria, phytoplankton metals, hydrocarbon and pesticides).

To examine potential flow-on effects of desalination discharges on Cockburn Sound, basin-scale surveys of benthic macroinvertebrate fauna composition and relative abundance were completed prior to commissioning (2006) and repeated in 2009 and 2013 (Oceanica 2013). These investigations determined that during this period, there was a shift in sediment characteristics and benthic macrofaunal communities throughout the deep basin of Cockburn Sound (Oceanica 2013). However, it was concluded that the changes in benthic communities were the result of regional effects and natural shifts, rather than the result of the operation of the desalination plant (Oceanica 2013); there was no evidence to suggest that the composition or relative abundances of the taxa were indicative of a disturbed state. These outcomes also corroborate with additional monitoring of benthic macroinvertebrate fauna that targeted a period immediately following a low DO event in April 2006 (Oceanica 2006) and provide evidence to suggest that the desalination discharge from PSDP1 is not enhancing stress on benthic macroinvertebrate communities, either during normal climatic conditions, or following low DO events.

4. Modelling Set-up and Scenarios

4.1 Hydrographic model set-up and description

4.1.1 Model set-up

The hydrodynamic model construction, calibration, assumptions and independent peer review process are described in full by BMT (2018a). In summary, the modelling package includes:

- OpenFOAM (Open Field Operation and Manipulation) which was developed for detailed representation of the nearfield dilutions, and
- TUFLOW FV and Aquatic Ecosystem Model v.2 (AED2) were used for three dimensional simulation of temperature, salinity and DO.

OpenFOAM was adopted as the computational fluid dynamics (CFD) modelling tool for the diffuser assessment performance, while AED2 was coupled to TUFLOW FV to simulate dissolved oxygen in Cockburn Sound (Hipsey et al., 2013).

In AED2, dissolved oxygen dynamics account for atmospheric exchange, sediment oxygen demand, microbial consumption during organic matter mineralisation and nitrification, photosynthetic oxygen production and respiratory oxygen consumption, and respiration by other optional biotic components (Hipsey et al. 2013). TUFLOW FV was used to calculate water levels and both advection and diffusion of scalars (temperature, salinity and DO), AED2 was applied to calculate source and sink terms specific to the DO dynamics.

The hydrodynamic modelling component of these assessments was undertaken using the TUFLOW FV software. TUFLOW FV is a numerical hydrodynamic model for the two-dimensional (2D) and three-dimensional (3D) Non-Linear Shallow Water Equations (NLSWE). The model is suitable for simulating a wide range of hydrodynamic systems ranging in scale from open channels and floodplains, through estuaries to coasts and oceans. The three-dimensional model was deployed in this study.

4.2 Scenario establishment

Scenario modelling was designed to simulate the fate of discharges from both the proposed PSDP2 outfall and the existing PSDP1 outfall under various current and future states. The scenarios that were modelled are summarised in Table 4.1. The order of the scenario modelling was developed to progressively inform decision making on the location of the proposed SDP brine outfall and seawater intake.

The broad objectives of the scenario modelling were to:

- Guide location and concept for the PSDP2 outfall to achieve environmental mixing criteria defined for outfall/diffuser performance
- Inform decisions on construction methodology for the intake and outfall works (addressed separately from this report)
- Generate a Low Ecological Protection Area (LEPA) management boundary for the Future Proof Option in accordance with EPA guidance
- Confirm that the Preferred Option discharge will meet the requirements of the existing Low Ecological Protection Area (LEPA), and,
- Inform the Environmental Impact Assessment (EIA) process.
- Guide location of the PSDP2 outfall to preferably eliminate interference / intersection with the existing PSDP1 outfall plume, and avoid impact on the PSDP1 seawater intake

- Guide location of the PSDP2 seawater intake to avoid/minimise risk associated with recirculation of discharges from the PSDP1 and PSDP2 outfalls

The scenario modelling commenced with baseline scenarios that correspond to Water Corporation's existing PSDP1 operation and the preferred PSDP2 development option which locates the seawater intake and brine outfall for PSDP2 within the shallower shelf area of Cockburn Sound similar to the existing PSDP1 marine assets on the landward side of the shipping channel that services the FPA bulk handling terminal (referred to as "Preferred Option").

On completion, the modelled scenarios were required to sufficiently define the characteristics and fate of the PSDP1 and PSDP2 discharges under various seasonal and climatic conditions to provide regulatory agencies with confidence that the potential environmental risks have been adequately quantified and assessed for project approvals. In addition, the scenario results provided Water Corporation with an assessment of potential re-circulation risks to provide a level of assurance that both PSDP1 and PSDP2 operation will not be compromised by the proposed siting of PSDP2 marine assets.

- **Scenario 1A NoDESAL** – this is a baseline scenario that assumes there are no desalination plant intakes or discharges in Cockburn Sound. This scenario was required to support the method of presentation of model results
- **Scenario 1A** – this is a scenario of existing conditions, which assumes only the PSDP1 intake and discharge operate in Cockburn Sound at a production rate of 45 GL/year, and that discharges occur via the existing diffuser arrangement
- **Scenario 2A** – This is a scenario based on proposed conditions, which assumes both PSDP1 and PSDP2 intakes and discharges operate in Cockburn Sound. For this scenario, PSDP2 operating at a 50GL/year production rate was included in the simulation, in addition to the 45 GL/year PSDP1 production rate. The PSDP1 and PSDP2 discharges were delivered through separate diffusers
- **Scenario 2C** – This is a scenario based on proposed conditions at a reduced production rate (25 GL/year) from PSDP2 in Scenario 2a.

Table 4.1 PSDP2 Modelling scenarios

Modelling scenario	Timing	Discharge (ML/d)		Diffuser design		Modelling outcome
		PSDP1	PSDP2	PSDP1	PSDP2	
1A. Existing PSDP1 baseline	All year	195	0	Length: 163 m No. of ports: 40 Port diameter: 13 cm Port spacing: 4 m Port orientation: north	Length: 245 m No. of ports: 50 Port diameter: 12 cm Port spacing: 5 m Port orientation: alternating (north, south)	Define extent of existing brine effluent plume under worst-case mixing conditions Examine risk of recirculation (brine effluent entering intake)
2A. PSDP2 baseline 50 GL with existing PSDP1	Applied for summer, winter and spring	195	202			Define extents of both brine effluent plumes under worst-case mixing conditions Confirm estimated impact of construction on suspended sediment and light Assess scale of entrainment risk to snapper eggs/larvae Assess interaction between PSDP1 and PSDP2 brine effluent plumes

2C. PSDP2 baseline 25 GL with existing PSDP1	Applied for autumn	195	101			Define extents of both brine effluent plumes under worst-case mixing conditions Assess interaction between PSDP1 and PSDP2 brine effluent plumes

4.2.1 Timings

Scenarios were initially assessed over a four week period 19 February to 18 March, in the year 2008. This year was chosen as it is known to have experienced depletion of deep basin near bed DO (BMT 2018, BMT 2019) and therefore represents a conservative approach to the EIA. The relatively short run time over the initial testing period allowed for a rapid turnaround and identification of alternative outfall locations if/as needed.

Once the elected scenario across 2A and 2C had been finalised, a full year run - 01 March 2008 to 01 March 2009 - was undertaken to assess footprints and the potential for entrainment of brine. Post processing of model outputs was undertaken to further examine seasonal variations:

Autumn: 1 March 2008 to 1 June 2008
Winter: 1 June 2008 to 1 September 2008
Spring: 1 September 2008 to 1 December 2008
Summer: 1 December 2008 to 1 March 2009

To simulate worst-case conditions, modelling was undertaken based on climatic conditions experienced in autumn 2013, when a low DO event occurred (BMT 2018). This simulation period covered 5 April to 1 May 2013.

4.2.2 Climatic conditions

BMT set conditions using the following ambient forcings:

- TOPEX astronomical tide boundaries;
- HYCOM+NCODA for currents, mean water levels, temperature and salinities at the open boundaries
- Combination of CFSRv2 and BoM at Garden Island data for meteorological boundary conditions
- No influences from Swan River flows
- PSDP1 discharge.

5. Model simulations

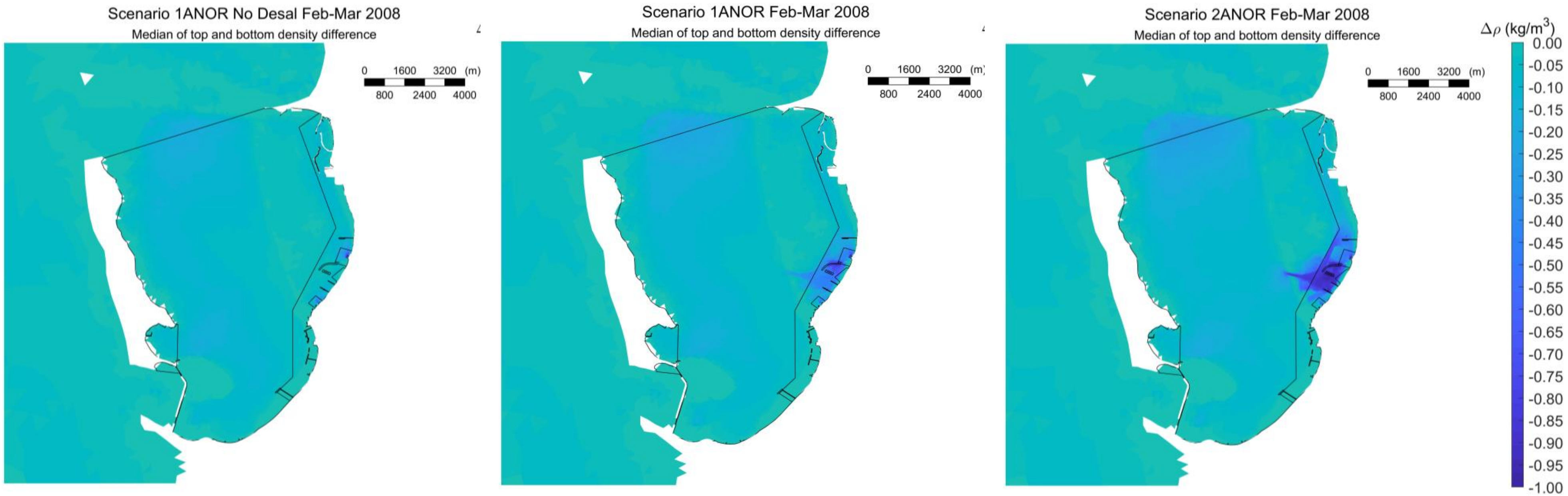
5.1 Normal climatic conditions

The results of modelling are in agreement with accepted conceptual models of stratification in Cockburn Sound (D'Adamo 2002) and demonstrate that surface-bottom water density differences occur naturally across the entire deep basin (Figure 5.1), and that these differences are more pronounced in autumn (BMT 2019). Assessment of the effects of the PSDP2 proposal also indicate that the desalination discharge does not enhance density above background levels for most of the year under 'normal' conditions (BMT 2019), except in autumn where modelling predicted a marginal elevation in density above expected background densities (Figure 5.2). During autumn, which is generally considered the period most conducive to low DO events, increases in ambient density were greatest in the north of the deep basin, mostly in the range of ~0.2–0.4 kg/m^3, but fluctuating by as much as 1.3 kg/m^3 for periods up to 10 days (Figure 5.2). However, the surface-bottom density difference caused by desalination discharges was predicted to be far lower (<0.1 kg/m^3) than density differences induced by natural fluctuations, which ranged up to 1.3 kg/m^3 (BMT 2019). Differences in density gradients between scenarios 1A (PSDP1 only) and 2A/2C (PSDP and PSDP2) were negligible (Figure 5.2).

Modelling outputs show a clear north–south transition in both the strength of density gradients (north being stronger than south), and the species (salinity versus salt) driving those gradients (Figure 5.2). The data suggests a spatial gradient of temperature stratification in the south, salt stratification in the north and a combination in the central part of the Sound. The addition of the desalination discharges does not affect these density patterns (Figure 5.2).

