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# Hypoxic events in freshwater ecosystems: A literature review to inform regional management and policy

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# Acknowledgements

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# Abstract

Dissolved oxygen (DO) is a master variable that fundamentally controls the ecological quality of freshwaters and their associated capacity to support aquatic life, potable water uses, and cultural values. The perennial or periodic occurrence of low DO concentrations (hypoxia) or complete depletion of DO (anoxia) is a natural feature of some aquatic ecosystems such as wetlands. However, anthropogenically mediated increases to the magnitude, frequency, duration, and spatial extent of hypoxia in aquatic ecosystems such as lakes and rivers can have major adverse ecological effects, including fish kills. Developing effective tools and strategies to manage hypoxia in the region's freshwaters has been identified as a priority by Waikato Regional Council. This literature review considers causes, effects, forecasting approaches, and mitigation of hypoxia in lakes, streams, and rivers worldwide to inform regional policy and management by synthesising lessons from elsewhere in the context of the Waikato.

Key controls and drivers of hypoxia (Section 2) are described to inform understanding of key causes of hypoxic events. Many of these drivers are intrinsically linked to land-use intensification, which is associated with eutrophication and hydrological modification. Additionally, climate change is a key driver that is likely to exacerbate hypoxic events in the Waikato region due to increased water temperatures and reduced flows during droughts, as well as due to floods that inundate floodplains and associated stores of organic material that accumulate during periods of drought.

The potential effects of hypoxic events on freshwater ecosystems (Section 3) are summarised, including physiological and behavioural effects on fish and invertebrates. Broader impacts to aquatic ecosystems due to hypoxia can occur such as adverse effects on water chemistry, including increased concentrations of dissolved metals and nutrients. Restoring degraded aquatic ecosystems that have shifted to a state with frequent hypoxia can be challenging, with long recovery timelines likely, e.g., decades for estuarine systems.

Modelling approaches to forecast hypoxic events are reviewed and their applicability to the Waikato region is considered (Section 4). Broadly, modelling approaches are categorized as 1) regression-based approaches, 2) process-based simulation models, and 3) machine learning and artificial intelligence approaches.

The first category of models (regression-based approaches) comprises relatively simple empirical models to predict hypoxia characteristics based on system-specific relationships. Examples are regression models used to predict summer anoxic volume in estuaries based on total nitrogen loads in spring. Disadvantages of such models include that suitable predictions can only be made within the ranges of observed data and at low spatiotemporal resolution.

The second category of models (process-based simulation models) comprises models that include mathematical descriptions of key processes that control DO. These models are generally less suitable than the other model categories for routine forecasting; however, such tools can be valuable to inform planning based on scenario analysis, e.g., to evaluate the effects of hypothetical management interventions or land-use changes. Several process-based modelling systems have been developed, most notably in Australia, to simulate hypoxic events in forested floodplains and connected wetlands alongside large rivers. With sufficient effort allocated to model development, such conceptual approaches could theoretically be applied in regions such as the lower Waikato River floodplain.

The third category (machine learning and artificial intelligence approaches) holds greatest promise as a tool to forecast hypoxic events in the short (hours to days) to medium (weeks to months) term to inform management. Such approaches could be applied to develop forecasts based on existing high-frequency monitoring of variables such as antecedent DO concentrations, specific conductivity, water temperature, stage, and precipitation. Approaches to forecast DO that are based on machine learning and artificial intelligence have been developed and applied in several jurisdictions worldwide; however, it is not clear that such approaches are yet being routinely used by managers as part of day-to-day operations.

