UNIVERSITY of TASMANIA
IMAS
Institute for Marine and Antarctic Studies

# Aquaculture Environment Review Series

# Ecological effects of finfish aquaculture on the water column

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# Contents

# 1 Introduction

**This is the second in a series of independent literature reviews about marine farming interactions and the environment.**

The Department of Natural Resources and Environment Tasmania (DNRE Tas) commissioned the University of Tasmania's Institute for Marine and Antarctic Studies (IMAS) to perform these reviews to support the planning and regulation of marine farming in Tasmania, and to provide a reference source for people with an interest in Tasmanian aquaculture. It is intended to cover all forms of existing or proposed marine-based aquaculture within Tasmanian state waters and will be regularly updated and revised to consider new scientific information. This review will focus on the interaction between the water column and finfish aquaculture.

The oceanic water column is the largest ecological system on the planet, and is a productive and dynamic environment within temperate zones (Angel 1993). The physicochemical and biological characteristics of the water column influence local ecosystems and shape the ecosystem services provided by the water column (Angel 1993). One of the most important functions of the water column is primary productivity, where atmospheric and dissolved nutrients, along with carbon, are fixed into pelagic food webs by photosynthetic or other autotrophic plankton, thereby supporting higher levels of marine life (Edwards 2021, Naselli-Flores & Padisák 2023). Ecosystem services and functions of the water column also shape connected benthic habitats through pelagic-benthic coupling (Nunnally 2019). Shifts in water column health and functioning can thus have wide-reaching effects in the marine environment.

Coastal areas are subject to a range of nutrient inputs, from both environmental and anthropogenic sources. Environmental sources include inputs from oceanic circulation, upwelling and estuarine systems (Gaylard et al. 2020), while anthropogenic inputs tend to result from human activities in the coastal zone. These include urban inputs such as sewage outfalls and stormwater, agriculture run-off and coastal aquaculture (Stenton-Dozey 2013). Nutrients from both natural and anthropogenic sources are assimilated within the water column, and this nutrient processing is a key ecosystem function (Gaylard et al. 2020).

Finfish aquaculture produces dissolved nutrient waste products, as well as particulate forms from uneaten fish feed and fish faeces (Strain & Hargrave 2005). In open-cage fish farming, these waste nutrients are discharged directly to the water column (Stenton-Dozey 2013), with the risk of nutrient enrichment arising when inputs exceed the assimilative capacity of a system (Pitta et al. 2006, Navarro et al. 2008). The enhancement of nutrients may stimulate primary productivity, causing reduced light penetration and the sedimentation of organic matter following phytoplankton senescence. Excess nutrient enrichment can also cause changes in connected habitats (e.g. rocky reefs and other vegetated habitats) and food webs (e.g. pelagic). These water column interactions can act cumulatively or synergistically with other activities or environmental forcings, and the assimilative capacity of a system will subsequently vary with the characteristics of the environment, notably the amount of water flow and flushing.

The majority of finfish aquaculture in Tasmania occurs in either southeast Tasmania or Macquarie Harbour on Tasmania's west coast. The southeast coast contains both sheltered and more exposed farming areas, while Macquarie Harbour is a sheltered and more enclosed system with a tannin-rich surface layer. These contrasting systems mean interactions between the water column and finfish aquaculture are likely to be site and region specific.

The purpose of this review is to explore and establish the existing state of knowledge of interactions between the water column environment and finfish aquaculture, both globally and locally, with a focus on water quality and an emphasis on Tasmania. Methods used to monitor these interactions, along with mitigation and management strategies for managing ecological risks are also discussed.

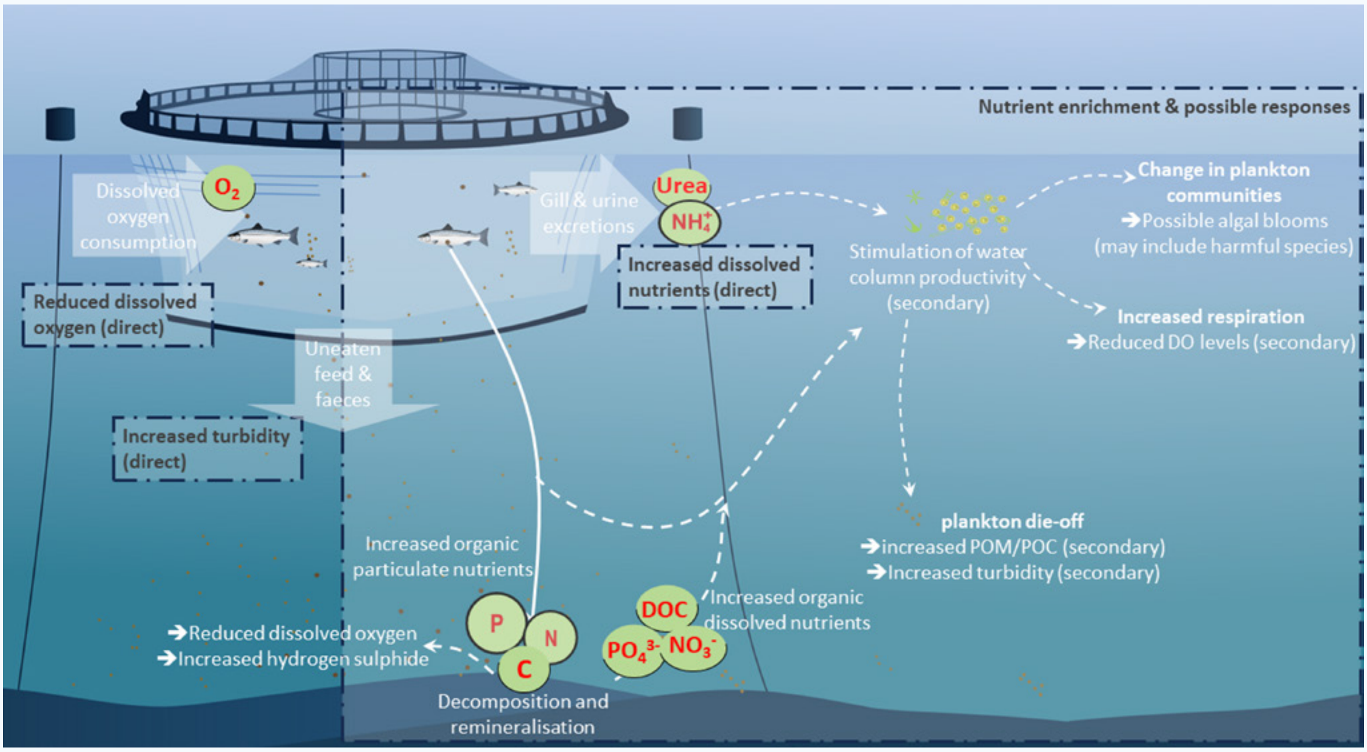
# 2 Effects on the water column

**Finfish aquaculture primarily interacts with the water column through dissolved waste streams that have the potential to enhance primary productivity.**

Dissolved nutrients are released from finfish aquaculture into the environment through excretion of soluble metabolic waste products (nitrogen), and via leaching of nutrients from faecal material and uneaten feed (carbon, nitrogen and phosphorus; Wang et al. 2012; Figure 1).

Open-cage finfish farms can therefore influence water quality directly through increased soluble nutrients and organic particulates in the water column, which can lead to a range of ecosystem responses (Hartstein & Oldman 2015). Respiration by the farmed fish themselves can also affect water quality through the uptake of oxygen within the water column (Elvines et al. 2019). The scale and magnitude of interactions between finfish aquaculture and the water column are affected by both farm practices and the physical environment.

**Figure 1: Key ecological interactions associated with open cage finfish farms and water quality**




| | | | | | |
|---|---|---|---|---|---|
| **P** | phosphorus | **$NH_4^+$** | ammonium | **DOC** | dissolved organic carbon |
| **N** | nitrogen | **$NO_3^-$** | nitrate | **$PO_4^3$** | phosphate |
| **C** | carbon | | | | |

## 2.1 Dissolved nutrients

Excretion of metabolic waste products by fish will release dissolved inorganic nitrogen (DIN) directly into the water column, generally in the form of ammonium and urea (Navarro et al. 2008; Figure 1). DIN represents ~85% of the nitrogen released by finfish aquaculture and commonly results in elevated nutrient levels within the immediate vicinity of the finfish farm (Wu et al. 1994, MacKenzie et al. 2011, Strain et al. 2023). Once in the water column, DIN is immediately available to phytoplankton and other primary producers that can rapidly assimilate these nutrients (Olsen & Olsen 2008, Pitta et al. 2009, Bell et al. 2017). Bacterial digestion of particulate wastes (from feed and faecal material) also releases dissolved organic nitrogen and carbon into the water column. The dissolved organic fractions can persist for longer periods because they are taken up by phytoplankton less readily than DIN (Olsen 2007, Olsen & Olsen 2008). Phosphorus is also discharged, mainly in particulate form, but is typically of lower concern in most marine systems, since nitrogen is usually the limiting nutrient (Sarà 2007, Price et al. 2015, Ross et al. 2022).