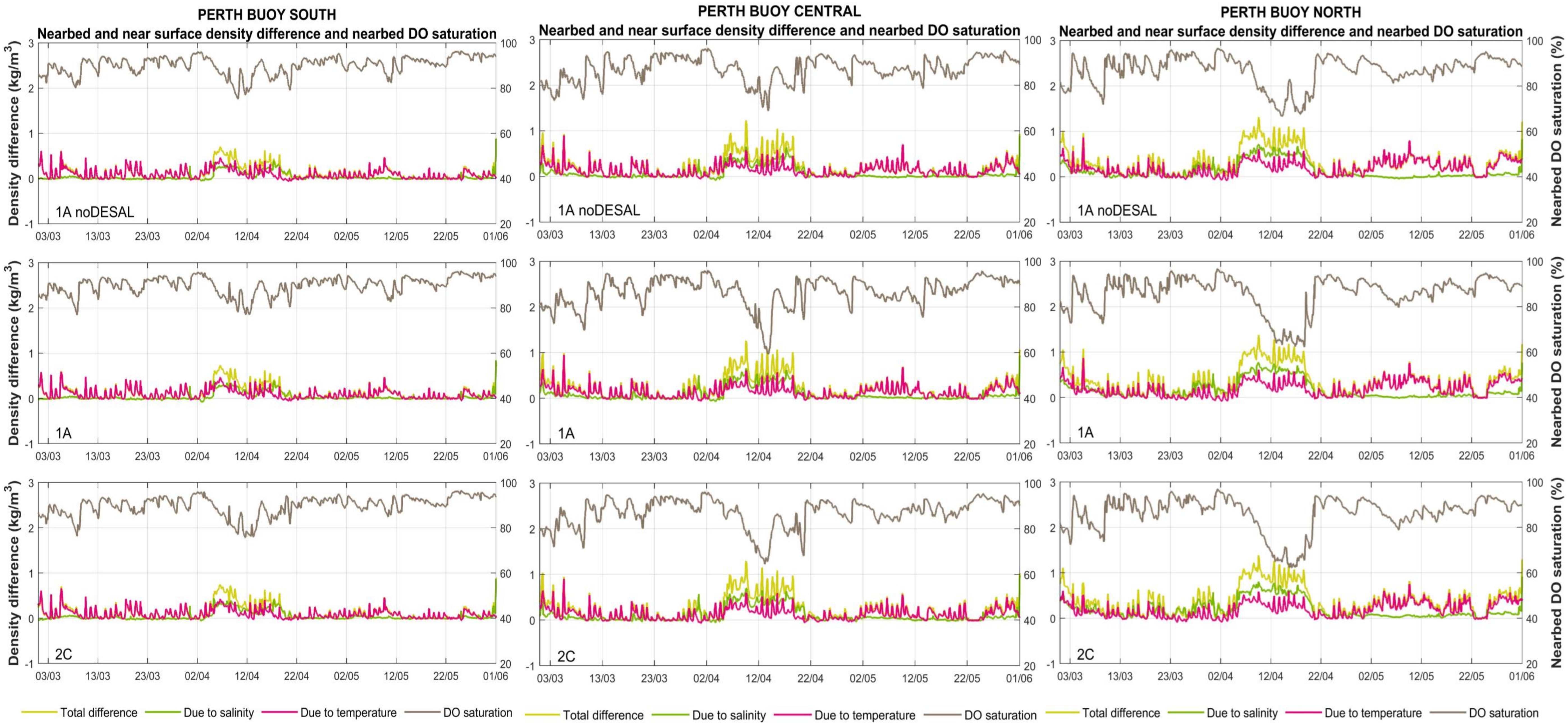
DO (% saturation) was plotted on density graphs to assess the relationship to density when brine effluent is discharged (Figure 5.2). From these results, it is clear that while DO depletion in the deep basin is related to overall stratification strength, the effect of brine effluent on DO is very subtle and appears to account for less than 2–3% of the decline in DO (and often much less). This decline in DO is only a fraction of the change in DO driven by natural density changes, which can induce declines by up to 35% (Figure 5.2). The addition of the brine effluent, however, did increase the period that DO concentrations are held low, mostly by hours, but up to days (Figure 5.2).

The above results suggest that (i) desalination discharges have only a very subtle influence on density gradients relative to natural mechanisms, and (ii) that the PSDP2 proposal does not appear to have an additive effect on density gradients above the effect of discharges already released into Cockburn Sound via PSDP1. However, they also indicate that brine effluent may impede oxygen replenishment at times.



Autumn 2008

Figure 5.1 Top-to-bottom density difference with no desal (left), PSDP1 (middle) and PSDP2 (right) under imposed 'normal' conditions in Feb-March 2008



Notes:

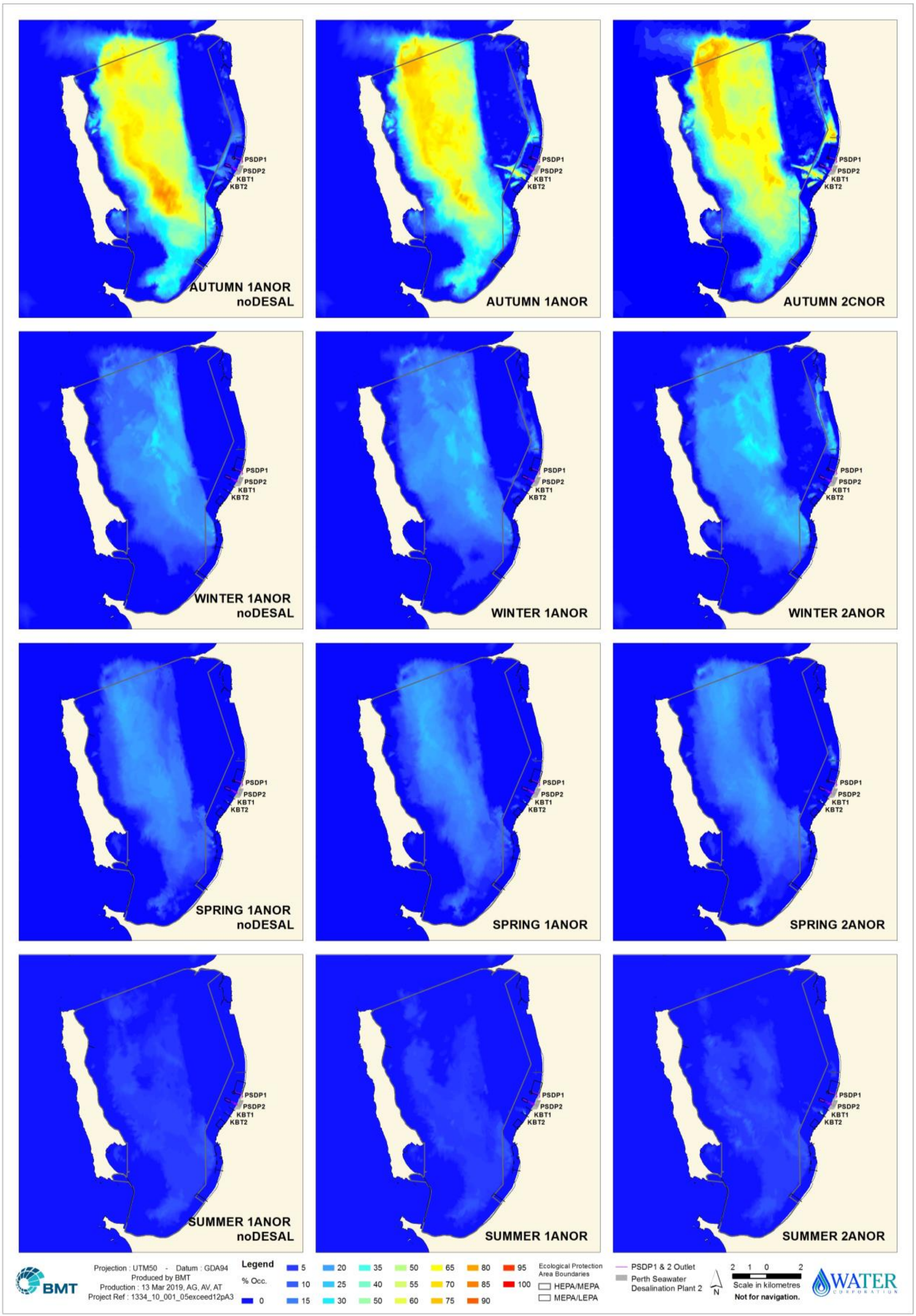
1. DO differences are shown as bottom minus top
2. Top layer is 0.5 m below surface, bottom layer is 0.5 m above seabed
3. 1ANOR noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2ANOR = PSDP1 and PSDP2 desalination discharges

Figure 5.2 Time series of simulated top-to-bottom density difference at Perth Buoy South (left) and Perth Buoy North (right) based on climatic conditions experienced in autumn 2008

During the 2008 summer, winter and spring periods (and when waters are frequently mixed by wind), hydrodynamic modelling predicted that the 7-day rolling median of DO (% saturation) with the PSDP2 proposal would mostly be above 90% in the deep basin bottom waters (Figure 5.3). During these months, differences in DO saturation between 'with' desalination discharges versus 'without' desalination discharges were predicted to rarely exceed 5% (equivalent to ~0.43 mg/L at 23°Celsius), while differences between 1A (PSDP1) and 2A (PSDP1 plus PSDP2) scenarios were typically <1% (Figure 5.4).

During autumn months, modelling predicted that DO concentrations in bottom waters are likely to remain below 90% for most of the time (Figure 5.5), especially in the north of the deep basin (see Figure 5.3 and Figure 5.5) At Perth Buoy North, the lowest DO was predicted to reach ~71% saturation (equivalent to ~6.1 mg/L at 23°Celsius) without desalination discharges and ~66–67% (equivalent to ~5.7 mg/L at 23°Celsius) for 1A (PSDP1) and 2C (PSDP1 and PSDP2) scenarios (Figure 5.5), with the decline in DO for all scenarios anticipated to last for ~7 days. In the south of the deep basin, DO was predicted to remain above 80% for the duration of autumn, and differences between 'with' and 'without' desalination discharge were typically <3% (Figure 5.5). DO was not predicted to drop below 60% structuration at any point during a year experiencing normal climatic conditions.

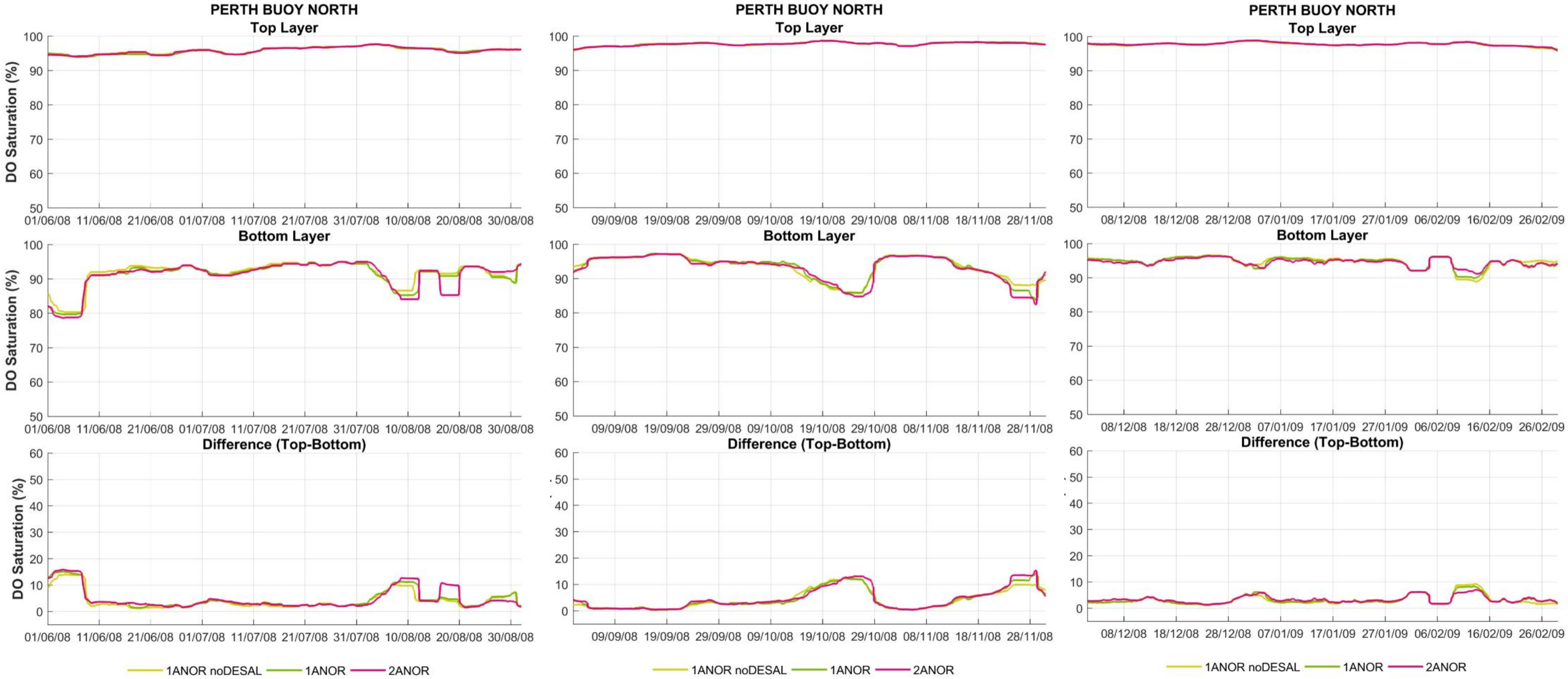
From these results, it can reasonably be expected that there are no cumulative effects of PSDP1 and PSDP2 on DO (Figure 5.5). However, predicting the impact of desalination discharges on exceedance of EPA (2017) trigger values for DO concentrations in the bottom waters of Cockburn Sound is problematic – as shown by modelling and verified by sampling (Water Corporation 2013) – because the trigger values are frequently exceeded across the whole of Cockburn Sound due to natural mechanisms, especially in autumn. This can be seen in Figure 5.3, which shows the proportion of time that Cockburn Sounds likely to be exceeding EQG; common to all maps is the similarity between scenario 1A noDesal (baseline conditions), and the discharge scenarios (1A = PSDP1 only; 2A and 2C = PSDP1 + PSDP2 discharges), particularly throughout the deep basin.



