9.14 Dissolved oxygen in water (trophic state)

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State of Knowledge of the "Dissolved oxygen conc. in estuary/coastal water" attribute: Excellent / well established – comprehensive analysis/syntheses; multiple studies agree.

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

There is a strong record of evidence in New Zealand and globally to show that dissolved oxygen content in seawater relates to ecological integrity of coastal waters [1-3]. Oxygen is required for many chemical and biological processes in the ocean and even periodic declines in oxygen levels cause changes in coastal productivity, biodiversity, and biogeochemical cycles [4]. Tolerance of marine biota to oxygen depletion is well understood; some marine and estuarine species are more tolerant to low oxygen levels than others [5], so changes in oxygen availability change which species are present in coastal waters [1, 6]. Increased respiration during decomposition of organic material tends to drive down oxygen levels. This process typically shows daily and seasonally cycles - oxygen minima occur at times when respiration exceeds primary production (photosynthesis) [4].

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

There is strong evidence of impact of seawater hypoxia on biological integrity of coastal waters globally [2, 7, 8], and in New Zealand [3, 9, 10]. Recorded impacts include mortality events such as fish kills but can include changes to growth, movement, and behaviour of marine organisms. It is well documented that the magnitude of these impacts are not consistent spatially. Waters with the greatest tendency to become hypoxic are those that receive high nutrient loads [11], and those that stratify [12]. Relatively deep and poorly flushed hydrosystems have greater tendency to stratify [13] and thus deep waters within these systems have a greater tendency to become hypoxic. However, reductions in oxygen content of waters have also been observed in well-mixed estuaries receiving high nutrient loads from land [14]. Reduced seawater oxygen concentrations are also common in waters around intensive marine aquaculture, especially those that add large amounts of nutrients to confined areas such as fish farms [15, 16]. Reduced seawater oxygen concentrations are known to impact aquaculture production in some species [17].

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

Reduction in dissolved oxygen in coastal waters is largely a result of increased flows of nutrients (which increases growth of plants and algae) [18] and direct addition of labile organic matter from land. These additions have increased due to land use change globally, including in New Zealand, with worsening impacts to dissolved oxygen levels [3, 10, 11]. The number of hypoxic zones globally in the coastal margin is approximately doubling every decade [19]. We would expect the trajectory of this attribute to track the future pace and trajectory of loading of nutrients and organic material from land to the ocean. However, several factors may affect that relationship. The susceptibility of ecosystems depends on factors including warming of coastal waters, the depth of the water body, and the tendency of waters within the water body to mix [20]. Water bodies that stratify will tend to develop zones of low oxygen availability near the seabed, where declines in seawater oxygen levels caused by respiration are not balanced by oxygen produced by photosynthesis (which occurs mostly in surface waters). Increasing seawater temperatures are expected to exacerbate coastal de-oxygenation by reducing the solubility of oxygen in seawater, increasing ecosystem metabolism rates, and increasing the tendency of the ocean to stratify [20, 21]. The degree of reversibility of hypoxia in coastal waters depends on flushing, as well as organic content of bottom sediments.

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

Most monitoring of coastal waters carried out by regional council scientists uses in situ probe measurement of dissolved oxygen concentration and saturation [22-26]. These samples are almost always carried out during the day, in the top 30 cm of the water column, and are most commonly at monthly frequency. This sampling is likely to miss most of the problems associated with de-oxygenation of bottom water in sub-tidal parts of estuaries and, even in well-mixed estuaries may miss oxygen minima that often occur at night. There is a standard for measurement of dissolved oxygen in coastal waters [27]. Measurement of dissolved oxygen across depth profiles (e.g., using boat-deployed instruments) is carried out more rarely [22]. Continuous monitoring, e.g., using sensors deployed on moorings, or attached to submerged structures, is carried out by some councils and the feasibility of this approach is being investigated by others [28].

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

While depth profile sampling is the most appropriate method of monitoring coastal waters for oxygen depletion, expense hinders its use. Depth profile sampling typically can’t be done from the shore unless a suitable structure such as a bridge is in a useful position across an estuary. Because most (but not all) regional council state of the environment (SoE) sampling for coastal water quality is conducted from shore or helicopter [22], depth profile sampling of dissolved oxygen levels would require considerable extra expense.