Despite the release of nutrients into the environment, the ability to detect elevated nutrients in proximity to finfish aquaculture activities tends to be highly variable (Price et al. 2015). Most studies report either localised elevated nutrient concentrations which quickly diminish within a few hundred metres from the farm or no evidence of elevated concentrations (Price et al. 2015). However, a handful of studies report elevated and persistent dissolved nutrients. For example, at a farm culturing sea bass and croaker in Nansha Bay, China, concentrations of ammonium inside the farm were found to be double the levels recorded 1000 m away during spring, and DIN concentrations were also found to be significantly higher in bottom waters due to release from sediments (Jiang et al. 2012).

Similarly, upon cessation of finfish aquaculture in Tapong Bay, Taiwan, the annual mean concentrations of DIN dropped significantly across the bay (Hung et al. 2008). In both these instances, finfish aquaculture was occurring in small semi-enclosed systems with minimal water exchange.

In south-eastern Tasmania, elevated levels of ammonium and a decline in dissolved oxygen (DO) concentrations in the bottom waters of the semi-enclosed Huon/D'Entrecasteaux Channel farming region has been cautiously linked to the cumulative inputs from finfish aquaculture (Ross & Macleod 2013). However, there was no clear evidence of flow-on effects to phytoplankton communities (Ross & Macleod 2013). In Long Bay, a sheltered and relatively poorly flushed bay in the Tasman Peninsula farming region, nutrient and chlorophyll *a* concentrations have been observed to increase in proximity to the local finfish farm (EPA 2023a). Near-continuous sampling methods in the more exposed Storm Bay farming area have shown spatially and temporally variable increases in ammonium in proximity to fish farms (Strain et al. 2023). In this instance, the application of near-continuous sampling highlighted the patchy distribution of ammonium in the environment, and thus the difficulties in detecting elevated ammonium using conventional sampling methods. Despite the patchy distribution of nitrogen in the environment, discrete sampling in Storm Bay has documented increases in nitrogen due to farming at the local scale (<500 m; Strain et al. 2023). However, no effects associated with nutrient release from farms in Storm Bay were evident at the broadscale over three years of comprehensive monitoring concurrent with fish farm expansion (Strain et al. 2023).

In Macquarie Harbour, a large stratified system on the west coast of Tasmania, where salmon farming expanded rapidly between 2009/10 and 2015/16, increases in nutrient concentrations, notably nitrogen, and a reduction in dissolved oxygen (DO) levels have been reported at the broad (harbour-wide) scale (Ross et al. 2022). Although modelling and empirical studies demonstrate the important role of other factors (e.g. river flow and climate change), a subsequent reduction in farmed biomass has coincided with a reduction in ammonia and nitrate levels (Ross et al. 2022) and an increase in DO concentrations across the harbour (EPA 2024).

## 2.2 Enhancement of water column productivity

The release of dissolved nutrients and solids from finfish aquaculture can stimulate water column productivity, potentially altering the composition of the planktonic communities. Where nutrient inputs exceed the assimilative capacity of a system, excess primary productivity in the water column, otherwise known as eutrophication, can occur (Folke et al. 1994, Macleod et al. 2008, Kang et al. 2021). Eutrophication is associated with reduced water clarity and light penetration, enhanced sedimentation of organic matter to the seabed and lower oxygen levels as microbes degrade the additional organic matter (Cloern 2001, Forrest et al. 2007, Olsen & Olsen 2008).

Changes to phytoplankton communities due to nutrient enhancement are well understood, as the growth of different phytoplankton species can be limited by the relative availability of certain nutrients. For example, increased DIN availability tends to favour dinoflagellates and flagellates over diatoms because the growth of diatoms is limited by the availability of dissolved silicate when DIN concentrations are elevated (Martin-Jézéquel et al. 2000, Olsen et al. 2014). Fish farm nutrients can also interact with bacterial and zooplankton communities.

For example, recent work around leases in Macquarie Harbour has indicated some localised shifts in bacterioplankton community composition (Da Silva et al. 2022). Likewise, the water column around salmon farms in Scotland has shown enhanced heterotrophic bacterioplankton activity (Buschmann et al. 2007, Navarro et al. 2008), with microbial degradation of uneaten feed and fish faeces having the potential to reduce DO levels in the water column by increasing biological oxygen demand (Forrest et al. 2007, Stenton-Dozey 2013).

Enhanced zooplankton biomass around farms may occur due to increased phyto- or bacterioplankton food supply to grazing zooplankton species, reflecting trophic transfer of fish farm nutrients (Olsen 2007). In surface waters, this grazing effect may provide a buffer to algal growth-related eutrophication symptoms (Buschmann et al. 2007, Pitta et al. 2009).

In Tasmania, elevated levels of chlorophyll and phytoplankton biomass have been reported at a local scale associated with farming operations in Storm Bay, although there is less evidence of broadscale increases to primary productivity (Strain et al. 2023). The use of metatranscriptomics around a finfish lease in southern Tasmania indicated a localised shift in phytoplankton community dynamics consistent with an increase in dinoflagellate activity and decrease in diatom activity (Hook et al. 2021). Potentially, harmful algae occur naturally in the environment and can bloom under the right conditions. Although rare, there have been cases overseas of harmful algal blooms (HABs) caused by a synergistic combination of fish farming-associated nutrient enrichment and environmental forcings (Mardones et al. 2015, Mardones et al. 2021), although at present there has been no clear evidence of this occurring in Tasmania.

While the pathways of effect of nutrient enrichment on the receiving environment are well established, the evidence of major effects from finfish aquaculture beyond the local scale remains limited. This might reflect the inability of traditional sampling designs to detect and attribute change in an environment that is typically dynamic and highly variable, but it may also reflect the capacity for nutrients to be dispersed and assimilated without major effects in certain systems (Pitta et al. 2006, Price et al. 2015, Strain et al. 2023). Those studies that do provide evidence of significant effects on primary production are typically in locations with poor flushing and limited vertical mixing (Honkanen & Helminen 2000, La Rosa et al. 2002, Nordvarg & Johansson 2002, Dalsgaard & Krause-Jensen 2006, Rensel & Forster 2007).

## 2.3 Other interactions

Beyond the enhancement of nutrient concentrations and primary productivity in the water column, finfish farming can also lead to increased turbidity and reduced oxygen levels, particularly at a local scale. For example, faecal waste, waste feed and feed dust can all directly contribute to increased turbidity (Buschmann et al. 2007). Water from freshwater bathing activities also has the potential to influence turbidity, nutrient levels and DO. These effects, when present, are likely to be localised to the immediate proximity of the farm, and more evident in sheltered locations with lower water movement. The consequences of increased turbidity due to feed and faecal inputs is typically considered negligible at a broader spatial scale (Price et al. 2015).

Respiration by farmed fish can cause localised oxygen depletion (Forrest et al. 2007, Reid et al. 2009, Stenton-Dozey 2013). Reduced oxygen can be detrimental to both the farmed fish and wild species living in the water column, and accordingly, improved water flow and oxygen renewal are important priorities for the siting and operational management of farms. On that basis, these effects are rarely problematic, with most observations of reduced oxygen being within the range of naturally driven fluctuations (Price et al. 2015).

Changes in dissolved oxygen from fish respiration are usually localised, where detected. In Macquarie Harbour on Tasmania's west coast, the influence of finfish aquaculture on dissolved oxygen levels is well documented (Ross et al. 2022), but this is principally observed in the middle and bottom waters below the halocline where the farmed fish reside. Particulate waste (faeces and uneaten feed) that sinks below the halocline influences these oxygen levels, whereas fish respiration is considered to principally demand oxygen above the halocline where effects on oxygen levels are reported to be localised (Maxey et al. 2020). Above the halocline, oxygen levels are typically higher and are replenished through wind-driven mixing and river inputs (Revill et al. 2016).