Finally, mitigation options are reviewed (Section 5). The basis for mitigation options to directly manage hypoxia is either to physically increase aeration, augment hypoxic water with water of better quality, or to manage floodplain inundation to isolate hypoxic water from the most sensitive habitats and/or limit the accumulation of organic material on floodplains. Again, research has been particularly active in Australia, notably the Murray-Darling catchment. There, a range of methods has been applied to mitigate the risks of hypoxic 'blackwater' events caused by inundation of floodplains and associated accumulated organic matter, causing rapid oxygen consumption and hypoxia. Pending assessment of environmental and socioeconomic risks, potential options that have been successfully applied in Australia and elsewhere could be considered for lakes and rivers in the Waikato, including within the Waikato River floodplain. Such methods include using physical aerators to provide temporary refuge for sensitive fish species; managing flood/tidal gates and other regulation structures to augment hypoxic water with water of better quality; using off-channel storage to retain hypoxic water and limit ecological effects on mainstem habitats; and adaptively managing water infrastructure to control the accumulation of organic material on floodplains, while maximising lateral connectivity. Less directly, taking measures to manage eutrophication (e.g., reduce nutrient loads) or ameliorate the occurrence of high water temperatures (e.g., riparian planting) can also support with managing hypoxia risks. Confirming the feasibility of mitigation options and refining management strategies will require careful and focused planning to ensure that strategies are well-suited to the biophysical and socioeconomic characteristics of the Waikato. Strategic planning should also ensure that trade-offs among values such as environmental protection, flood risk management, cultural priorities, and interests of industries such as agriculture are appropriately considered.

# 1 Introduction

***Key Points***

- ***Dissolved oxygen (DO) refers to the amount of oxygen dissolved in water.***
- ***'Hypoxia' refers to conditions of low DO. Thresholds to define hypoxia vary and are arbitrary, although hypoxia is frequently defined as DO concentration ≤ 2 mg/L.***
- ***The aim of this literature review is to assist Waikato Regional Council with effectively managing environmental risks associated with hypoxia in lowland lakes, streams, and rivers.***

Dissolved oxygen (DO) refers to the amount of oxygen dissolved in water, measured as a concentration (mg/L) or saturation (%) relative to the amount of DO held by water in equilibrium with the atmosphere (Kalff 2002). The availability of DO is fundamentally important to the ecological and physicochemical condition of aquatic ecosystems, and is a key factor that controls the presence and distribution of aquatic life, including fish and invertebrates (Kramer 1987; Saari *et al.* 2018). Additionally, DO concentrations exert a major control on oxidation-reduction (redox) processes that govern aspects of water chemistry, such as the concentrations and forms of dissolved elements, including metals (Søndergaard 2009).

'Hypoxia' refers to conditions of low DO, whereas 'anoxia' refers to a complete absence of DO (Chapra *et al.* 2021). Various thresholds are used to define hypoxia, yet it is conventionally defined as DO ≤ 2 mg/L (Chapra *et al.* 2021). Despite this convention, thresholds at which hypoxia can cause acute physiological effects are higher for many species (Vaquer-Sunyer and Duarte 2008), including some species endemic to New Zealand (Franklin 2014). The occurrence of hypoxia or anoxia can have profound effects on aquatic ecology and water quality, e.g., by causing fish kills (Borsuk 2004). Thus, understanding, predicting, and managing occurrences of hypoxia in surface waters that are otherwise oxygenated ('hypoxic events') are important for managing freshwaters to support aquatic life, water quality, and cultural services such as the provision of *mahinga kai*.

Perennial or periodic hypoxia is a natural feature of aquatic ecosystems such as wetlands, shallow productive ponds, and hypolimnia in fjords (Rabalais *et al.* 2010; Diaz and Rosenberg 2011). However, human pressures (Section 2.2) have led to an increase in the extent and magnitude of hypoxic events (Rabalais *et al.* 2010; Jenny *et al.* 2016). As discussed in Section 2.1.2, the risk of hypoxic events is generally greatest in productive lowland waterbodies, including low-gradient streams, riverine lakes, wetlands, and agricultural drains. In the Waikato, such waterbodies are most prevalent in the floodplains of larger rivers, notably the Waikato River floodplain in the northwest of the region, which contains a network of laterally connected habitats including drains, lowland streams, wetlands, and peat and riverine lakes (Hamilton *et al.* 2010).

In the Waikato Region, several drivers (Section 2.2) have potential to increase the frequency and severity of hypoxic events, supporting an imperative to develop effective tools and strategies to manage hypoxic events in the region's freshwaters. Research and management approaches from other jurisdictions have the potential to inform environmental policy in the Waikato Region; thus, it is valuable to synthesise lessons from elsewhere in the context of the biophysical and environmental management characteristics of the Waikato to inform regional policy and management.