Note:

1. 1A noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2A/2C NOR = PSDP1 and PSDP2 desalination discharges

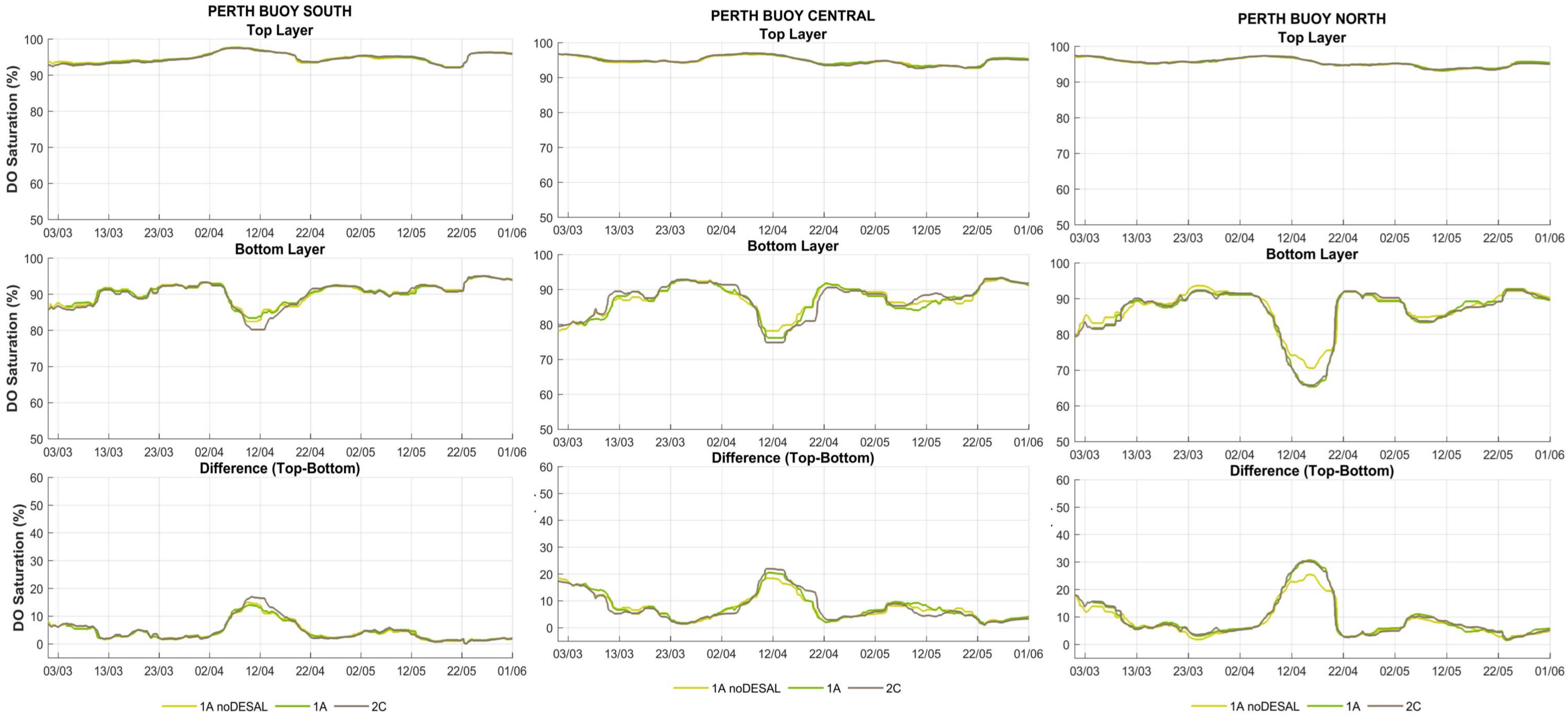
Figure 5.3 Proportion (% occurrence) of Autumn (2008) that bottom waters in the deep basin fall below 90% saturation without desalination discharges (left), with PSDP1 discharges (middle) and PSDP2 desalination discharges (right)



Notes:

1. DO differences are shown as top minus bottom
2. Top layer is 0.5 m below surface, bottom layer is 0.5 m above seabed
3. 1ANOR noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2ANOR = PSDP1 and PSDP2 desalination discharges

Figure 5.4 DO (% saturation, rolling median) at Perth Buoy North in winter 2008 (left), spring 2008 (middle) and summer 2008/09 (right)



Notes:

1. DO differences are shown as top minus bottom
2. Top layer is 0.5 m below surface, bottom layer is 0.5 m above seabed
3. 1ANOR noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2CNOR = PSDP1 and PSDP2 desalination discharges

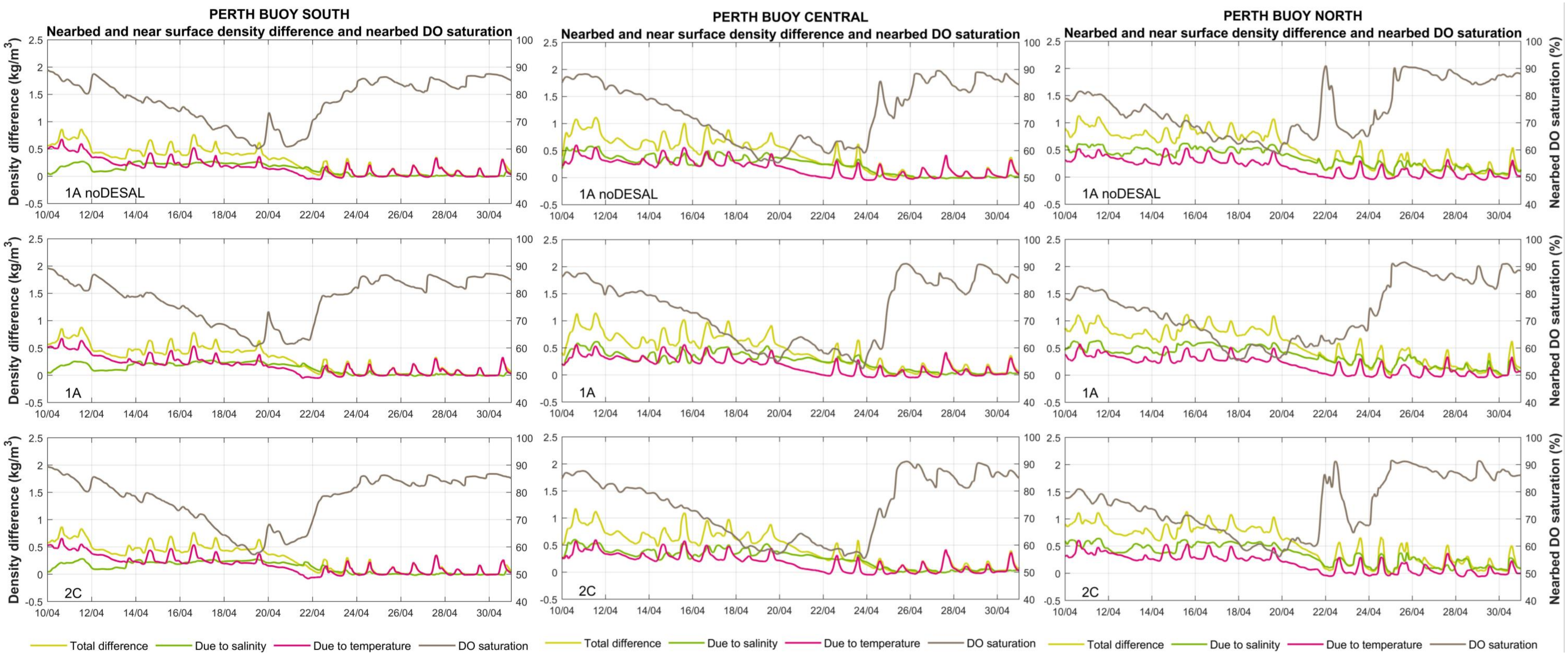
Figure 5.5 DO (% saturation, rolling median) at Perth Buoy South (left), Perth Buoy Central (middle) and Perth Buoy North (right) in autumn 2008

5.2 Influence of worst case climatic conditions

The effect of desalination discharges on density gradients under 'worst case' conditions (experienced during April 2013) were not equal across Cockburn Sound. In the south of Cockburn Sound, top-bottom density differences were slightly enhanced with desalination discharges during the first half of the April (by ~0.2–0.3 kg/m^3,Figure 5.6) but moderated over the course of the month. In the north of the deep basin, while top-bottom differences in density were also generally greater in the first half of April, they remained variable through-out the month and were slightly enhanced on occasions by the addition of desalination discharges (by ~0.1 kg/m^3, Figure 5.6). The data suggests a spatial gradient of temperature dominated stratification in the south, salt dominated stratification in the north and a combination in the central part of the Sound

While patterns in DO in bottom waters appear similar between locations (south, central and north of the deep basin), there are slight but significant differences (Figure 5.7). In the south of Cockburn Sound, modelling predicted that DO concentrations would be lower for 2C than 1A and '1A noDesal' by ~2% (Figure 5.7), but in all scenarios, the rolling 7-day median remained above 60% saturation. Results are similar in the north of the deep basin for 2C, but 1A is slightly lower than 2C by ~1% (Figure 5.7). In contrast, in the centre of the deep basin, the rolling 7-day median for DO for both scenarios 1A and 2C was predicted to drop to 59% (or ~5.06 mg/L based water temperature of 23°C) for ~ 2 days (Figure 5.7), while 1A noDesal, was predicted to drop to ~61% (or 5.23 mg/L at the same temperature) for the same duration of time. As such, EPAs (2017) environmental quality standard for DO would be exceeded in the central of the basin.