## 2.4 Factors affecting scale and magnitude of nutrient enrichment

The spatial extent and magnitude of nutrient enrichment will be influenced by both environmental factors and on-farm management practices (Islam 2005, Sarà 2007). Dilution is a key factor in reducing nutrient enrichment in the water column, with eutrophication less likely in systems with strong local currents and vertical mixing of the water column, or in more open systems with high water exchange (Nixon et al. 2001, Herzfeld et al. 2005, Buschmann et al. 2007, Herzfeld 2008, Nash et al. 2008, Olsen & Olsen 2008). If detectable at all, effects are usually localised to within hundreds of metres of fish farms, although this is dependent on the local oceanography, primarily circulation, flushing rates and biological activity (Stenton-Dozey 2013, Price et al. 2015). Particulate nutrient enrichment is typically localised due to short residence times prior to settlement on the seabed (Jansen et al. 2018).

Nutrient inputs increase with farm biomass, thus the highest nutrient inputs from fish farming occur at peak biomass (Buschmann et al. 2007, Wang et al. 2012). Although the level of nutrient input is important, other seasonal factors can also influence interactions. These include water temperature, seasonal changes in plankton communities and the type and timing of nutrient delivery from other sources linked to the hydrodynamic regime of the region (Crawford 2003, Jiang et al. 2012, Ross & Macleod 2018). The risk of oxygen depletion from nutrient enrichment can also be seasonal depending on feed inputs and local water temperatures, phytoplankton growth and stratification (Plew 2013, Stenton-Dozey 2013, Revill et al. 2016).

For example, in Macquarie Harbour, monitoring demonstrates a seasonal decline in bottom-water dissolved oxygen each spring before natural recharge, which typically occurs through late summer-autumn (Ross et al. 2019). Conversely, reductions in DO in surface waters can be exacerbated during the warmer summer months when oxygen replenishment via wind-driven mixing and river inputs are reduced (Revill et al. 2016).

Where stimulation of primary productivity occurs, effects will be governed by water circulation and residence time, as well as the biophysical properties of the receiving water body. Bioassays overseas have suggested that phytoplankton growth is most likely to be enhanced immediately downstream of the finfish farm (Dalsgaard & Krause-Jensen 2006, Sarà et al. 2011, Tsagaraki et al. 2013). In contrast, effects have also been hypothesized in the far-field (Nash et al. 2008) as phytoplankton can take several days to respond to increased nutrients (Olsen & Olsen 2008). Far-field eutrophication may occur in instances where nutrient-rich waters become entrapped in sheltered areas for relatively long periods (Broekhuizen & Hadfield 2016a, Elvines et al. 2019). In these instances, it can be challenging to establish whether or to what extent fish farms have contributed to such eutrophication (Elvines et al. 2019, Strain et al. 2023).

# Summary of potential interactions between finfish farming and pelagic ecosystems and key management practices to mitigate these interactions

## Potential ecological interactions

The ecological interactions between finfish aquaculture and the water column are mainly linked to the release of waste products in the form of dissolved nutrients or particulate material.

- Farmed fish can enhance nutrient levels in the water, via excretion of dissolved nutrients (primarily urea and ammonia) and via organic waste inputs (uneaten feed and faeces).
- Elevated nutrient levels can potentially lead to enhanced phytoplankton growth and primary production, including harmful algal blooms (HABs), changes in plankton composition, and increasing biological oxygen demand as the increased primary producer biomass decays.
- Fish respiration can reduce oxygen levels inside the cages, and thereby in the water passing through the farm.
- Microbial degradation of uneaten fish feed, fish faeces or dead organic material from phytoplankton fall-out also increases oxygen demand and releases dissolved organic nutrients into the water column.
- Fish faeces and uneaten feed have the potential to increase localised turbidity, which can in turn reduce light penetration and limit primary productivity.

The magnitude of these effects depends on the environmental setting, farm practices and local water column biology and can range from undetectable to major impacts, depending on the receiving environment.

## Spatial and temporal scales

Direct effects are mostly observed locally (less than 500 m) and are often not detectable, but in systems with high water residence times, effects may become evident at the broadscale.

Effects on the function and composition of photosynthetic organisms are difficult to predict, but there are examples of these occurring at both the local and broadscale.

The spatial extent, duration and magnitude of effects are largely governed by the dispersal capacity and the extent of flushing and water exchange. The level and timing of feed inputs (i.e. stocking cycle) will also directly influence that scale in space and time and thus the intensity of potential impacts.

## Management and mitigation

Management actions to mitigate the effects of nutrient enrichment in the water column include:

- appropriate site selection (accounting for the assimilative capacity of the system and the potential for cumulative effects)
- baseline environmental monitoring before farming commences
- system and/or site-specific limits on farming via limits on feed inputs or biomass
- local and broadscale environmental monitoring to inform farm management

## Knowledge gaps

Although the pathways of impact of nutrient enrichment in the water column are well understood, there are some inherent challenges in capturing and attributing change given the highly dynamic nature of the water column environment.

Active areas of research that have the potential to improve our ability to track system responses in the water column include remote sensing, more advanced molecular techniques and instrumentation for continuous and in situ monitoring (refer Section 4).

# 3 Mitigation and management of impacts

**Mitigation and management of water column interactions with finfish aquaculture is largely focused around nutrient enrichment and the subsequent ecosystem response.**

Key mitigation and management aspects include site selection, limits on feed inputs and performance-based management which includes limits of acceptable change to the environment (DNRET 2023, see 4.2). Appropriate management also relies on environmental monitoring which feeds back into management actions as necessary (Wu 1995, EPA 2022, Fletcher et al. 2022).

## 3.1 Planning frameworks, site selection and production constraints

Low energy and poorly flushed systems will be more sensitive to nutrient enrichment and oxygen depletion (Wu et al. 1994, La Rosa et al. 2002, Buschmann et al. 2007, Price et al. 2015). As such, more dispersive, higher energy sites with greater flushing rates are increasingly preferred for finfish aquaculture (Benetti et al. 2010, Lacharité et al. 2021). Connectivity with surrounding habitats that are susceptible to nutrient enrichment is also a major consideration.

Therefore, understanding background environmental water column dynamics is critical to informing selection of new fish farming sites (Swadling et al. 2017). This information may already exist for the region or may need to be collected through baseline assessments. Ideally, baseline datasets should contain multiple years of data to incorporate multiple seasonal cycles and natural interannual environmental variability.

In conjunction with baseline environmental data, numerical modelling can be used to predict how nutrient inputs will affect the system dynamics. Either hydrodynamic or biogeochemical models, or a combination of both, may be used. Hydrodynamic models simulate water movement and are used to predict the dispersal and fate of dissolved or solid tracers released from a farm/s. Biogeochemical models are used to examine how the released nutrients are incorporated into recipient ecosystems (e.g. the uptake of nitrogen by phytoplankton; Yakushev et al. 2020). Under different farming scenarios, models can be used to predict the spread and effects of released nutrients on the receiving environment. This helps evaluate the ecological risks of different farm siting and production scenarios (Butler et al. 2000, Wild-Allen et al. 2010, Broekhuizen & Hadfield 2016a, Broekhuizen & Hadfield 2016b).

During the planning stages of a new farm development, careful consideration of farm biomass and feed inputs should be made to manage risks to water quality. Establishing the carrying capacity of the receiving system for both dissolved and particulate loadings from finfish aquaculture is paramount (Wu 1995, Stigebrandt et al. 2004, Sim-Smith & Forsythe 2013, Hadley et al. 2017, Chary et al. 2021). In Tasmania, marine farming development plans (MFDPs) include management controls for stocking density and maximum biomass (which can be set at the region or lease scale).

Increasingly, feed limits in the form of allowed dissolved nitrogen outputs (e.g. Total Permissible Dissolved Nitrogen Output [TPDNO]) are set and applied by the Environment Protection Authority (EPA Tasmania) in the major growing areas (see EPA 2022).

TPDNO limits the amount of nitrogen which can be released into the environment via feed inputs in a defined area. This is primarily to manage the risk of water column eutrophication because nitrogen is considered the key nutrient that limits primary production in coastal waters. For example, in the D'Entrecasteaux Channel and Huon Estuary MFDP area, changes in the trophic status based on annual near-surface chlorophyll concentrations was used to guide decision-making on sustainable production levels and the associated TPDNO limit (Wild-Allen et al. 2010).