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

Up-front costs differ depending on measurement method. For discrete sampling from land, a hand-held dissolved oxygen sensor is required [27]. Deployable dissolved oxygen loggers are also available and some offer both relative reliability and low cost (e.g., PME Minidot loggers cost ca. $5,000 per unit). Upfront costs are markedly higher for depth-profile sampling performed from boats/ships. In addition to purchase or hire of a boat and qualified crew, the instruments used (e.g., YSI EXO Sondes with dissolved oxygen measurement capability) typically cost in the order of $NZ40,000. If sensors for continuous long-term measurement are attached to moorings, the mooring itself requires substantial additional up-front costs. All dissolved oxygen sensor options require periodic calibration, as well as staff expertise for measurement and interpretation of data, databasing and reporting. Deployed sensors for continuous long-term measurement in coastal environments require periodic maintenance in the order of 1-2 months, including cleaning, batteries, and recalibration.

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

We (the authors and John Zeldis, also of NIWA) are not aware of any monitoring being carried out by representatives of iwi/hapū/rūnanga. The exception may be Māori-owned marine businesses (e.g., green-lipped mussel farmers) who may be required to monitor water quality including DO as part of consent conditions.

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Eutrophication is a main cause of fluctuations in dissolved oxygen. Because of this, seawater dissolved oxygen tends to co-vary with other seawater indicators of eutrophication. These include chlorophyll *a* concentrations, and total nutrient concentrations (e.g., total nitrogen (TN), and total phosphorus (TP))[29]. Seawater hypoxia and acidification also co-occur in coastal waters globally because respiration of organic matter increases dissolved inorganic carbon (DIC) and drives down pH and O_2 [3, 30]. These respiration-driven reductions in pH can significantly outpace other drivers of ocean acidification [31], and reach levels that cause substantial harm to marine life [32].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

The current state of seawater dissolved oxygen in New Zealand's deep (stratifying) estuaries is not well understood because of practical issues associated with sampling. As described above, depth profiles of seawater dissolved oxygen are expensive to measure and high frequency or continuous monitoring is required to measure diel fluctuations in dissolved oxygen concentration. For these reasons there is a lack of national-scale monitoring at the sites and times where problems are likely to occur. However, limits/thresholds for life are well understood [5]. Measurement methods are well established, and we have good understanding of state in a few areas of New Zealand [3]. Dissolved oxygen could be used as a national indicator.

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

Yes. Those systems with consistently high but not supersaturated oxygen saturation values provide reference conditions. Reference conditions sit consistently near 100% saturation. Undersaturation associated with other indicators of eutrophication (e.g., high TN, TP, chlorophyll-*a*, DIC) indicates a problem.

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

Yes, this is well understood. Metadata studies provide thresholds of dissolved oxygen concentrations required for survival of various taxa across hundreds of estuaries [5]. The 2000 ANZECC guidelines give maximum and minimum values for dissolved oxygen in estuaries at 110% and 80% saturation, respectively [33]. Regional councils also provide site-specific standards for estuaries (e.g., [34]).

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

Yes, for ecological integrity there is consensus on the requirements for life for varying taxa [5, 21, 35]. This attribute relates to those species that take their oxygen from seawater so does not relate directly to human health.

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

It is likely that lag-times to both hypoxia onset and recovery are site-dependent, and recovery of ecosystems tends to be more linear in response to reductions in nutrients and labile organic matter when the reductions are from point sources (such as sewage outfall diversion), rather than attempts to reduce diffuse sources [36]. System flushing and muddiness are also likely controlling factors of recovery lag times [37]. As described above, cyclical or long-term changes in climate that affect water temperatures (and thus water column stratification and ecosystem carbon balance) are also likely to affect seawater dissolved oxygen levels.

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

Mana whenua have long advocated for more holistic approaches to inform estuarine and coastal health (e.g., ki uta ki tai) and this drive has seen for instance efforts towards understanding ecological condition and the need for better protection of significant areas such as Ōreti (New River Estuary; e.g., [50]. A key example of how mana whenua have shaped the approaches to improving management for land, freshwater and estuaries are evident within Murihiku (aka Southland). For instance, having estuaries included within Freshwater Management Units (FMUs) have been strongly advocated for by iwi, including Ngāi Tahu ki Murihiku [51, 52]. The involvement of mana whenua within decision-making, including the provisions of management policy statements (e.g., NPSFM), and the values set out within Iwi Environmental Management Plans is essential. It is therefore advised that an approach towards developing bands and allocation is done more appropriately. The requirement for engagement and collaboration with mana whenua is shared in the following example, where a multi-disciplinary study (mātauranga and Western science), co-lead with kairangahau Māori (who have expertise within the economic, freshwater ecology, marine ecology and mātauranga Māori) within the National Science Challenge, have suggested expanding beyond upstream, leading with three steps: (1) understanding iwi aspirations for place, (2) estuarine ecologists being able to identify freshwater contaminant thresholds or load limits for achieving or moving towards those aspirations, and (3) catchment modellers determining the necessary mitigations or changes in land use to achieve the necessary loads [53].