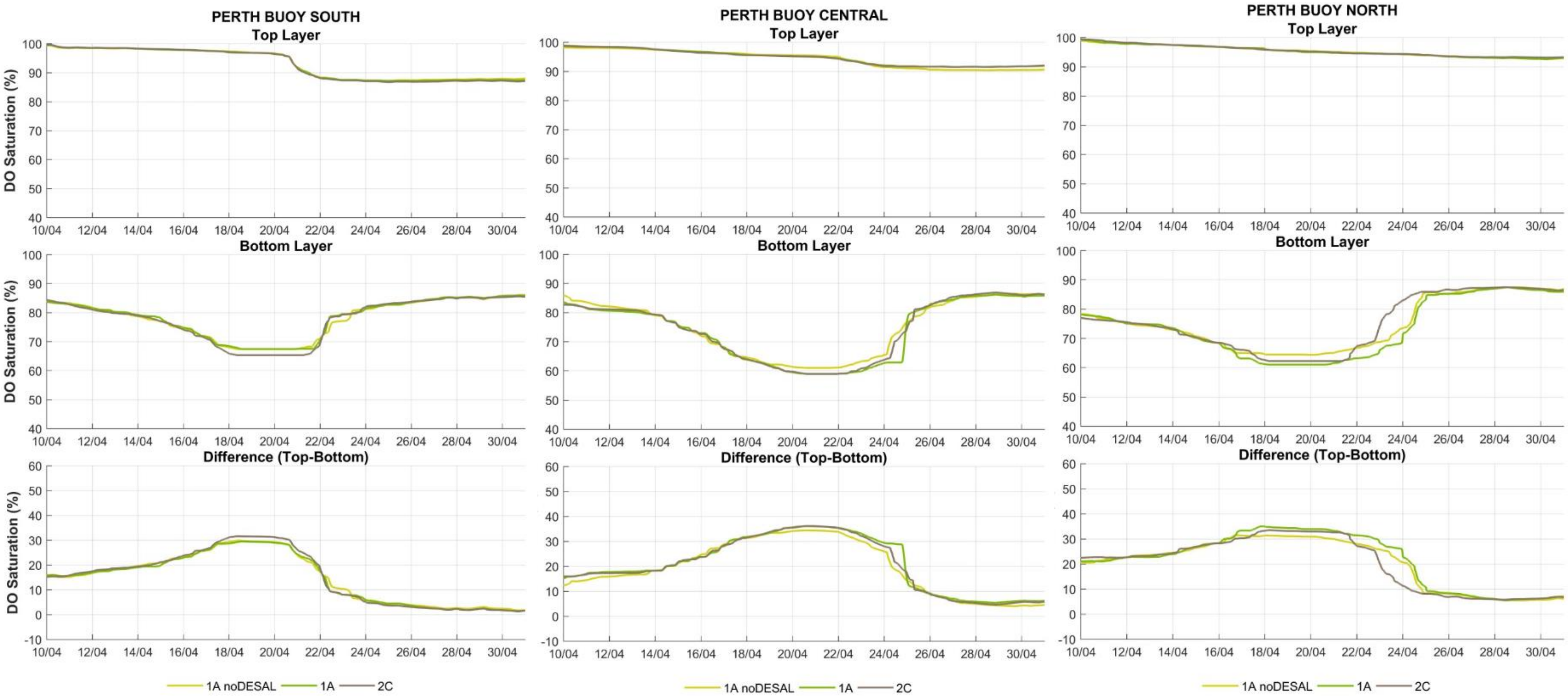
From results described above, and in Section 5.1, is it apparent that brine effluent discharges can have a temporary and subtle effect on DO concentrations (accounting for ~2–3% in change from baseline conditions). However, applying EPA (2017) trigger values to determine acceptability can be ambiguous since low risk criteria (EQG) are regularly exceeded across the whole of Cockburn Sound even in the absence of brine effluent, while marginal differences in DO due to the discharge of brine effluent can potentially lead to high risk criteria (EQS) being exceeded. Discussion is provided in Section 6, supported by a thorough review of the literature (Appendix A) to better understand the ecological consequences of these DO values and implications for marine biota.



Notes:

1. Density differences are shown as top minus bottom
2. Top layer is 0.5 m below surface, bottom layer is 0.5 m above seabed
3. 1ANOR noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2ANOR = PSDP1 and PSDP2 desalination discharges

Figure 5.6 Top-to-bottom density difference time series at Perth Buoy South (left) and Perth Buoy North (right) based on 'worst case' climatic conditions experienced in April 2013



Notes:

1. Density differences are shown as top minus bottom
2. Top layer is 0.5 m below surface, bottom layer is 0.5 m above seabed
3. 1ANOR noDESAL = no desalination discharge, 1ANOR = PSDP1 desalination discharge only, 2ANOR = PSDP1 and PSDP2 desalination discharges

Figure 5.7 Top-to-bottom density difference time series at Perth Buoy South (left), Perth Buoy Central (Middle) and Perth Buoy North (right) based on 'worst case' climatic conditions experienced in April 2013

6. Discussion

Due to the risk of desalination discharges promoting conditions which can lead to reductions in DO, and to meet regulatory requirements for assessing the fate and mixing of wastewater discharges into the marine environment, Water Corporation commissioned BMT to develop a hydrodynamic and water quality model of Cockburn Sound (described in full in BMT 2018x and BMT 2018x). This report provides a synthesis of modelling results to help advance our understanding of hydrographic mechanisms that impact patterns in DO concentration, and the ecological consequences of these impacts, in the deep basin of Cockburn Sound.

6.1 Mechanisms driving DO in Cockburn Sound

The general conceptual model for Cockburn Sound is for naturally occurring longer periods of stratification, typically in autumn although not restricted to this timing, that can inhibit vertical mixing and downward transport of DO from the near surface oxygen-rich waters (van Senden & Millar 2005). Oxygen consumption by micrbobes and chemical processes at the bed sediments leads to decreases in DO concentrations in deeper stratified layers. The dissolved oxygen concentration in the deep water is determined by a balance between consumption, vertical mixing and horizontal transport of heavier waters from the adjacent areas (van Senden & Millar 2005). However, patterns in stratification and the mechanisms driving those patterns are known to vary across the deep basin, and there is a known transition from north to south (Okely et al. 2007).

The outcomes of modelling results presented here mostly align with this conceptual model and stratification has generally been shown to be good predictor of DO concentrations in bottom waters of the Sound; during both 'normal' and 'worst case' conditions it was clear that DO depletion (<80%) at all stations was driven by stratification strength. However, at times, DO declines were also predicted when top-bottom density differences were only very small (<0.2 kg/m^3) and continued to propagate after the stratification had been broken, demonstrating the very subtle balance of DO in this system.

Results here also demonstrated a clear north–south transition in stratification, thus conforming with previously documented spatial patterns of temperature stratification in the south, salt stratification in the north and a combination in the central part of the Sound (Okely et al. 2007); however, modelling here predicted that under certain conditions, density gradients in the north of the deep basin were likely to be more significant, resulting in greater DO drawdown than in the south (although salinity was still confirmed to be the dominant stratifying species). Okely et al (2007) suggest that greater DO draw-down occurs in the south under weaker stratification due the sediment characteristics which support elevated rates of flux (Okely et al. 2007), however, the modelling here also highlighted the important influence of boundary inputs and horizontal transport of heavier waters, e.g. from riverine influences.

6.2 Influence of the PSDP2 Proposal

According to Okely et al. (2007) in order for brine effluent to impact DO conditions in Cockburn Sound, the duration and intensity of episodic stratification events must increase (relative to background conditions) to the point whereby oxygen consumption in the sediment causes significant additional depletion. Modelling investigations indicate that even in 'worst case' calm weather conditions, duration of stratification remains unaffected, although slightly enhanced stratification can occur (~0.1-02 kg/m^3), which is why subtle (~2–3% or ~0.23 mg/L) differences in DO saturation between ‘with’ desalination discharges versus ‘without’ desalination discharges, were predicted. However, the discharge of brine effluent did appear to impede oxygen replenishment for periods of hours to days, and in worst case conditions, would have led to an exceedance of EPAs (2017) EQS trigger value in central Cockburn Sound (noting that natural background DO concentrations without desalination discharge were also within 2% of exceeding the EQS trigger at the same location).

Modelling also revealed a stronger effect of desalination discharges on DO in the north of the deep basin relative to the south. These results are not consistent with the conceptual model presented by Okely et al. (2007) who suggest a spatial gradient in DO depletion, such that for a certain stratification, oxygen depletion in the south will be greater than in the central station, which in turn will be greater than in the north. It is likely that results presented here reflect the combined effect of boundary inputs and slightly enhanced influence of desalination discharges on salinity stratification in the north.

Results combined suggest that: (i) the system is dynamic and sensitive to discharges, in particular in the north of the deep basin; (ii) however, desalination discharges have only a very subtle influence on density gradients and DO relative to natural mechanisms; and (iii), that the PSDP2 proposal does not appear to have an additive effect on density gradients above the effect of brine effluent already released into Cockburn Sound via PSDP1.

6.3 Potential ecological risks to marine biota

Most aquatic organisms require oxygen in specific concentration ranges for respiration and efficient metabolism, and concentration changes outside this range can have adverse physiological, behavioural and ecological effects (ANZECC/ARMCANZ 2000). The effects of low DO concentrations on marine organisms are a function of:

- the temporal variation and timing, intensity and duration of periods of exposure to reduced oxygen concentrations—many species can survive short periods of reduced oxygen, but not longer periods, and
- the absolute concentration of DO.

The sensitivity and response of marine fish and invertebrates to low dissolved oxygen concentrations are provided in Appendix A. In general, DO concentrations of 5–6 mg L^{-1} are considered sufficient for most aquatic species and levels of 3–5 mg L^{-1} are considered potentially stressful for many aquatic species, especially if exposed to these conditions for prolonged periods (Diaz & Rosenberg 1995). The DO concentration threshold for most marine benthic organisms is widely considered to be ~2 mg L^{-1} (~23% saturation at 23°C), with some species able to tolerate very low DO concentrations for several days, surviving concentrations as low as 1 mg L^{-1}(Diaz & Rosenberg 1995). Even those benthic communities that tolerate low DO concentrations, can become degraded as DO declines to < 1 mg L^{-1} and anoxic conditions manifest (Diaz & Rosenberg 1995). Studies suggest that mortality is initiated at oxygen concentrations close to 1.4 mg L^{-1} (~15% saturation) and that mass mortality is initiated at about 0.7 mg L^{-1} (approximately 7% saturation) (Diaz & Rosenberg 1995).

It is apparent from hydrodynamic modelling that under some circumstances, desalination discharges may prevent oxygen replenishment by up to 24 hours or more, thus elevating the risk to marine biota until the stratification has been broken. It appears that that this effect is greatest in the north of the deep basin. However, the additional brine effluent from PSDP2 does not appear to enhance effects already associated with PSDP1, and therefore, the level of risk has not changed. Further, while desalination discharges can act to reduce DO concentrations during low DO events, such changes are typically subtle with DO sitting 5% (or ~0.43 mg/L) below natural background concentrations (71% or ~6.09 mg/L) and therefore, well above any ranges considered harmful to marine biota.

For most species during 'worst case' episodic low DO events, similar to those that occurred in 2013 (DO with desalination = ~5.09 mg/L, DO without brine effluent = ~5.2 mg/L), such levels of decline would be unlikely to exceed tolerance thresholds, but may temporarily result in additional sublethal stress to more sensitive species (Appendix A). At a community level, the temporary nature of low DO events would be unlikely to induce changes in species patterns (composition, richness, trophic order, etc), especially given species that presently occur in Cockburn Sound would have evolved under a long-term regime of stochastic low DO events. These outcomes are supported by basin wide benthic invertebrate surveys, undertaken in 2006, 2008 and 2013, respectively (Oceanica 2013) and benthic invertebrate monitoring undertaken immediately post a low DO event (Oceanica 2006).

6.4 Implications for EIA and future monitoring and management

The modelling approach applied here to spatially define and assess the effects of the Proposal on DO concentrations in Cockburn Sound meets EPA (2016) technical guidance requirements. The model construction and calibration process has undergone extensive peer review (BMT 2018a) and there is general agreement that model predictions are reliable and provide a close representation of hydrodynamic behaviour in Cockburn Sound.

Model outcomes show that the behaviour of additional desalination discharges associated with the Proposal (PSDP2) are highly unlikely to result in a different outcome on DO compared to existing ambient conditions associated with operation of the PSDP1, either under 'normal' or 'worst-case' conditions. It is relevant to highlight that the implementation of trigger levels as part of the approvals conditions for PSDP1 proved problematic as it was shown that trigger levels could be exceeded due to the natural variations of water quality parameters. Further, because of these trigger exceedances, various studies were commissioned by Water Corporation, all of which demonstrated that the effect of desalination discharge on DO concentrations appears minor (negligible) relative to natural drivers of stratification in the Sound, and there is no evidence to suggest that the discharge has led to flow-on effects to benthic biota.

In-light of the complexities raised above, it is apparent that application of EPAs EQMF to both EIA and monitoring and management of PSDP2 is confounded by natural exceedances in DO in the deep basin, which in turn, make determining the acceptability of desalination discharges on DO, difficult. However, given the long-term pattern of naturally occurring low DO events that result in concentrations nearing management trigger levels (60%), there is merit in determining the ecological risk of any differences caused by desalination discharges.

Advances in modelling have reduced the uncertainty associated with the available predictions of DO concentrations (and stratification) in the Cockburn Sound basin resulting from the release of brine and are the subject of the remainder of this report. It is anticipated that these findings will be used to further inform the environmental impact assessment process.