This classification is based on Smith (1998), who found:

- oligotrophic conditions when annual mean chlorophyll is $<1$ mg m$^{-3}$
- mesotrophic conditions when annual mean chlorophyll is 1–3 mg m$^{-3}$
- eutrophic conditions when annual mean chlorophyll is $>3$ mg m$^{-3}$.

The TDPNO limits are applied using a rolling 12-month sum of predicted dissolved nitrogen output based on feed input information (EPA 2022). The TPDNO is set and allocated to a farm or group of farms within a region. In conjunction with baseline surveys and ongoing environmental monitoring, modelling often plays a key role in informing the carrying capacity of a region along with smaller areas within. As such, these management tools are critical in setting the original TPDNO limit, along with its ongoing management and refinement.

Management tools such as TPDNO, biomass limits and modelling also provide a means to control the staged development of farming in new areas while information on environmental impacts (and their management) is still being gathered (Giles et al. 2021). Other actions may also be taken to manage nutrient inputs, including optimising feed formulations, feeding patterns/timing, and cage design and orientation (Einen et al. 1995, Stenton-Dozey 2013).

Mitigation measures beyond planning and management tools also exist. For instance, submerged aeration systems are sometimes used by the fish farming industry to mitigate low dissolved oxygen when environmental conditions become unfavourable for the cultured fish (Price et al. 2015 and references therein). These are usually implemented at the lease-scale, although trials are being undertaken to investigate the feasibility of larger scale oxygen replenishment in Tasmania's most enclosed system, Macquarie Harbour (IMAS 2025).

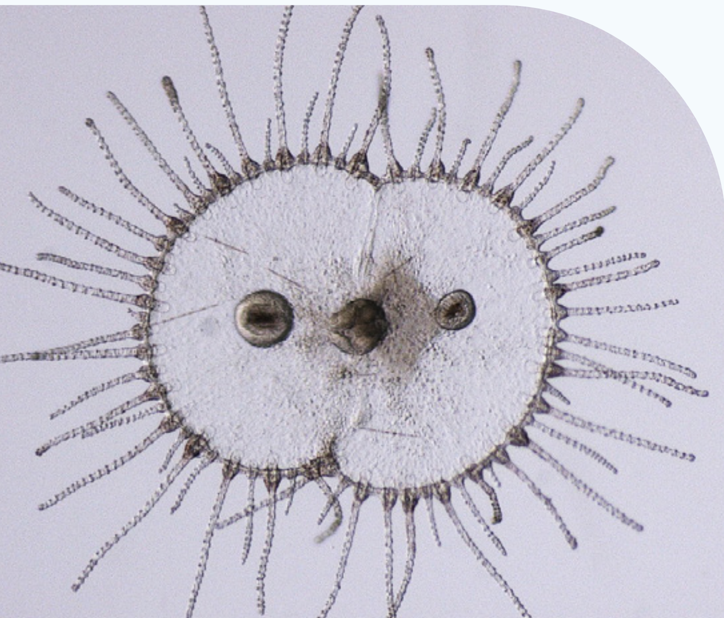
Integrated multi-trophic aquaculture (IMTA) is regularly suggested as a method to mitigate the addition of nutrients to aquatic and marine systems (Cranford et al. 2013, Azhar & Memiş 2023, Nissar et al. 2023). Conceptually, these culture systems grow extractive species (e.g. seaweed) adjacent to a feed-added species (e.g. finfish) to facilitate fixation of waste nutrients from the system, utilising them to enhance productivity of the extractive species being grown. While numerous feasibility studies and small-scale trials have been undertaken (Hadley et al. 2013, Hadley et al. 2015, Wiltshire et al. 2015, Hadley et al. 2016, Hadley et al. 2018, Chambers et al. 2024), commercially scaled IMTA operations are globally scarce (Hossain et al. 2022).

## 3.2 Environmental performance frameworks

### 3.2.1 Environmental requirements

The monitoring required in conjunction with farming operations will vary depending on jurisdiction. In Tasmania, an environmental license is required for finfish farming operations. The environmental license contains conditions for environmental monitoring requirements and performance standards. For water quality, investigative trigger levels are typically specified, and any exceedance requires additional investigation and analysis of monitoring data to determine to what extent the exceedances are caused by marine farming operations and whether mitigation actions are required (DNRET 2023). At present, the approach to water quality performance is inconsistent across the different growing regions in Tasmania. Under the new Environmental Standards (DNRET 2023), the Technical Standard for water quality will provide a consistent performance framework for all regions.

Current water quality limits are typically region- or site-specific and ideally based on baseline data collected before, or in the early stages of the development and/or at reference locations. In the Huon Estuary and D'Entrecasteaux Channel where the industry was first established in Tasmania, water quality trigger levels were proposed by Thompson et al. (2008) based on a combination of historical water quality data collected in the region and biogeochemical model predictions.



These triggers have subsequently been adopted in the annual reviews of the Broadscale Environmental Monitoring Program (BEMP) data for the region to assess performance (Ross & MacLeod 2013, Aquenal 2022), but the limits are not statutory. In Macquarie Harbour, water quality limits were derived from the literature (Tassal Operations Pty Ltd et al. 2011) and compliance is assessed using the rolling annual median for combined compliance region sites for selected water quality parameters and depths.

The environmental licenses in Macquarie Harbour were varied in 2023 to include specific conditions with respect to the management of DO in the harbour, and this includes performance assessment against interim Default Guideline Values (DGVs) published by the EPA for different depths of the water column (EPA 2023b, EPA 2023c, EPA 2023d).

In Tasmania, the State Policy on Water Quality Management (1997) aims to safeguard and enhance water quality while supporting sustainable development under the framework of Tasmania's Resource Management and Planning System. The Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG 2018) establish guideline trigger values for physical and chemical stressors in aquatic ecosystems, along with other environmental indicators. The trigger values serve as early warning thresholds. If exceeded, they signal potential environmental concerns and prompt management responses, such as further investigation or corrective action. These guidelines provide default trigger values for various Australian water bodies, including regional standards for Tasmania. However, they recommend refining these values using locally relevant data to ensure accuracy and applicability.

Image: Anita Slotwinski


EPA Tasmania has further developed DGVs for assessing water quality and associated aquatic ecosystem protection, which provide a reference point for determining the potential influence of activities such as finfish farming on water quality. The DGVs have been developed in accordance with the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG 2018) for regions around Tasmania and are being progressively adopted as 'Investigative Trigger Values' (ITVs) in environmental licences for salmonid aquaculture. For the major growing regions, the guideline values have been derived using local data.

For example, in the case of Storm Bay, DGVs have been developed for three subregions (Figure 2, Box 1). The ITVs in the environmental licences are based on the 80th or 20th percentile, depending on the parameter of interest, and have been developed from historical data (Table 2).

For each environmental license in Storm Bay, performance against the ITVs for the respective lease is typically assessed at the closest broadscale environmental monitoring site. For example, BEMP site SB3 is the water quality compliance site for marine farming lease MF279 (Figure 2).

At this site, the environmental license condition specifies that if the annual rolling median for any of the parameters (Table 2) exceeds the levels specified under region 93, additional investigations and analysis of the monitoring data are required. From this, the extent to which the exceedances are caused by marine farming operations is determined, along with the appropriate management response. Strain et al. (2023) provide recommendations and guidance on how the monitoring data is best analysed to determine attribution.