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

Process relationships between loading of nutrients and organic matter to estuaries, eutrophication, and impacts to seawater dissolved oxygen content are well understood [3, 39, 40]. The New Zealand Estuarine Trophic Index gives an example of tools to quantify these relationships in a management context [41, 42], however links within these tools between nutrient loading and seawater oxygen levels are indirect (based on a Baysian belief network [43]) and tenuous due to lack of available data. See https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

Key mechanisms to affect this attribute are controls on nutrient loading initiated by councils to give effect to the (central government initiated) National Policy Statement for Freshwater Management (NPSFM), and resource consents on point sources of nutrients (e.g., wastewater).

C2-(i). Local government driven

Diversion of the Christchurch wastewater treatment plant outflow to the Ihutai (Avon-Heathcote) estuary provides perhaps the best example nationally of the potential to improve seawater oxygen content by removing point source discharges. This diversion represented a reduction of around 90% of the total nitrogen load to this estuary. Seawater and sediment chemistry, and indices of primary production in the estuary were measured before and after the diversion [37, 44, 45]. The diversion resulted in improvement in oxygen content of waters at the sediment/seawater interface at sites near the outfall.

C2-(ii). Central government driven

There is currently little evidence to suggest that controls on nutrient loading initiated by councils to give effect to the NPSFM are causing improvement in dissolved oxygen levels in estuaries; despite long-term trends indicating strongly that dissolved oxygen levels in estuaries are increasing nationally [22, 23]. This is because council sampling is carried out in surface waters during daylight hours, where we would expect photosynthesis to drive oxygen saturation. As such, these increasing trends in seawater dissolved oxygen are not necessarily reflective of improving ecological integrity of estuaries, in fact, the opposite may be true if increasing daytime productivity is balanced by higher respiration/decomposition rates at night and in deeper waters [3]. Long-term, continuous sampling of seawater oxygen content across depth gradients is required to infer changes in this attribute. Conducting these measurements over timescales when changes in nutrient loads take place would provide evidence to show whether load changes are effective in improving seawater oxygen conditions.

C2-(iii). Iwi/hapū driven

We are not aware of interventions/mechanisms being used by iwi/hapū/rūnanga to directly affect this attribute. However, there are many examples of where variables, such as oxygen/dissolved oxygen (and indicated by for instance changes in colour and smell), are considered within a holistic approach to supporting estuarine and coastal health (e.g., [54, 55]). For instance, within land to sea management plans led and co-developed with hapū and iwi towards informing approaches towards key indicators for supporting environmental health and associated culturally important ecosystems (e.g., [54]). It is difficult to measure the improvements given the legacy issues in estuaries, and the more recent collaborations that acknowledge a systems approach is required [53].

C2-(iv). NGO, community driven

We are unaware of initiatives to improve dissolved oxygen in coastal waters being carried out by representatives of NGOs.

C2-(v). Internationally driven

We are unaware of international initiatives that are driving improvement of dissolved oxygen conditions in coastal waters.

Part D—Impact analysis

D1. What would be the environmental/human health impacts of not managing this attribute?

Changes in the attribute state affect ecological integrity as described in A1 above. Not managing eutrophication processes in coastal waters to provide sufficient oxygen for biota will likely lead to degradation of inshore fisheries, including mahinga kai species, especially in already degraded environments [46, 47]. Reduced oxygen will continue to contribute to species loss and displacement, and stress ecological function of eutrophic waters [48]. Frequency of hypoxia-driven fish kills is likely to increase [49].

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

Impacts have long been acknowledged and addressed by hapū and whānau, for instance Ngāi Tahu whānau and hapū in relation to estuarine and coastal ecosystems, including inshore fisheries [55-58].

These impacts may be direct (e.g., via fatally hypoxic waters [5]), or indirect (e.g., via decreased food availability for fisheries species [48]). Demersal and benthic species (those that live and feed on or near the bottom of seas) are likely to be disproportionally affected [2]. Reduced seawater oxygen concentrations are known to impact aquaculture production in some species [17].

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Even under current loading levels of nitrogen to coastal waters from land, increasing seawater temperatures are expected to exacerbate coastal de-oxygenation both by reducing the solubility of oxygen in seawater, increasing ecosystem metabolism rates, and increasing the tendency of the ocean to stratify [20, 21]. An appropriate management response would be to manage loads of organic material and nitrogen from land to levels that are unlikely to cause damaging hypoxia in coastal waters, with sufficient tolerance to negate climate-change-driven effects.

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