7. References

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Appendix A

Literature review of effects of low DO on marine organisms

Table 7.1 Sensitivity of marine fish and invertebrates to low dissolved oxygen concentrations from laboratory studies

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
Species Mean Acute Values(1) LC50: Invertebrates: < 0.34—1.27 mg/L Fish: 0.55—1.63 mg/L Criterion Maximum Concentration(2): 2.27 mg/L	24—96 hours	12 species of invertebrates (e.g. crabs, amphipods, mysids, shrimps, clams, oysters) and 11 species of fish (e.g. flounder, stickleback, bass, pipefish)	Juvenile, young-adult and adult (most data for juveniles)	Acute sensitivity (survival) to low DO—juvenile fish more sensitive that juvenile crustaceans	US EPA 2000 (see Table 1 + Appendix B)
NOEC(3): Invertebrates: 2.30—7.70 mg/L Fish: 2.50—7.50 mg/L HOEC(4): Invertebrates: 1.51—5.45 mg/L Fish: 1.50—4.49 mg/L Genus Mean Chronic Values(5): > 1.97—4.67 mg/L	4—29 days	7 species of invertebrates (e.g. crabs, lobsters, mysids, shrimps, clams) and 4 species of fish (e.g. minnow, bass, flounder)	Embryo, larva, post-larva and juvenile	Effects of low DO on growth—most sensitive species were crustaceans. Note that chronic values for DO do not change substantially for exposures ranging from a few days to several weeks for most species tested. The consequences of reduced growth in the field are uncertain.	US EPA 2000 (see Table 2 + Appendix C)
Species Mean Acute Values(1) LC50: Invertebrates: < 0.71—2.54 mg/L Fish: 1.00—2.50 mg/L	24 hours	10 species of invertebrates (e.g. crabs, lobsters, shrimps, squid, clams) and 7 species of fish (e.g. red drum, bass, blenny) Virginian Province	Embryo, larva, post-larva and juvenile	Acute sensitivity to low DO	Various references (cited in USA EPA 2000, Appendix D)
Species Mean Acute Values(1) LC50: Invertebrates: 1.58-2.78 mg/L Fish: < 0.76—2.43 mg/L	96 hours	7 species of invertebrates (e.g. crabs, lobsters, shrimps) and 4 species of fish (e.g. minnow, bass, silverside)	Embryo, larva and post-larva	Acute sensitivity to low DO	Various references (cited in USA EPA 2000, Appendix D

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
FISH					
LC5(6): 0.56—0.81 mg/L LC50(7): 0.49—0.70 mg/L LC95(8):0.43—0.60 mg/L	1—96 hours	Spot (Leiostomus xanthurus)	?Juvenile	Sensitivity to low DO	Burton et al. 1980 (cited in US EPA 2000, Appendix J)
LC5: 1.00—1.55 mg/L LC50: 0.70—1.90 mg/L LC95:0.49—0.69 mg/L	2—96 hours	Atlantic menhaden (Brevoortia tyrannus)	?Juvenile	Sensitivity to low DO	Burton et al. 1980, Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
LC25(9): 3.62 mg/L	7 days	Inland silverside (Menidia beryllina) [FISH]	Embryo-hatch	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 0.53 mg/L	7 days	Sheepshead minnow (Cyprinodon variegatus)	Larva	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 0.6 mg/L	96 hours	Northern sea robin (Prionotus carolinus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 0.74—0.89 mg/L	6 hours	Mummichog (Fundulus heteroclitus)	Adult	Sensitivity to low DO	Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
LC50: 0.8 mg/L	96 hours	Tautog (Tautoga onitus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 0.9 mg/L	24 hours	Windowpane flounder (Scophthalmus aquosus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 0.9 mg/L	96 hours	Fourspine stickleback (Apeltes quadracus)	Juvenile + adult	Sensitivity to low DO	Miller et al. 2002
LC50: 1.1—1.6 mg/L	72—96 hours	Summer flounder (Paralichthys dentatus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.2 mg/L	96 hours	Atlantic menhaden (Brevooria tyrannus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.3 mg/L	24 hours	Scup (Stenotomus chrysops)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.4 mg/L	24—96 hours	Inland silverside (Menidia beryllina)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 1.4 mg/L	96 hours	Winter flounder (Pleuronectes americanus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.5 mg/L	24 hours	Pipe fish (Syngnathus fuscus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.59 mg/L	72 hours	Summer flounder (Paralycthys dentatus)	Juvenile	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 1.6 mg/L	12 hours	Bay anchovy (Anchoa mitchilli)	Yolk-sac larva	Sensitivity to low DO	Chesney & Houde 1989 (cited in US EPA 2000, Appendix J)

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
LC50: 1.6 mg/L	96 hours	Striped bass (Morone saxatilis)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.8 mg/L	24 hours	Red drum (Sciaenops ocellatus)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.1 mg/L	6 hours	Atlantic silverside (Menidia menidia)	?Juvenile	Sensitivity to low DO	Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
LC50: 2.38 mg/L	8 days	Inland silverside (Menidia beryllina)	Embryo-hatch	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 2.4 mg/L	24—96 hours	Striped bass (Morone saxatilis)	Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.8 mg/L	12 hours	Bay anchovy (Anchoa mitchilli)	Egg	Sensitivity to low DO	Chesney & Houde 1989 (cited in US EPA 2000, Appendix J)
LC50: 2.8 mg/L	12 hours	Atlantic herring (Clupea harengus)	Yolk-sac larva	Sensitivity to low DO	DeSilva & Taylor 1973 (cited in US EPA 2000, Appendix J)
IC50(10): > 3.26 mg/L	5 days	Sheepshead minnow (Cyprinodon variegatus)	Embryo-hatch	Delayed hatching	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
EC25(11): 2.27 mg/L	14 days	Sheepshead minnow (Cyprinodon variegatus)	Larva	Growth	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
EC50(12): < 1.42 mg/L	7 days	Sheepshead minnow (Cyprinodon variegatus)	Embryo-hatch	Hatching	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
EC50: 3.9 mg/L	27 days	Mummichog (Fundulus heteroclitus)	Embryo	Hatching	Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
CRUSTACEANS					
LT50(13): 0.21 mg/L	2 hours	Common Shrimp (Crangon crangon)	Adult	Sensitivity to low DO	Theede et al. 1969
LT50: 0.21 mg/L	6 hours	Isopod (Idotea baltica)	Adult	Sensitivity to low DO	Theede et al. 1969
LT50: 0.21 mg/L	15 hours	Amphipod (Gammarus oceanicus)	Adult	Sensitivity to low DO	Theede et al. 1969
LT50: 0.21 mg/L	48 hours	Green crab (Carcinus maenas)	Adult	Sensitivity to low DO	Theede et al. 1969
LT50: 0.6 mg/L	24 hours	Copepod (Eurytemora affinis)	Adult	Sensitivity to low DO	Davis & Bradley 1990 (cited in US EPA 2000, Appendix J)

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
LC50: 0.34—5.20 mg/L	2—4 hours	Rock crab (Cancer irroratus)	Different larva stages and megalopa	Sensitivity to low DO	Vargo & Sastry 1977 (cited in US EPA 2000, Appendix J)
LC50: 0.51—1.55 mg/L	0.5 hours	Copepod (Eurytemora affinis)	Adult	Sensitivity to low DO	Vargo & Sastry 1978 (cited in US EPA 2000, Appendix J)
LC50: 0.7 mg/L	96 hours	Daggerblade grass shrimp (Palaemonetes pugio)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 0.9 mg/L	96 hours	Giant tiger prawn (Penaeus monodon)	Juvenile	Sensitivity to low DO	Allan & Maguire 1990 (cited in Khoa & Bai 1999)
LC50: 0.91 mg/L	80 hours	Sand shrimp (Crangon septemspinosa)	Young adult	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 1 mg/L	96 hours	Marsh grass shrimp (Palaemonetes vulgaris)	Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 1 mg/L	96 hours	American lobster (Homarus americanus)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1 mg/L	96 hours	Marsh grass shrimp (Palaemonetes vulgaris)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1 mg/L	96 hours	Sand shrimp (Crangon septemspinosa)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.2 mg/L	96 hours	Mysid (Americamysis bahia)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 1.4 mg/L	96 hours	American lobster (Homarus americanus)	Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 1.42—3.32 mg/L	5-20 days	American lobster (Homarus americanus)	Different larval stages	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 1.6 mg/L	96 hours	Daggerblade grass shrimp (Palaemonetes pugio)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 1.76 mg/L	28 days	Flat mud crab (Eurypanopeus depressus)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: 1.89—4.41 mg/L	7-11 days	Say mud crab (Dyspanopeus sayi)	Different larva stages and megalopa	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 1.9 mg/L	96 hours	Say mud crab(Dyspanopeus sayi)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.00—2.19 mg/L	7 days	Marsh grass shrimp (Palaemonetes vulgaris)	Different larval stages	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 2.1 mg/L	96 hours	Marsh grass shrimp (Palaemonetes vulgaris)	Larva	Sensitivity to low DO	Miller et al. 2002

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
LC50: 2.14 mg/L	28 days	Daggerblade grass shrimp (Palaemonetes pugio)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: 2.2 mg/L	96 hours	Flat mud crab (Eurypanopeus depressus)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.2 mg/L	96 hours	Rock crab (Cancer irroratus)	Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.34 mg/L	72 hours	Longnose spider crab (Labinia dubia)	Megalopa	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 2.39—3.03 mg/L	72 hours—10 days	Rock crab (Cancer irroratus)	Different larval stages and megalopa	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 2.5—3.7 mg/L	96 hours—10 days	Say mud crab (Dyspanopeus sayi)	Larva—Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.6 mg/L	96 hours	Rock crab (Cancer irroratus)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.65 mg/L	28 days	Estuarine mud crab (Rhithropanopeus harrissii)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: 2.7 mg/L	96 hours	Longnose spider crab (Libinia dubia)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 2.8 mg/L	4—5 days	American lobster (Homarus americanus)	Larva—Post-larva	Sensitivity to low DO	Miller et al. 2002
LC50: 3 mg/L	7 days	Rock crab (Cancer irroratus)	Larva—Post-larva	Sensitivity to low DO	Miller et al. 2002

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
LC50: 3.1 mg/L	96 hours	American lobster (Homarus americanus)	Larva	Sensitivity to low DO	Miller et al. 2002
LC50: 4.08—6.44 mg/L	28 days	Blue crab (Callinectes sapidus)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: 4.55—5.79 mg/L	28 days	Brown shrimp (Penaeus aztecus)	not specified	Sensitivity to low DO	Stickle et al. 1989
EC25: < 2.3 mg/L	not specified	Green crab (Carcinus maenas) [red morph]	Adult	Low DO avoidance	Reid & Aldrich 1989
EC50: 0.11—0.17 mg/L	5—11 days	Copepod (Centropages hamatus)	Egg	% hatching	Lutz et al. 1992 (cited in US EPA 2000, Appendix J)
EC50: 0.17—0.21 mg/L	60 hours—5 days	Copepod (Acartia tonsa)	Egg	% hatching	Lutz et al. 1992, 1994 (cited in US EPA 2000, Appendix J)
EC50: 0.28 mg/L	5 days	Copepod (Tortanus discaudatus)	Egg	% hatching	Lutz et al. 1992 (cited in US EPA 2000, Appendix J)
EC50: 0.32—0.42 mg/L	72 hours—5 days	Copepod (Labidocera aestiva)	Egg	% hatching	Lutz et al. 1992, 1994 (cited in US EPA 2000, Appendix J)
EC50: 1.8 mg/L	not specified	Green crab (Carcinus maenas) [red morph]	Adult	Low DO avoidance	Reid & Aldrich 1989
EC50: 3.46 mg/L	5 days	American lobster (Homarus americanus)	Larva	Moulting	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
TLm(14): 0.6—1.18 mg/L	28 days	Isopod (Limnoria lignorum)	not specified	Burrowing activity related to available DO	Anderson & Reish 1967 (cited in Davis 1975, p. 2316)
TLm: 0.6—1.18 mg/L	28 days	Isopod (Limnoria quadripunctata)	not specified	Burrowing activity related to available DO	Anderson & Reish 1967 (cited in Davis 1975, p. 2316)