### Table 1: Investigative trigger values (determined from historical data) for each of the three subregions in Storm Bay[1]

| Parameter (mg/L) or (mg/m³) | Region 93 | Region 81 | Region 80 |
|---|---|---|---|
| Ammonia (surface) | 0.006 | 0.008 | 0.009 |
| Ammonia (10 m) | 0.007 | 0.006 | ~0.006 |
| Ammonia (bottom) | 0.010 | 0.016 | 0.017 |
| Total Nitrogen (surface) | 0.31 | 0.31 | 0.33 |
| Total Nitrogen (10 m) | 0.30 | 0.32 | ~0.33 |
| Total Nitrogen (bottom) | 0.33 | 0.34 | 0.34 |
| Nitrite & Nitrate (surface) | 0.039 | 0.017 | 0.015 |
| Nitrite & Nitrate (10 m) | 0.036 | 0.015 | ~0.002 |
| Nitrite & Nitrate (bottom) | 0.042 | 0.044 | 0.035 |
| Total Phosphorus (surface) | 0.05 | 0.04 | 0.04 |
| Total Phosphorus (10 m) | 0.04 | 0.03 | ~0.04 |
| Total Phosphorus (bottom) | 0.04 | 0.04 | 0.04 |
| Dissolved Reactive Phosphate (surface) | 0.013 | 0.011 | 0.008 |
| Dissolved Reactive Phosphate (10 m) | 0.012 | 0.009 | ~0.006 |
| Dissolved Reactive Phosphate (bottom) | 0.014 | 0.012 | 0.012 |
| Oxygen (surface) (lower limit) | 7.7 | 7.9 | 7.8 |
| Oxygen (10 m) (lower limit) | 7.5 | 8.0 | 7.8 |
| Oxygen (bottom) (lower limit) | 7.0 | 7.5 | 7.5 |
| Chlorophyll *a* (mg/m³) | 1.5 | 2.4 | 2.2 |

## Measures of significant ecosystem change

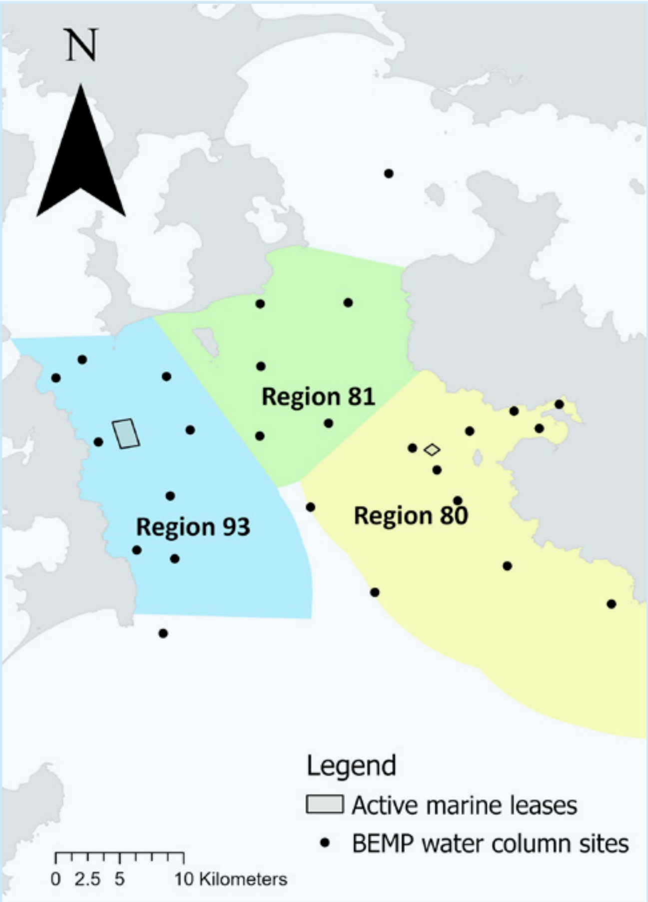
The EPA have adopted the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZG 2018) approach for determining significant ecosystem change. Using this approach, a significant change is likely when the median of the predicted water quality value is greater than the 80th percentile or less than the 20th percentile, depending on the parameter of interest. In Tasmania, Default Guideline Values (DGVs) have been derived for Tasmanian coastal and marine waters by the EPA to establish reference conditions, including the upper and lower percentiles (EPA 2021). In Storm Bay, DGVs have been developed for three subregions (80, 81 and 93; see Figure 2) and for the entire Storm Bay.

Each DGV subregion contains either active or proposed marine finfish farming leases.

For region 80, DGVs were calculated based on data from seven sites collected between February 2014 and June 2019 (Figure 2). For region 81, DGVs were calculated based on data from four sites collected between October 2016 and October 2020, and for region 90, DGVs were calculated based on data from three sites collected between January 2018 and June 2019 (Figure 2). For the entire Storm Bay, the DGVs were calculated based on data from 14 sites collected from February 2014 to October 2020 (Figure 2).

1 Only the nutrients and environmental parameters reported in the environmental licences are shown.

**Figure 2: Map showing the three DGV subregions within Storm Bay (blue – region 93, green – region 81 and yellow – region 80) and the BEMP water column monitoring sites**




## 3.2.2 Operational practices

Operational practices used to manage water column effects from marine finfish farming are typically focused on dissolved nitrogen output limits, biomass and feed management systems.

### Dissolved nitrogen output limits (feed-N input limit) and biomass

Feed caps (via the total permissible dissolved nitrogen output, TPDNO) and farmed biomass are the common management measures used to limit the scale of marine farming activities across a region. They are also an important means to control the staged development of farming in new areas while information on environmental impacts and their management is still being developed (Giles et al. 2021). In Norway, biomass limits continue to be used (Oppedal et al. 2011), but in New Zealand, total feed input limits are the primary means by which inputs are regulated, sometimes in conjunction with nitrogen-feed limits (CBOI 2013, MDC 2016).

TPDNO limits the amount of nitrogen that may be released via feed inputs (primarily for management of water column eutrophication) into a defined area over a specified time (i.e. a 12-month rolling period; EPA 2022). Maximum permissible biomass is a fixed limit on farmed biomass in the system at any one time, set for a MFDP area and/or a specific area within. This has been a common way to regulate the scale of finfish farming activity in Tasmania in the past, although maximum permissible biomass is now superseded by TPDNO across the state.

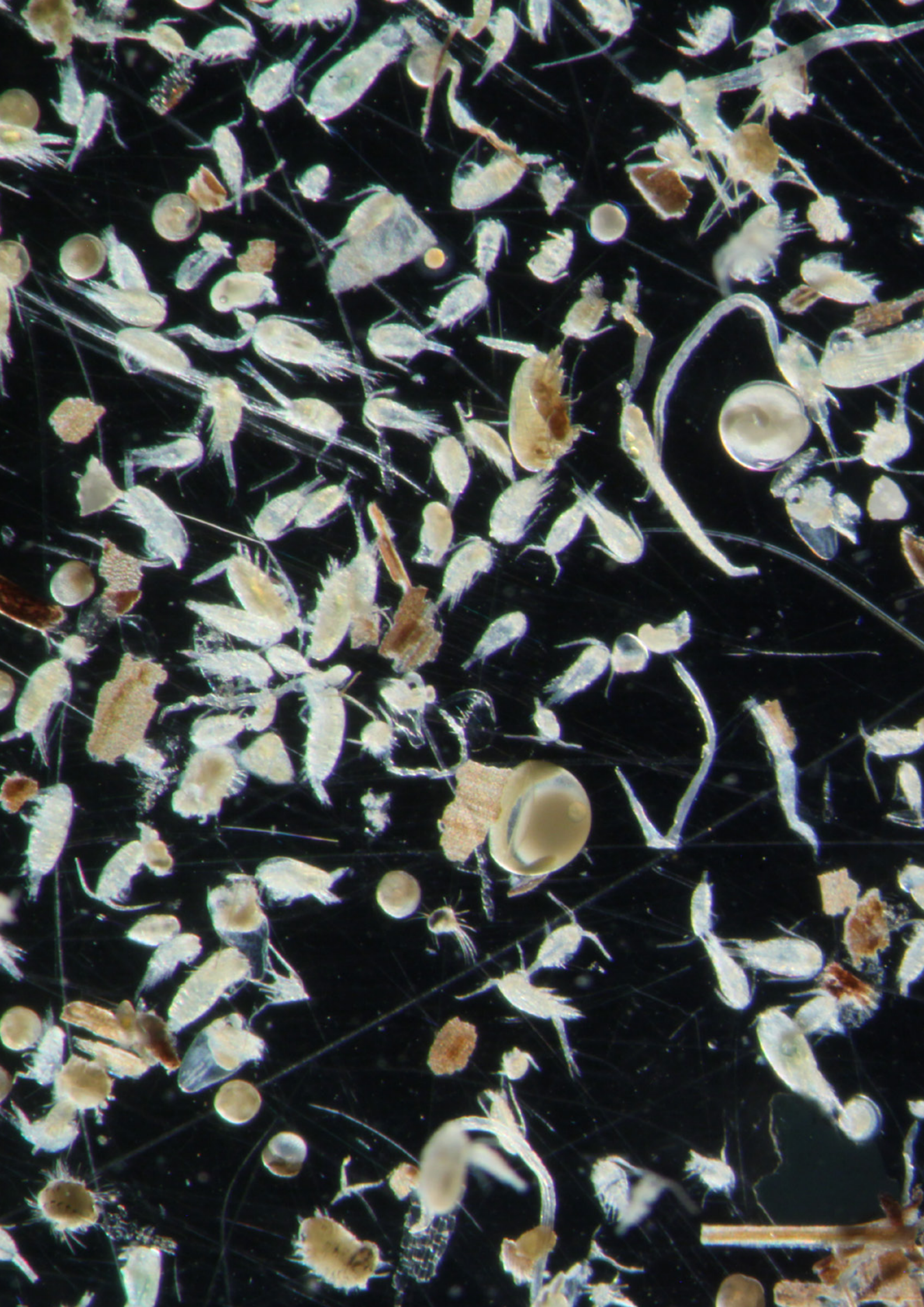
### Feed management

The most effective feed delivery systems minimise overfeeding and maximise uptake by the caged fish, thereby reducing benthic organic enrichment (Ackefors & Enell 1994, Backman et al. 2009, Bureau & Hua 2010, White 2013). In recent years there have been significant technical advancements in feed delivery systems. Similarly, the use of higher quality feed has also driven improvement in feed conversion ratios (i.e. less feed required to grow the same amount of fish), resulting in reduced emissions into the environment.

### Production cycles and stocking density

Production cycles can be managed to avoid heavy stocking densities during periods of higher water temperature and lower ambient oxygen levels. Stocking density varies and this in turn will also influence the magnitude of waste loading to the water column and the potential for localised oxygen depletion.

In Tasmania, fish stocking density at farms can be set at the region-level, whereby maximum density is set at a fixed level. The stocking level for a given region can be found in the associated MFDP for that region.



# 4 Methods for monitoring

**Monitoring of the water column is generally undertaken with the aim of better understanding the physico-chemical environment, nutrient dynamics and and any change to primary productivity that might occur as a result of finfish aquaculture.**

## 4.1 Overview of indicators

Key symptoms of nutrient enrichment include reduced DO levels, increased dissolved nutrient concentrations, increased primary productivity (i.e. chlorophyll concentrations) and reduced water clarity (Andersen et al. 2006). Therefore, a range of physicochemical and biological parameters are routinely included in water quality sampling to provide both information on potential responses to farm inputs and important environmental context for data interpretation (Table 2, Table 3).

More recently, molecular techniques including eDNA and transcriptomics have been employed as research tools for studying farm effects in the water column. In Tasmania, both methods have been used for investigating shifts in the composition and functioning of phytoplankton (Hook et al. 2021) and bacterioplankton (Da Silva et al. 2022) at a local scale, as well as examining broadscale patterns in plankton dynamics (Da Silva et al. 2021). Given the cost and expertise required for both methods, they are yet to be considered for regulatory monitoring, although eDNA is now used for monitoring sediment impacts in some locations (e.g. Marlborough Sounds, New Zealand; Fletcher et al. 2022).

Depending on the indicator, measurements are either taken from discrete water samples or using sensors on a multiparameter sonde (e.g. EXO sonde platforms, YSI). Discrete water samples are typically collected via Niskin bottles or similar at set depths, dispensed among sample bottles at the surface and sent for laboratory analysis (Figure 3). Depending on the parameter of interest, samples can be either filtered (e.g. dissolved nutrients) or not (e.g. total nutrients). Depth integrated water samples can also be collected via a Lund tube, which captures a vertical section of water from the surface down to the specified depth; this is often used to characterise phytoplankton community composition. Multiparameter sondes, including CTDs (Conductivity, Temperature and Depth; Table 2) equipped with sensors to measure a range of parameters (e.g. temperature, conductivity, pH, dissolved oxygen and depth) are also a standard feature of water quality monitoring programs. In Tasmania, the environmental licences provide detailed specifications on the sampling requirements (parameters, depths, sites, collection and processing instructions, laboratory accreditation and QA/QC procedures). Although not routinely used in monitoring programs, remote sensing methods offer information on sea surface temperature, turbidity and phytoplankton biomass as well as community composition indicators (Giles et al. 2021, Strain et al. 2023).

**Table 2: Overview of physico-chemical indicators for assessing finfish aquaculture interactions with the water column**

| Indicators | Information provided | Collection method/s |
|---|---|---|
| **Physico-chemical (exc. nutrients)** | **Physico-chemical parameters provide important context for data interpretation. The measurements are most commonly acquired using specialist sensors and instrumentation.** | |
| Conductivity (for salinity)<br>Temperature<br>Depth | Provides important information about physical properties including stratification/vertical mixing within water bodies and mixing between different water bodies. Commonly measured in a vertical profile down the water column. Instrumentation is also used for measuring horizontal profiles or collecting continuous time-series through deployments at a set depth. | Commonly integrated within a single instrument. Surface temperature can also be obtained via remote sensing (Giles et al. 2021, Strain et al. 2023). |
| Oxygen concentration (mg/L)<br>Oxygen saturation (%) | The decay of farm-derived organic matter and dieback of enhanced water column productivity creates an oxygen demand. Reduced oxygen availability is therefore an indicator of nutrient enrichment and can occur either near the seabed or in the water column. Oxygen levels are also influenced by upwellings of oceanic water and other water body mixing, stratification, and water temperature. | Instrument sensor most commonly.<br><br>Biological oxygen demand can also be measured from discrete water samples (Maxey et al. 2016). |
| Water clarity (e.g. turbidity, Secchi depth) | Provides information on suspended particulate material increases around the farm, or reductions in water clarity. Turbidity is the inverse of, and thus a proxy for, water clarity. It is assessed via an optical sensor that measures scatter from particles in the water. Turbidity is not the most reliable indicator in many systems due to the complex nature of particulates in the water column. Secchi depth is a measure of visibility distance in the water, and while a quantitative measure, it is more simplistic than turbidity. | Secchi disc (Secchi depth), nephelometer (turbidity), remote sensing (Giles et al. 2021). |

| Indicators | Information provided | Collection method/s |
|---|---|---|
| **Nutrients** | **Nitrogen is the key nutrient of concern from fish farms, but phosphorus and silicate are also potentially important for phytoplankton growth dynamics. Dissolved nutrients are the main indicators, but particulate nutrients can also provide useful information.** | |
| Total nitrogen (TN) | All nitrogen, dissolved and particulate. | Measured from discrete water samples; sample water is either filtered (for dissolved) or unfiltered (includes particulate and total forms), before being frozen, or chilled for same-day analysis.<br><br>Auto-analysers and sensors are available for some forms of dissolved nitrogen (Strain et al. 2023). |
| Particulate nitrogen and carbon (PN, PC) | Sourced from feed/faeces, and organic forms are an indicator of system productivity (Table 3). | |
| Dissolved inorganic N<br>N Kjeldahl (organic N + ammonia)<br>Ammonium ($NH_4^+$) and urea<br>Nitrate ($NO_3^-$)<br>Nitrate/ nitrite ($NO_x$) | Ammonium and urea are directly excreted by farmed fish. While ammonium has many other sources in the marine environment (e.g. shellfish farming), urea has relatively few. What is not taken up by phytoplankton is converted to nitrate-N/nitrite-N (which are in a constant state of flux). Nitrate may be taken up by phytoplankton or denitrified and lost from the system on timescales of days to weeks. | |
| Phosphorus and silicate<br>Total phosphorus (TP)<br>Dissolved reactive phosphorus (DRP)<br>Dissolved reactive silicate (DRSi) | Phytoplankton use dissolved phosphorus (DRP) for growth and dissolved reactive silicate (DRSi) is used by diatom phytoplankton. Shifts in ratios of available P, Si and N may also alter phytoplankton composition, e.g. Si limitation favours dinoflagellate growth. In some systems, P can be limited, in which case sustained enhancement of P may cause algal proliferation. | |

A generalised overview of indicators is provided in Appendix 4 of Elvines et al. (2019), to which readers are referred for further information. Further evaluation of data collection techniques in Tasmania is provided in Strain et al. (2023).

## Table 3: Overview of biological indicators for assessing finfish aquaculture interactions with the water column

A generalised overview of indicators is provided in Appendix 4 of Elvines et al. (2019), to which readers are referred for further information. Further evaluation of data collection techniques in Tasmania is provided in Strain et al. (2023).