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
TLm: 0.6—1.18 mg/L	28 days	Isopod (Limnoria tripunctata)	not specified	Burrowing activity related to available DO	Anderson & Reish 1967 (cited in Davis 1975, p. 2316)
MOLLUSCS					
LT50: 0.21 mg/L	4.3 days	Common cockle (Cardium edule)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	6 days	Rough periwinkle (Littorina saxatilis)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	15.2 days	Common periwinkle (Littorina littorea)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	21 days	Softshell clam (Mya arenaria)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	21-25 days	Peppery furrow shell (Cyprina islandica)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	35 days	Blue mussel (Mytilus edulis)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.21 mg/L	55 days	Queen quahog (Cyprina islandica)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: 0.29 mg/L	8.4 days	Gastropod (Neritina virginea)	not specified	Sensitivity to low DO	Hiroki 1978 (cited in Khoa & Bai 1999)
LT50: 0.29 mg/L	26 hours	Gastropod (Olivella verreauxii)	not specified	Sensitivity to low DO	Hiroki 1978 (cited in Khoa & Bai 1999)
LT50: 0.29 mg/L	78 hours	Zebra periwinkle) (Littorina ziczac	not specified	Sensitivity to low DO	Hiroki 1978 (cited in Khoa & Bai 1999)
LC30(15): 1.04 mg/L	14 days	Coot clam (Mulinia lateralis)	Juvenile	Effects of low DO on growth	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 0.45 mg/L	10 days	Atlantic surfclam (Spisula solidissima)	Juvenile	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 0.5 mg/L	96 hours	Atlantic surfclam (Spisula solidissima)	Juvenile	Sensitivity to low DO	Miller et al. 2002
LC50: 0.50—1.43 mg/L	28 days	Oyster drill (Thais haemastoma)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: 0.83—4.98 mg/L	28 days	Eastern oyster (Crassostrea virginica)	not specified	Sensitivity to low DO	Stickle et al. 1989
LC50: < 0.9 mg/L	14 days	Coot clam (Mulinia lateralis)	Juvenile	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: 1.36—2.11 mg/L	16-25 days	Long fin squid (Loligo pealii)	Embryo-larva and embryo-hatch	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
LC50: > 3.43 mg/L	48 hours	Burryi’s octopus (Octopus burryi)	Embryo-hatch	Sensitivity to low DO	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)

DO Concentrations	Exposure Duration	Species	Life-Stage	Effect Reported	Source
EC50: < 1.4 mg/L	48 hours	Blue mussel (Mytilus edulis)	Embryo-larva	Sensitivity to low DO	Wang & Widdows 1991 (cited in US EPA 2000, Appendix J)
POLYCHAETE WORMS					
LT50: < 0.21 mg/L	5 days	Nereis diversicolor	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: < ≈ 1mg/L	5 days	Loimia medusa	not specified	Sensitivity to low DO	Llansó 1992
EC25: 0.9 mg/L	not specified	Nereis virens	not specified	Emergence from sediment	Vismann 1990 (cited in US EPA 2000, p.32)
OTHER SPECIES					
LC50: < 0.5 mg/L	96 hours	Ctenophore (Mnemiopsis leidyi)	Juvenile and adult	Sensitivity to low DO	Breitburg et al. 2003
LC50: 0.5 mg/L	24 hours	Scyphozoan jellyfish (Chrysaora quinquecirrha)	Juvenile and adult	Sensitivity to low DO	Breitburg et al. 2003
LC50: 1.0 mg/L	24 hours	Ctenophore (Beroe ovata)	Juvenile and adult	Sensitivity to low DO	Breitburg et al. 2003
LT50: < 0.21 mg/L	31 hours	Ophiuroid (Ophuira albida)	Adult	Sensitivity to low DO	Theede at al. 1969
LT50: < 0.21 mg/L	84 hours	Starfish (Asterias rubens)	Adult	Sensitivity to low DO	Theede at al. 1969

Notes:

1. The geometric mean of the results of all acceptable flow-through acute toxicity tests (for which concentrations of the test material were measured) with the most sensitive test life-stage of the species.
2. An estimate of the highest (although in the case of DO more appropriately defined as the minimum) concentration of a toxicant in the water column to which aquatic organisms can be exposed to for a short period of time without resulting in an unacceptable effect.
3. No observed effect concentration.
4. Highest observed effect concentration.
5. The geometric mean of the Species Mean Chronic Values for the genus. The Species Mean Chronic Value is the geometric mean of the results of all acceptable life-cycle and partial life-cycle toxicity tests with the species.
6. LC5 = concentration yielding 5% mortality.
7. LC50 = concentration yielding 50% mortality.
8. LC95 = concentration yielding 95% mortality.
9. LC25 = concentration yielding 25% mortality.
10. IC50 = concentration yielding a 50% inhibition in hatching.
11. EC25 = concentration expected to produce an effect in 25% of the population.
12. EC50 = concentration expected to produce an effect in 50% of the population.
13. LT50 = time to 50% mortality.
14. TLm = median tolerance limit.
15. LC30 = concentration yielding 30% mortality.

Table 7.2 Observed effects of low dissolved oxygen concentrations on marine fish and invertebrates (mainly from laboratory studies with some field observations)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
FISH				
0.1-0.3 mg/L	Milkfish (Chanos chanos)	Juvenile	Lethal minimum DO	Bogarinao 1991 (cited in Khoa & Bai 1999)
0.15—1.02 mg/L	Naked goby (Gobiosoma bosc)	Juvenile	15%—100% mortality after 1—24 hours exposure	Saksena & Joseph 1972 (cited in US EPA 2000, Appendix J)
0.24—0.26 mg/L	Naked goby (Gobiosoma bosc)	Adult	Death	Breitburg 1992 (cited in US EPA 2000, p.32)
0.27 mg/L	Sea robin (Prionotus carolinus)	Juvenile	100% mortality after 2 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
0.28—0.58 mg/L	Tautog (Tautoga onitis)	Juvenile	100% mortality after 3—7 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
0.3 mg/L	Naked goby (Gobiosoma bosc)	Adult	Abandoned nests	Breitburg 1992 (cited in US EPA 2000, p.32)
0.3—0.4 mg/L	Hogchoker (Trinectes maculatus)	not specified	Decline in ventilation after which all fish died within 5—22 hours	Pihl et al. 1991
0.38 mg/L	Naked goby (Gobiosoma bosc)	Adult	Abandoned shelters	Breitburg 1992 (cited in US EPA 2000, p.32)
0.4 mg/L	Red hake (Urophycis chuss)	Age 0+	Loss of equilibrium	Bejda et al. 1987 (cited in US EPA 2000, p.30)
0.50—1.23 mg/L	Skilletfish (Gobiesox strumosus)	Juvenile	10—100% mortality after 1—24 hours exposure	Saksena & Joseph 1972 (cited in US EPA 2000, Appendix J)
0.58 mg/L	Winter flounder (Pleuronectes americanus)	Juvenile	100% mortality after 6 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
0.6 mg/L	Red hake (Urophycis chuss)	Age 1+ and 2—3+	Loss of equilibrium	Bejda et al. 1987 (cited in US EPA 2000, p.30)
0.70—2.07 mg/L	Striped blenny (Chasmodes bosquianus)	Juvenile	5%—100% mortality after 1—24 hours exposure	Saksena & Joseph 1972 (cited in US EPA 2000, Appendix J)
0.75 mg/L	Bay anchovy (Anchoa mitchilli)	Larva	100% avoidance following 1 hour exposure	Breitburg 1994 (cited in US EPA 2000, p.32)
0.8—1 mg/L	Spot (Leiostomus xanthurus)	not specified	Ventilation rate was three times higher compared to controls. All fish died within 4 hours.	Pihl et al. 1991
0.80—1.23 mg/L	Inland silverside (Menidia beryllina)	Larva	90%—100% mortality after 2—5 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
0.84 mg/L	Tautog (Tautoga onitis)	Juvenile	40% mortality after 24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
< 1 mg/L	Red hake (Urophycis chuss)	Age 0+	Most locomotor and other behavioural activity ceases	Bejda et al. 1987 (cited in US EPA 2000, p.30)
1 mg/L	Milkfish (Chanos chanos)	Juvenile	Asphyxia	Bogarinao 1991 (cited in Khoa & Bai 1999)
1—1.1 mg/L	Hogchoker (Trinectes maculatus)	not specified	15% reduction in mean ventilation rate in fish held at this DO for 10 days	Pihl et al. 1991
1.3 mg/L	Summer flounder (Paralycthys dentatus)	Juvenile	100% mortality after 24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
1.35 mg/L	Striped bass (Morone saxatilis)	Juvenile	100% mortality after 24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
1.5—1.9 mg/L	Striped bass (Morone saxatilis)	Larva	100% mortality after 2—24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
< ≈ 2—3 mg/L	Gilthead seabream (Sparus aurata)	Juvenile	20—40% mortality after 96 hours exposure	Wajsbrot et al. 1991 (cited in Khoa & Bai 1999)
2 mg/L	Naked goby (Gobiosoma bosc)	Larva	Avoidance with 1 hour exposure	Breitburg 1994 (cited in US EPA 2000, p.32)
2 mg/L	Naked goby (Gobiosoma bosc)	Larva	Avoidance of predator (sea nettle Chyrsaora quinquecirrha) reduced 60% following 3 hours exposure	Breitburg et al. 1994 (cited in US EPA 2000, p.32)
2 mg/L	Striped bass (Morone saxatilis)	Juvenile	Predation on Naked Goby larvae reduced 50% after 1 hour 35 minutes exposure	Breitburg et al. 1994 (cited in US EPA 2000, p.32)
> 2—3 mg/L	Pacific cod (Gadus macrocephalus)	Egg	DO level required for optimal hatching	Voyer & Hennekey 1972 (cited in Davis 1975, Table 4)
2.4 mg/L	Mummichog (Fundulus heteroclitus)	Embryo	23%—27% mortality after 24 hours—14 days exposure	Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
2.4—3.0 mg/L	Spot (Leiostomus xanthurus)	not specified	Ventilation rate doubled compared to controls. Survived for at least 6 days.	Pihl et al. 1991
2.7 mg/L	Inland silverside (Menidia beryllina)	Embryo-hatch	33% reduction in hatch after 8 days exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
2.8 mg/L	Atlantic silverside (Menida menidia)	Embryo	92% survival but no growth surviving individuals	Poucher 1988 (cited in US EPA 2000, Appendix C)
3 mg/L	Atlanic sturgeon (Acipenser oxyrinchus)	Juvenile	22—92% mortality after 10 days	Secor & Gunderson 1998 (cited in Breitburg 2002)
3.9 mg/L	Atlantic silverside (Menida menidia)	Embryo	40% mortality and 24% reduction in growth	Poucher 1988 (cited in US EPA 2000, Appendix C)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
< 4.2 mg/L	Red hake (Urophycis chuss)	Age 0+	Leave preferred bottom habitat and begin to swim continuously; food search time reduced as a consequence	Bejda et al. 1987 (cited in US EPA 2000, p.30)
4.5 mg/L	Mummichog (Fundulus heteroclitus)	Embryo	10% mortality after 24 hours exposure	Voyer & Hennekey 1972 (cited in US EPA 2000, Appendix J)
4.5 mg/L	Mummichog (Fundulus heteroclitus)	Eggs	Reduced hatching compared to 7.5 mg/L	Voyer & Hennekey 1972 (cited in Davis 1975, Table 4)
CRUSTACEANS				
0.1—0.9 mg/L	White shrimp (Penaeus schmitti)	not specified	Lethargic, no signs reflexes	MacKay 1974 (cited in Khoa & Bai 1999)
0.22—1.05 mg/L	Blue crab (Callinectes sapidus)	Adult	5%—100% mortality after 6—24 hours exposure	Carpenter & Cargo 1957 (cited in US EPA 2000, Appendix J)
0.24—1.80 mg/L	Amphipod (Anisogammarus pugettensis)	not specified	Mortality after 36 hours exposure	Davis 1975 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
0.3 mg/L	Squat lobster (Munida quadrispina)	not specified	Cessation of intra-specific aggression	Burd & Brnkhurst 1984 (cited in Diaz & Rosenberg 1995, Table 4)
≈ 0.5 mg/L	Common prawn (Crangon vulgaris)	Adult	50% mortality in less than 15 minutes	Huddart & Arthur 1971
0.63 mg/L	Marsh grass shrimp (Palaemonetes vulgaris)	Juvenile	100% mortality after 96 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
< 0.69 mg/L	Glass prawn (Palaemon elegans)	not specified	Torpid, but could survive 6 hours of anoxia	Morris & Taylor 1985
< 0.7 mg/L	Kuruma prawn (Penaeus japonicus)	not specified	Emergence from burrows	Egusa & Yamamoto 1961 (cited in Diaz & Rosenberg 1995, Table 4)
0.7 mg/L	Mantis shrimp (Squilla empusa)	not specified	Individuals immobile while maintaining elevated body position with pereiopods and raptorial claws fully extended; ventilation decreased	Pihl et al. 1991
0.74—1.8 mg/L	Amphipod (Anisogammarus confervicolus)	not specified	All amphipods survived 24 hours exposure but mortality after 36 hours exposure	Davis 1975 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
0.76 mg/L	Brown shrimp (Penaeus aztecus)	not specified	Mean lethal DO concentration	Kramer 1975 (cited in Khoa & Bai 1999)
0.78 mg/L	Daggerblade grass shrimp (Palaemonetes pugio)	Larva	100% mortality after 24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
0.8 mg/L	Daggerblade grass shrimp (Palaemonetes pugio)	Adult	84% reduction in locomotor activity after 20 minutes exposure	Hutcheson et al. 1985 (cited in US EPA 2000, Appendix J)
0.8 mg/L	Daggerblade grass shrimp (Palaemonetes pugio)	Adult	61% mortality after 24 hours exposure	Hutcheson et al. 1985 (cited in US EPA 2000, Appendix J)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
1.2 mg/L	Giant tiger prawn (Penaeus monodon)	Juvenile	Growth reduced after 16 days exposure	Seidman & Lawrence 1985 (cited in Khoa & Bai 1999)
1.2 mg/L	Daggerblade grass shrimp (Palaemonetes pugio)	Adult	38% mortality after 24 hours exposure	Hutcheson et al. 1985 (cited in US EPA 2000, Appendix J)
1.2 mg/L	White shrimp (Penaeus schmitti)	not specified	Swim to water surface, jump out of water, then swim rapidly, falling to bottom	MacKay 1974 (cited in Khoa & Bai 1999)
< 1.4 mg/L	Norway lobster (Nephrops norvegicus)	Adult	Ratio females to males increased from 0.07—0.38 to 0.74—0.77	Baden et al. 1990 (cited in Diaz & Rosenberg 1995, p. 278)
≈ 1.4 mg/L	Green crab (Carcinus maenas)	not specified	Depressed metabolism	Hill et al. 1991 (cited in Diaz & Rosenberg 1995, Table 4)
≈ 1.5 mg/L	Common prawn (Crangon vulgaris)	Adult	10% mortality after 6 hours	Huddart & Arthur 1971
1.59—5.40 mg/L	American lobster (Homarus americanus)	Different larva stages	Delayed moult after 96 hours—20 days exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
1.8 mg/L	Daggerblade grass shrimp (Palaemonetes pugio)	Adult	66% reduction in locomotor activity after 20 minutes exposure	Hutcheson et al. 1985 (cited in US EPA 2000, p.32)
1.83 mg/L	American lobster (Homarus americanus)	Larva	95% mortality after 24 hours exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
2 mg/L	Penaeid shrimp (Penaeus semisulcatus)	not specified	No moulting and steady and high mortality over 17 days	Clark 1986 (cited in Khoa & Bai 1999)
≈ 2 mg/L	Blue crab (Callinectes sapidus)	not specified	32% reduction in metabolic rate compared to normal DO concentrations	Stickle et al. 1989
≈ 2 mg/L	Flatback mud crab (Eurypanopeus depressus)	not specified	47% reduction in metabolic rate compared to normal DO concentrations	Stickle et al. 1989
≈ 2—3 mg/L	Common prawn (Crangon vulgaris)	not specified	Larger numbers migrated vertically through water column, involves escape responses and passive sinking to seafloor	Huddart & Arthur 1971
≈ 2 mg/L	Penaeid shrimp (Penaeus semisulcatus)	Juvenile	10—35% mortality after 96 hours exposure	Wajsbrot et al. 1990 (cited in Khoa & Bai 1999)
≈ 2 mg/L	Mantis shrimp (Squilla empusa)	not specified	Ventilation rate double that of controls; individuals at first actively swimming and cleaning gills, but adapted when kept at DO concentrations for	Pihl et al. 1991
2.17 mg/L	Mysid (Americamysis bahia)	Juvenile	Reproduction reduced by 76%	Poucher 1988 (cited in US EPA 2000, Appendix C)
2.17—3.17 mg/L	Mysid (Americamysis bahia)	Juvenile	20%—27% reduction in growth	Poucher 1988 (cited in US EPA 2000, Appendix C)
2.2 mg/L	Giant tiger prawn (Penaeus monodon)	Juvenile	< 10% mortality after 96 hours exposure	Allan et al. 1990 (cited in Khoa & Bai 1999)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
2.2 mg/L	School prawn (Metapenaeus macleayi)	Juvenile	< 10% mortality after 96 hours exposure	Allan et al. 1990 (cited in Khoa & Bai 1999)
< ≈ 3 mg/L	Norway lobster (Nephrops norvegicus)	not specified	Emergence response in dim light/darkness, after 10 days moderate or low DO concentrations no emergence response shown even when DO concentration decreased to concentration at which non-adapted animals emerged	Hagerman & Uglow 1985
< ≈ 3 mg/L	Benthic amphipod (Corophium volutator)	not specified	After 24 hours exposure, tubes constructed protruding at least 1 cm from sediment surface into overlying water column	Eriksson & Weeks 1994
3.5 mg/L	Barnacle (Balanus amphitrite)	not specified	Respiratory regulation ceased and metabolic rate decreased with declines in DO; no gaseous exchange below 0.7 mg/L	Parasada Rao & Ganapati 1968 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
< 4.3 mg/L	Copepod (Calanus sp.)	not specified	Respiration decreases	Marshall et al. 1935 (cited in Davis 1975, p. 2318)
5 mg/L	Barnacle (Balanus tintinnabulum)	not specified	Respiratory regulation ceased and metabolic rate decreased with declines in DO; no gaseous exchange below 0.7 mg/L	Parasada Rao & Ganapati 1968 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
MOLLUSCS				
0.14—1 mg/L	Softshell clam (Mya arenaria)	not specified	Siphon stretching	Jorgensen 1980 (cited in Diaz & Rosenberg 1995, Table 4)
0.14—1 mg/L	Shellfish (Abra alba)	not specified	Siphon stretching	Jorgensen 1980 (cited in Diaz & Rosenberg 1995, Table 4)
0.14—1 mg/L	Common cockle (Cerastoderma edule)	not specified	Siphon stretching	Jorgensen 1980 (cited in Diaz & Rosenberg 1995, Table 4)
0.14—1 mg/L	Laver spire shell (Hydrobia ulvae)	not specified	Climbing structures	Jorgensen 1980 (cited in Diaz & Rosenberg 1995, Table 4)
0.2 mg/L	Hardshell clam (Mercenaria mercenaria)	Embryo-larva	100% mortality after 24 hours exposure	Morrison 1971 (cited in US EPA 2000, Appendix J)
< 0.4 mg/L	Eastern oyster (Crassostrea virginica)	Early post-settlement stage + older post-settlement stage	86—99% reduction in feeding rate of early post-settlement stage after 6 hours exposure 97—99% reduction in feeding rate of older post-settlement animals	Baker & Mann 1994 (cited in US EPA 2000, p.32)
0.6 mg/L	Blue mussel (Mytilus edulis)	Embryo-larva	No development beyond gastrula after 48 hours exposure	Wang & Widdows 1991 (cited in US EPA 2000, Appendix J)
0.6 mg/L	Blue mussel (Mytilus edulis)	Larva	21% reduction in shell growth after 10 days exposure	Wang & Widdows 1991 (cited in US EPA 2000, Appendix J)