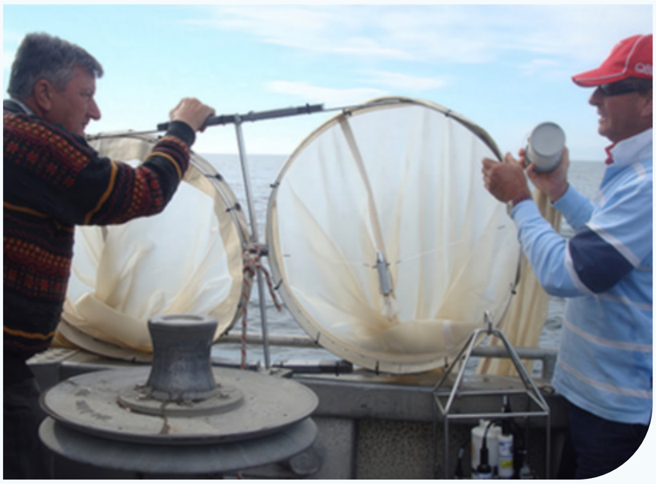
| Indicators | Information provided | Collection method/s |
|---|---|---|
| **Biological indicators** | **Biological measures include indicators of phytoplankton community biomass and composition, and can also include other components of plankton (e.g. zooplankton, microbes)** | |
| Chlorophyll-a (Chl a) | Chlorophyll a provides a proxy for phytoplankton biomass and primary production. Chlorophyll a is a key indicator of nutrient enrichment. | Measured from discrete water samples or inferred from fluorescence (using a fluorometer or from remote-sensing e.g. satellite data; Giles et al. 2021, Strain et al. 2023). The latter two methods often require calibration with water sample measurements. Water samples must be kept in the dark to prevent photosynthesis. |
| Phytoplankton communities | Phytoplankton community composition/ abundance can be determined by cell counts, and whilst not all species are identified, the major taxonomic groups (e.g. diatoms and dinoflagellates) or species of interest (e.g. those that are potentially toxic) may be determined by microscopy. Phytoplankton analyses are generally repeated over seasonal cycles and compared to reference stations. | Measured from discrete water samples via microscopic analysis.<br><br>Can also be analysed through automated techniques such as flow cytometry (Kolb et al. 2016) and molecular analysis (UNESCO 2010), although method development may be required depending on resolution and species information requirements. |
| Zooplankton communities | Although not routinely monitored, zooplankton may also be studied to examine trophic effects from nutrient enrichment. Dominant zooplankton groups within Tasmanian waters include copepods, euphausiids and gelatinous species (Swadling et al. 2017). | Measured through microscopic analysis of water samples or captured in plankton nets. |
| Particulate (organic) N and C (PN/ PON, PC/POC) | Can be a useful measurement of system productivity. In water samples, measured particulate organic N and C includes phytoplankton and zooplankton. | Particulate nitrogen and carbon are measured from filters, following sample filtration. |

## Figure 3: Equipment used for monitoring of the water column across field and laboratory

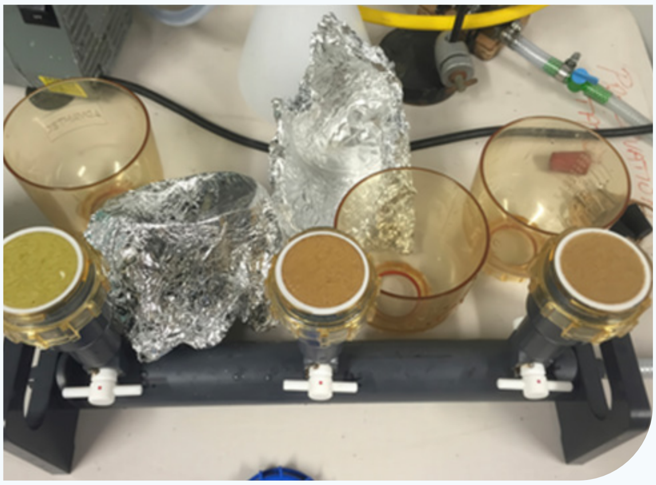
(a) CTD profiling instrument, dissolved oxygen sensor (attached to left side of steel frame) and Niskin rosette used to collect water samples (attached to right side of steel frame)

(b) preparation of syringe to filter particulates from raw water samples prior to analysis of soluble nutrients

(c) Lund tube for collecting depth-integrated water samples from the surface



(d) plankton tow-net



(e) vacuum filtering system, with sample funnels removed to show particulate residues on the filters following raw water sample filtration

## 4.2 Monitoring design

Quantifying water column interactions is largely dependent on the purpose of the monitoring and can comprise a range of survey designs depending on the system and question/s of interest. Quantifying the local (lease) scale effects of finfish wastes on water quality is complex due to the highly dynamic nature of the water column, with tides, currents, waves and mixing rates influencing the dispersion, accumulation and biological uptake of nutrients. As such, the timing and location of sampling is a critical consideration given that factors like the stage of tide will influence the direction and dilution of any finfish waste in the water column. Consistency in sampling is vital to eliminate as much variability as possible from results. In areas of high tidal currents, the water column is best sampled at slack water as this is likely to quantify the 'worst-case' nutrient concentrations, due to low water movement around the farm. However, capturing the spatial extent of a 'direct effect' footprint is more effective when sampling occurs during a running tide. Trackable additives such as a marker dye which can be measured using an optical sensor may be used to understand spatial footprints (Elvines et al. 2019). Similarly, some parameters (e.g. phytoplankton biomass) appear to be more affected by diurnal patterns than others; understanding fluctuations in the parameters of interest is key to assessing the sources of variation in subsequent data (Strain et al. 2023). The ability to detect nutrient plumes from fish farms is also likely influenced by the timing of feeding (Pitta et al. 2006, Jansen et al. 2016, Elvines et al. 2019). Careful planning is required when designing sampling programs given that both the episodic nature of farm inputs (i.e. timing of feeding) and the highly dynamic nature of the water column environment will influence the sensitivity and power of sampling techniques to detect changes in response to farming (Jansen et al. 2016, Strain et al. 2023).

The advent of *in situ* real-time moored sensor systems provides a more sensitive technique, but there are challenges in capturing spatial patterns given the costs in replicating these systems. There are also limits as to what parameters can be measured accurately with sensors/probes, so their application depends on the key response parameter of interest. For example, in Macquarie Harbour where DO concentrations are the principal concern, automated sensor networks are used extensively, along with sensors mounted on Autonomous Underwater Vehicle (AUV) platforms, as DO is readily measured using sensors (Revill et al. 2018). Conversely, sensor technology for measuring dissolved nutrient concentrations and phytoplankton biomass is presently limited and/or challenging to calibrate (Table 2, Table 3). In southeast Tasmania, high resolution nutrient mapping has been successfully trialled across successive research projects (Ross et al. 2021, Strain et al. 2023) using a vessel-based automated inline sampling system. This method successfully mapped highly labile forms of inorganic nitrogen. Rather than forming part of more regular monitoring, the research recommended that inline sampling should be considered when there is a clear need to document the spatial footprint of ammonium and nitrate + nitrite (NOx), such as when farming is commencing in a new environment, when there are major changes in production levels or when further investigation of the water column is required due to exceedances.


Given the challenges of capturing the local (lease) scale footprint, the main focus of monitoring water quality interactions is generally to capture the potential for cumulative impacts at the broadscale (DPIPWE 2013, DPIPWE 2015, Aquenal 2018, Elvines et al. 2019). Hydrodynamic and biogeochemical models often play an important role in informing the most effective sampling design (e.g. sample station placement; Elvines et al. 2019, Wild-Allen et al. 2020, Strain et al. 2023). A typical monitoring program would routinely comprise intensive temporal (e.g. monthly) sampling at stations dispersed across a broad (regional) spatial scale (Elvines et al. 2019, Ross & Macleod 2013).

In Tasmania, baseline surveys of water quality have historically not been a requirement prior to the commencement of marine farming activities, however, water quality monitoring data has typically been collected by the proponents prior to farming in most growing regions. Under the new Environmental Standards (DNRET 2023), water quality surveys are now required as part of baseline environmental assessments. Once farming commences, environmental licences now require monitoring of water quality at sites encompassing the region as part of a Broadscale Environmental Monitoring Program (BEMP).