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
0.8—1.8 mg/L	Hardshell clam (Mercenaria mercenaria)	not specified	Burrowing reduced 1.4—2-fold; ability to burrow when exposed to DO < 1 mg/L for up to three weeks not severely or permanently impaired	Savage 1976
1 mg/L	Shellfish (Mysella bidentata)	not specified	Emergence from burrow	Nilsson & Rosenberg 1994 (cited in Diaz & Rosenberg 1995, Table 4)
1.3 mg/L	Shellfish (Abra alba)	not specified	Water column siphon activity increased 3.5-fold	Rosenberg et al. 1991 (cited in Diaz & Rosenberg 1995, p. 273)
1.4 mg/L	Atlantic surfclam (Spisula solidissima)	not specified	Burrowing reduced 4-fold	Savage 1976
1.5 mg/L	Eastern oyster (Crassostrea virginica)	Larva	53% reduction in settlement after 24 hours exposure	Baker & Mann 1992 (cited in US EPA 2000, Appendix J)
1.5 mg/L	Eastern oyster (Crassostrea virginica)	Larva	52% reduction in settlement after 96 hours exposure	Baker & Mann 1992 (cited in US EPA 2000, Appendix J)
1.5 mg/L	Eastern oyster (Crassostrea virginica)	Post-larva	Delayed development to dissoconch after 96 hours exposure	Baker & Mann 1994 (cited in US EPA 2000, Appendix J)
1.5 mg/L	Eastern oyster (Crassostrea virginica)	Juvenile	50% mortality after 131 hours exposure	Baker & Mann 1992 (cited in US EPA 2000, Appendix J)
1.5 mg/L	Eastern oyster (Crassostrea virginica)	Juvenile	70% reduction in growth after 144 hours exposure	Baker & Mann 1992 (cited in US EPA 2000, Appendix J)
1.9 mg/L	Eastern oyster (Crassostrea virginica)	Early post-settlement stage	54—61% reduction in feeding rate after 6 hours exposure	Baker & Mann 1994 (cited in US EPA 2000, p.32)
1.9 mg/L	Eastern oyster (Crassostrea virginica)	Post-settlement juvenile	46% reduction in post-settlement ingestion rate after 24 hours exposure	Baker & Mann 1994 (cited in US EPA 2000, Appendix J)
≈ 2 mg/L	Oyster drill (Thais haemastoma)	not specified	76% reduction in metabolic rate compared to normal DO concentrations	Stickle et al. 1989
2.26—3.77 mg/L	Long fin squid (Loligo pealii)	Embryo-larva	Hatching delayed 1—5 days after 16—25 days exposure	Poucher & Coiro 1997 (cited in US EPA 2000, Appendix J)
2.6 mg/L	Blue mussel (Mytilus edulis)	Larva	13—14% reduction in shell growth after 6—8 days exposure	Wang & Widdows 1991 (cited in US EPA 2000, Appendix J)
< 8.42 mg/L	Octopus (Octopus dofleini)	not specified	Lowered arterial blood oxygen levels, elevated cardiac output	Davis 1975 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
POLYCHAETE WORMS				
0.5 mg/L	Streblospio benedicti	Adult	Adults survived for at least 2 weeks without significant mortality. Feeding stopped after initial exposure—feeding resumed after 4.5 days.	Llansó 1991

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
0.5 mg/L	Loimia medusa	Adult	Tolerates low DO for 3—5 days, after 14.5 days one of 12 worms alive	Llansó & Diaz 1994
0.9 mg/L	Nereis virens	not specified	Feeding stopped	Vismann 1990 (cited in US EPA 2000, p.32)
< 1 mg/L	Loimia medusa	Adult	Feeding stopped after < 20 hours exposure—tube irrigation continued. Five of 12 individuals in 1 mg/L DO concentration treatment resumed feeding after 42—113 hours. Activity (e.g. tube irrigation, protrusions of anterior thoracic region out of tube) declined to infrequent movements in tube. Seven worms alive after 14.5 days.	Llansó & Diaz 1994
1 mg/L	Loimia medusa	Adult	Feeding stopped after < 20 hours exposure—feeding resumed in 42—113 hours in 42% animals. General activity (tube irrigation, protrusion thoracic region out of tube, movement tentacles and branchia) declined.	Llansó & Diaz 1994
1 mg/L	Streblospio benedicti	Adult	Adults survived for at least 2 weeks without significant mortality. Burrowing and feeding stopped after initial exposure—feeding resumed after 3.5 days.	Llansó 1991
1 mg/L	Pectinaria koreni	not specified	After several days emerged from sediment with tube, later died.	Nilsson & Rosenberg 1994 (cited in Diaz & Rosenberg 1995, p. 275)
< 1.1 mg/L	Capitella sp.	not specified	Stopped burrowing and feeding	Rosenberg 1972
1.1 mg/L	Capitella sp.	not specified	Cessation of feeding and burrowing	Warren 1977 (cited in Diaz & Rosenberg 1995, Table 4)
1.3 mg/L	Capitella capitata	not specified	50% mortality after 13 days exposure	Rosenberg 1972
1.2 mg/L	Polyphysia crassa	not specified	50% mortality after 8 days exposure	Rosenberg 1972
1.2 mg/L	Nereis diversicolor	not specified	Feeding stopped	Vismann 1990 (cited in US EPA 2000, p.32)
1.5 mg/L	Polyphysia crassa	not specified	50% mortality after 10 days exposure	Rosenberg 1972
2.1 mg/L	Capitella capitata	not specified	20% mortality after 24 days exposure	Rosenberg 1972
3.4 mg/L	Malacoceros fuliginosus	not specified	Emerge from burrows and rise in water column; further decline DO undulatory body movements initiated	Tyson & Pearson 1991 (cited in Diaz & Rosenberg 1995, p. 278)
< 7.7 mg/L	Capitella sp.	not specified	Decrease in DO 7.7 mg/L to 2.1 mg/L up to 36% decrease in growth per day of large worms; decrease DO 2.3 mg/L to 1.1 mg/L further decreased growth 2—25% per day	Forbes & Lopez 1990

DO Concentrations	Species	Life-Stage	Ecological Effect Reported	Reference
OTHER SPECIES				
0.14—1.3 mg/L	Mud anemone (Cerianthiopsis americanus)	not specified	Emergence from tubes	Diaz unpublished data (cited in Diaz & Rosenberg 1995, Table 4)
0.5—0.7 mg/L	Anemone (Metridium senile)	not specified	Mortality after 120 hours	Sassaman & Mangum 1972 (cited in Ministry of Environment, Lands and Parks 1997, Table 5)
≈ 1.4 mg/L	Anemone (Metridium senile)	not specified	Depressed metabolism	Sassaman & Magnum 1972 (cited in Diaz & Rosenberg 1995, Table 4)
≈ 1.4 mg/L	Anemone (Bunodosoma cavernata)	not specified	Depressed metabolism	Ellington 1981 (cited in Diaz & Rosenberg 1995, Table 4)
2.8 mg/L	Anemone (Actinia sp.)	not specified	Migrated to surface	Nicol 1967 (cited in Davis 1975, p. 2316)
0.7 mg/L	Ophiuroid (Micropholis atra)	not specified	Emergence from burrows	Diaz et al. 1992 (cited in Diaz & Rosenberg 1995, Table 4)
0.7—0.9 mg/L	Ophiuroid (Ophiura albida)	not specified	Immobile standing on arm tips	Dethlefsen & Westernhagen 1983 (cited in Diaz & Rosenberg 1995, Table 4)
0.8 mg/L	Ophiuroid (Amphiura chiajei)	not specified	> 50% individuals moved to sediment surface	Rosenberg et al. 1991 (cited in Diaz & Rosenberg 1995, p. 273)
< 0.9 mg/L	Holuthurion (Holothuria forskali)	not specified	Evisceration	Astall & Jones 1991 (cited in Diaz & Rosenberg 1995, Table 4)
1 mg/L	Heart urchin (Echinocardium cordatum)	not specified	Emergence from burrows	Niermann et al. 1990 (cited in Diaz & Rosenberg 1995, Table 4)
1.2 mg/L	Ophiuroid (Amphiura filiformis)	not specified	> 50% individuals moved to sediment surface	Rosenberg et al. 1991 (cited in Diaz & Rosenberg 1995, p. 273)

Table 7.3 Field-studies on the effects of low dissolved oxygen concentrations on marine fish and invertebrates

DO Concentrations	Duration Low DO Events	Ecological Effect Reported	Location	Reference
0—3.7 mg/L	Brief periods of complete deoxygenation in bottom waters after floods or with thermal stratification usually in later summer but also other times of year	Macrobenthic communities: number of species, number of individuals and biomass lowest in deep basin site; distribution of common species limited by fluctuations in DO levels.	Port Hacking, NSW	Rainer & Fitzhardinge 1981
0.2—2 mg/L	Seasonal (summer) low DO—occur approx. once per month, 5—7 days duration	Sessile and mobile epifaunal assemblages: few differences in species composition between 2 areas that experience different DO conditions; differences in % cover and abundance of some species suggesting subtle species-specific effects on epifaunal community.	Chesapeake Bay, USA	Sagasti et al. 2000
0.3—2.9 mg/L	Months over winter	Macrofauna communities: macrofauna community disappeared completely. One and half years after collapse, macrofauna communities still impoverished—lower species richness and total abundance	Gullmar Fjord, western Sweden	Josefson & Widbom 1988
< 0.5—4 mg/L	Episodic diel seasonal (summer) low DO—hours to days duration	Naked Goby [Gobiosoma bosc]: juveniles and adults temporarily migrated away from low DO, population density and size structure declined at deeper sites; small, newly recruited juveniles absent presumed due to high mortality; effects on embryonic development—males abandoned egg-containing tubes at deeper sites and majority embryos dead, at shallower, less hypoxia-stressed site youngest embryos developed abnormalities following laboratory incubation.	Chesapeake Bay, USA	Breitburg 1992
0.66 mg/L		Fish: Fish catches low and contained dead fish (Agonis cataphractus, Pleuronectes platessa, Limanda sp., Callyonymus lyra, Ammodytes sp., flatfish) in oxygen deficient areas.	German and Danish coastal waters	Dethlefsen & von Westernhagen 1983 (cited in Khoa & Bai 1999)
< 1 mg/L	40% of time in bottom waters during first two weeks of experiments	Eastern Oyster (Crassostrea virginica): mortality of newly set spat (2—4 days old) during periods prolonged low DO—mortality corresponded to severity low DO; growth rate of surviving spat decreased following deployment with greater effect in low DO; greater tolerance of older animals.	Chesapeake Bay, USA	Osman & Abbe 1994 (cited in US EPA 2000, p.34)
< 1 mg/L		Copepods (Acartia tonsa and Oithona colcarva): disruption of diel vertical migration with implications for food intake and protection from predators.	Chesapeake Bay, USA	Roman et al. 1993 (cited in US EPA 2000, p.33)
≈ 1—< 2.9 mg/L	10 month declining and low DO period	Macrobenthic communities: degradation of benthic habitat and faunal behaviour, species richness, abundance and biomass; benthic successional stages declined from equilibrium to virtually azoic conditions; low benthic habitat quality indices. Critical DO level for survival of most benthic fauna and that forced changes in benthic faunal successional stages ≈ 1 mg/L.	Gullmarsfjord, Swedish west coast	Nilsson & Rosenberg 2000

DO Concentrations	Duration Low DO Events	Ecological Effect Reported	Location	Reference
1.4 mg/L		Macrobenthic communities: large numbers of infauna in areas of high abundance and biomass leave sediment, and lie exposed on sediment surface. No fish caught in demersal trawls, 200—400 kg/hour of benthic invertebrates collected (echinoderms, polychaetes).	Kattegat, Sweden	Baden et al. 1990 (cited in Diaz & Rosenberg 1995, p. 273)
< 2 mg/L	Seasonal (summer) low DO	Macrobenthic communities: 238 sites near-bottom DO > 5 mg/L, 20 sites DO < 2 mg/L. Species richness and density higher at high DO sites than at sites influenced by low DO. Communities at high DO sites included higher proportion of surface deposit feeders. Shifts in species distributions within trophic groups observed relative to variation in DO. Higher proportion carnivorous species at low DO sites than at high DO sites.	Northern Gulf of Mexico, USA	Brown et al. 2000
< 2 mg/L	Seasonal (summer) low DO—6–14 days duration	Demersal fish + crustaceans: migration to shallower and better oxygenated waters (degree and order of vertical movement function water column DO concentration and species sensitivity). Following water column destratification and re-aeration, majority of species returned to preferred deeper habitat areas.	Chesapeake Bay, USA	Pihl et al. 1991
< 2 mg/L	Seasonal (summer) low DO	Shellfish (Macoma balthica and Macoma mitchelli): 90—100% decline in abundance and biomass over an area of approx. 100 km² which equates to area of bottom habitat exposed to low DO over summer.	Neuse River Estuary, North Carolina, USA	Buzzelli et al. 2002
< 2 mg/L	Sites with > 20% summer DO measurements < 2 mg/L classified as anoxia/hypoxia affected	Macrobenthic communities: communities in low DO affected regions were classified as “stressed” (ABC comparison) more frequently than other communities, and had lower biomass and number of species.	Chesapeake Bay, USA	Dauer et al. 1993
< 2 mg/L	Seasonal (summer) intermittent low DO events, anoxia may become established during short periods of time (days)	Macrobenthic communities: reduction in species number, abundance and biomass and changes in species composition (few short-lived opportunistic species dominate), shift in vertical distribution (burrowing depth) in sediment—defaunation at some sites where DO < 1mg/L; fish and crabs absent from trawls at time of benthic faunal reductions which coincided with low DO levels.	Chesapeake Bay, USA	Llansó 1992
< 2mg/L	Seasonal summer low DO events: low DO intermittent, not severe and low DO prolonged and severe	Macrobenthic communities: areas that experienced severe declines in DO concentrations experienced greater mortality and had fewer species and lower biomass that areas with intermittent or less severe declines in DO. Functional shift away from equilibrium type community toward early success ional stage disturbance adapted community.	Gulf of Mexico, USA	Diaz & Solow 1999
< 2mg/L		Demersal fish: species move to adjacent areas with higher DO concentrations.	Gulf of Mexico, USA	Craig et al. 2001 (cited in Breitburg 2002)
< 2 mg/L	Seasonal summer low DO events—“…water column highly stratified for extended periods…”	Macrobenthic communities: lower species diversity, lower biomass, lower proportion of deep-dwelling biomass and changes in community composition—higher dominance density and biomass of opportunistic species and lower dominance of equilibrium species.	Chesapeake Bay, USA	Dauer et al. 1992

DO Concentrations	Duration Low DO Events	Ecological Effect Reported	Location	Reference
< 2 mg/L	Exposure to low DO estimated by % summer measurements < 2 mg/L	Macrobenthic communities: benthic community condition as estimated by the multimetric benthic index of biotic integrity (representing measures of species diversity, community abundance and biomass, species composition, depth distribution within sediment, trophic composition) negatively correlated with exposure to low DO/frequency of low DO events. Exposure to low DO accounted for 43% of variation in mean benthic index of biotic integrity.	Chesapeake Bay, USA	Dauer et al. 2000
< 2 mg/L	Intermittent seasonal (summer) low DO—duration hours to weeks	Fish + crustaceans: decreases in abundance, species diversity, richness and composition.	Neuse River Estuary, North Carolina, USA	Eby & Crowder 2004
< 2—3 mg/L	Seasonal (summer) low DO	Finfish, lobster + squid: declines in total species number and total catch with decrease in DO. Of 18 study species, 15 occurred at lower frequency when DO < 2 mg/L; 3 species also present at significantly lower frequency where DO 2—3 mg/L; 10 species never observed at sites when DO < 2 mg/L. Trawl samples taken from area which chronically experiences summer low DO yielded below average species number. No dead fish taken in trawls, but dead macro-invertebrates (sea stars and rock crabs) were—indicating mortalities limited to less mobile species.	Long Island Sound, USA	Howell & Simpson 1994
2.9 mg/L	Low DO conditions alleviated by exchange of deep bottom waters that takes place during winter at irregular intervals (1—8 years)	Macrobenthic communities: depauperate and patchily distributed, low biomass, vertical distribution fauna restricted to upper few cm of sediment, dominated by polychaetes with opportunistic features; low benthic habitat quality indices, indicative of environmental disturbance with presence pioneering benthic successional stage.	Koljöfjord, Swedish west coast	Rosenberg et al. 2001
< 3 mg/L		Dab (Limanda limanda): incidence of disease increased in year following low DO and remained elevated for 3—4 years.	Eastern North Sea and southern Kattegat	Mellergaard & Nielsen 1987 (cited in Breitburg 2002)
< 3.5—4 mg/L	Seasonal (summer) low DO	Fish and zooplankton: low DO creates temporal and spatial heterogeneity in physical habitat, reduces habitat extent and suitability for fish and invertebrates, alters distribution organisms and food web interactions and affects survival of early life stages of ecologically important summer-breeding fish.	Chesapeake Bay, USA	Breitburg et al. 2003
3.5 mg/L		Demersal finfish: 5% decline below a response asymptote for species richness (aggregate data for 23 species). Effects increasingly pronounced with further DO decline.	Long Island Sound, USA	Simpson et al. 1995 (cited in US EPA 2000, p.33)
3.7 mg/L		Demersal finfish: 5% decline below a response asymptote for total community biomass (aggregate data for 23 species). Effects increasingly pronounced with further DO decline with implications for secondary productivity.	Long Island Sound, USA	Simpson et al. 1995 (cited in US EPA 2000, p.33)
Not measured	Late summer following collapse of dinoflagellate bloom	Fish and macrobenthic communities: very low fish catches and greater catch of macrobenthic fauna as a result of infauna emerging onto surface from sediments.	West coast of Denmark	Dyer et al. 1983

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