# 5 Summary

**Finfish aquaculture can have direct effects on the water column, potentially altering the physico-chemical environment, nutrient regimes and primary productivity of these systems.**

- Open cage finfish farming in coastal waters has the potential to influence water quality with flow-on effects to connected food webs and ecosystems.
- A key effect of finfish aquaculture on water quality is the increase in dissolved nitrogen excreted as metabolic by-products from fish. This can influence system biochemistry and water column productivity, with potential flow-on effects up the food chain. If poorly managed, nutrient enrichment can lead to eutrophication.
- The level of change or severity of these interactions is related to the dispersal and assimilative capacity of local environments as well as farm management practices.
- Finfish farms can also affect oxygen levels, directly via fish respiration, or through oxygen consumption during decomposition of particulate wastes and dieback of stimulated growth from nutrient enrichment. Reduced oxygen levels can have detrimental effects to the local pelagic ecosystem, especially in poorly flushed or stratified environments.
- Key aspects of managing these ecological risks include well-sited farming locations and site-appropriate production levels, together with environmental monitoring to track water quality and ecosystem health. Environmental baseline data and numerical modelling feed into all these management aspects.
- Risks to the marine environment are reduced in more exposed, well-mixed coastal areas with high currents, mixing and flushing rates, and where production (and allowable nutrient outputs) are set at levels below the assimilative capacity of the receiving system.
- Monitoring of water quality plays an important role in tracking regional water quality health and provides early warning signs of undesirable change. When water column conditions become undesirable, certain management actions, such as reductions in feed input or limitations to biomass, may be required to mitigate effects.

# 6 Glossary and acronyms

### Bacterioplankton

The bacterial component of planktonic communities.

### Broadscale Environmental Monitoring Program (BEMP)

A monitoring program within Tasmania to understand potential aquaculture effects within a larger spatial context.

### Biological oxygen demand (BOD)

The amount of oxygen consumed by aerobic breakdown of organic material present in a water sample at a specific temperature over a specific time period. Synonymous with biochemical oxygen demand.

### Chlorophyll

Green pigment found in plants and algae. Chlorophyll *a* refers to a specific chlorophyll used in oxygenic photosynthesis.

### Conductivity, Temperature and Depth (CTD)

Used to measure the physical properties of seawater.

### Default guideline values (DGV)

Values for certain environmental parameters (in this case, water quality indicators) developed under the ANZG (2018) framework as part of the National Water Quality Management Strategy to aid management and protection, in this case, of coastal marine waters.

### Dissolved Inorganic Nitrogen (DIN)

Nitrate, nitrite and ammonium/ammonia.

### Dissolved oxygen (DO)

Oxygen dissolved within the water, measured either as an absolute amount (mg/L), or as percent saturation (with 100% being a fully saturated state). The amount of dissolved oxygen that a water body can hold changes with physical conditions such as temperature.

### Environmental Licence

Environmental licenses to operate salmon farms in Tasmania are issued by the Environment Protection Authority under the *Environmental Management and Pollution Control Act 1994*.

### Environment Protection Authority (EPA)

Tasmania's principal environmental regulatory body established as an independent statutory authority under the *Environmental Management and Pollution Control Act 1994*.

### Eutrophication

The enrichment of a body of water by increased nutrient levels resulting in ecosystem change, including excessive algae growth and other deteriorations in water quality. Eutrophication events occur both naturally and from anthropogenic inputs. 'Eutrophic' is used to refer to high nutrient environments, while 'oligotrophic' refers to low nutrient environments. Mesotrophic is a state between these two extremes.

### Harmful algal bloom (HAB)

Algal blooms harmful to aquatic systems e.g. species that reduce oxygen levels or produce toxins with harmful ecological effects.

### Hydrodynamics

Movement of fluids (in this context, seawater) within a system that might be affected by natural forces.

### Lease area

An area of water contractually allocated to a marine farming operator by the Tasmanian Government.

### Marine Farming Development Plan (MFDP)

Is prepared and approved under the *Marine Farming Planning Act 1995* and is designed to integrate marine farming activities with other marine and land uses, while minimising adverse impacts.

### Photic zone

The area within the pelagic zone which receives enough light for photosynthesis to take place. The depth of the photic zone depends on turbidity and light levels but is normally the top 200 m of the water column.

### Phytoplankton

Photosynthetic single-celled algae, that are mainly microscopic, are the autotrophic component of the plankton community and a key part of marine and freshwater ecosystems.

### Stratification

Layering of the water column because of density differences between the surface and the seabed associated with temperature and salinity.

### Total Permissible Dissolved Nitrogen Output (TPDNO)

A regulatory metric which limits the amount of dissolved inorganic nitrogen that can be released via feed inputs into a defined area over a specified time. The TPDNO is based on estimated dissolved nitrogen released through waste outputs from farmed fish (EPA 2022).

### Turbidity

The inverse of water transparency, used as a proxy for how clear (or transparent) the water is. Is determined by measuring optical scatter from particles within the water column.

### Zooplankton

The heterotrophic component of the planktonic ecosystem. These are generally small, drifting animals or animal-like organisms that feed on other plankton, including phytoplankton.

Image: Anita Slotwinski

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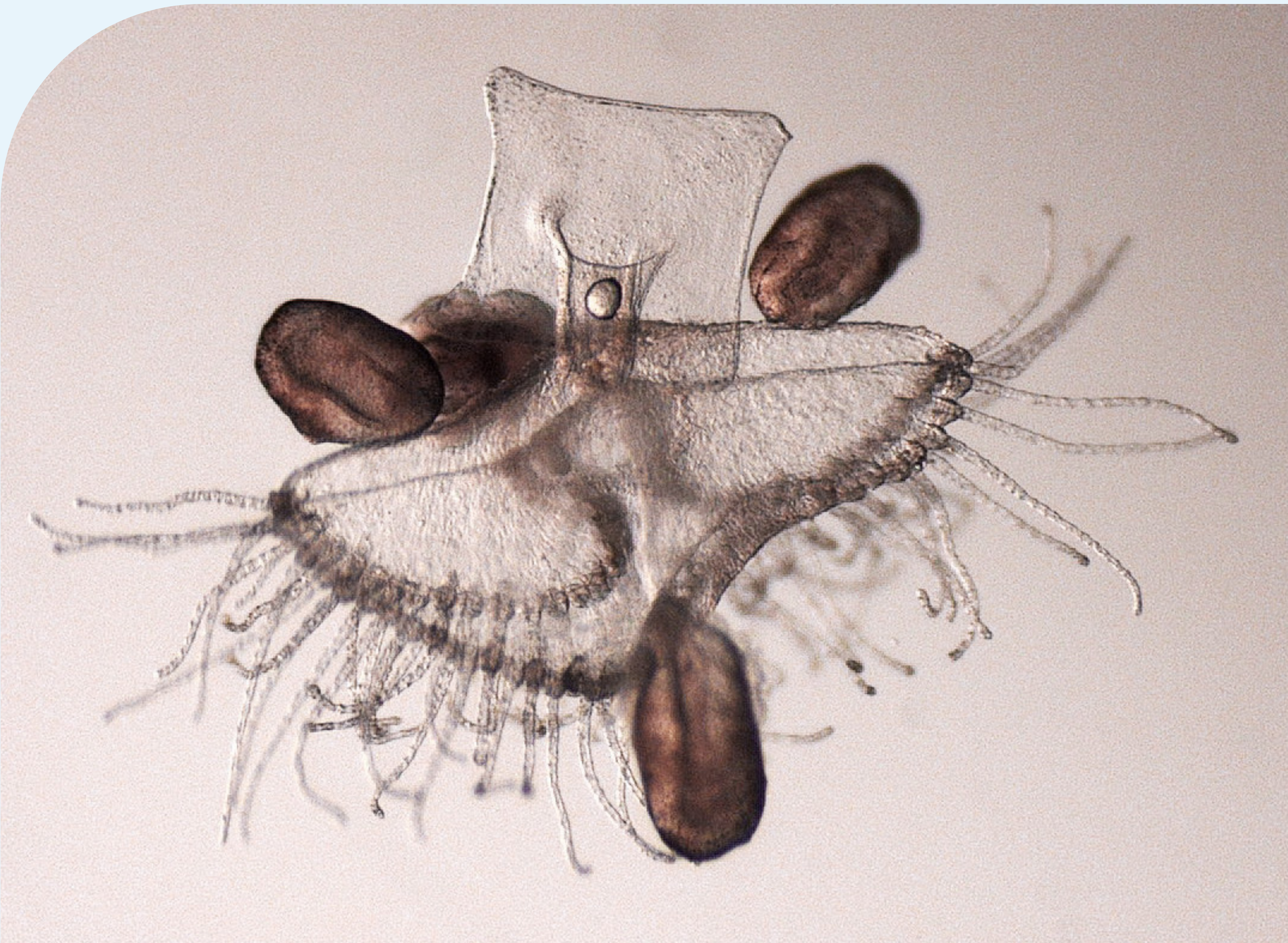

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