The aim of this literature review is to assist Waikato Regional Council with effectively managing environmental risks associated with hypoxic events. This review is applicable to freshwater ecosystems generally although, commensurate with risk, emphasis is given to considering rivers, lakes, and streams in lowland floodplain habitats such as the lower Waikato River floodplain. This review addresses the following questions in the context of freshwater ecosystems in the Waikato region:

1. What are the key causes of hypoxic events (Section 2)?
2. What are the potential effects of hypoxic events on freshwater ecosystems (Section 3)?
3. What tools are available to forecast hypoxic events and how might these be applied in the Waikato (Section 4)?
4. What options could be applied to mitigate hypoxic events (Section 5)?

# 2 Controls and Drivers of Hypoxia

***Key Points***

- ***The DO concentration in aquatic systems reflects the balance between oxygen supply and oxygen demand.***
- ***The supply of DO to fish and invertebrates is proportional to oxygen solubility, the diffusivity of oxygen in water, and oxygen partial pressure.***
- ***Key controls on DO concentration in freshwaters are reaeration (affected by water depth and turbulence), water temperature (which affects rates of biological processes and oxygen solubility), photosynthesis, respiration by organisms in the water column and benthos, and chemical oxygen demand, e.g., due to oxidation of acid sulphate soils.***
- ***The following key anthropogenic drivers of hypoxia are reviewed: climate change, eutrophication, water abstraction/diversion, deforestation and land drainage, and fire. Several of these drivers have potential to increase the frequency and severity of hypoxic events in the Waikato region.***

## 2.1 Biological and Physicochemical Controls

### 2.1.1 Theory

To understand the causes of hypoxic events, it is useful to first review the biological and physicochemical factors that control DO in aquatic systems. This context can inform the natural and anthropogenic drivers of hypoxic events (Section 2.2) that are relevant to forecasting and managing hypoxic events, including by seeking to address underlying drivers to prevent hypoxic events from occurring.

Rates of DO diffusion from the atmosphere to water are low, presenting a challenge to aquatic organisms that require oxygen for respiration, in contrast to terrestrial environments where oxygen diffuses rapidly in air (Kramer 1987). As summarised by Franklin (2014), changes in DO concentrations in time (ΔDO/At) can be described as follows:

$$\frac{\Delta \mathrm{DO}}{\Delta \mathrm{t}} = k_1(DO_{sat} - DO) + (photosynthesis - respiration) - BOD \quad \text{Eq. 1}$$

where $k_1$ is the reaeration coefficient (units of 1/t); $DO_{sat}$ is the temperature-dependent saturation concentration of DO (mg/L); $photosynthesis$ and $respiration$ can be quantified with units mg $O_2$/L/t, and; $BOD$ is biochemical oxygen demand (mg $O_2$/L/t). Thus, based on Eq. 1, key factors that affect DO are water depth and turbulence (which affect reaeration), water temperature, plant biomass (which affects photosynthesis and respiration by primary producers), organic matter content, which affects the rate of respiration by microbial decomposers, and biochemical reactions such as nitrification. More broadly, the main sources of DO to a waterbody are 1) reaeration from the atmosphere (which can be enhanced at structures such as weirs that promote water turbulence), 2) photosynthesis, and 3) DO introduced from sources such as tributaries (Cox 2003a). Conversely, the main DO sinks (loss terms) are 1) oxidation of organic material and other reduced substances in the water column, 2) degassing of DO in supersaturated water, 3) respiration by plants and other organisms, and 4) the biochemical oxygen demand of benthic sediments (Cox 2003a).

Thus, the DO concentration in aquatic systems reflects the balance between oxygen supply and oxygen demand, with water temperature a key influencing factor. As is common in aquatic ecology, DO concentration is used in this report to describe the availability of DO to aquatic organisms. However, more precisely, the supply of DO to aquatic ectotherms such as fish and invertebrates is proportional to oxygen solubility (which decreases with increasing temperature (Figure 1) and to a lesser extent salinity, but is invariant to altitude), the diffusivity of oxygen in water, and oxygen partial pressure (which is invariant with temperature but decreases with altitude) (Verberk *et al.* 2011). These nuances can lead to non-intuitive implications, e.g., invertebrates in high-altitude streams (not necessarily applicable to the Waikato) can be more sensitive to DO deficiency than the typically cool and turbulent characteristics would otherwise suggest (Jacobsen *et al.* 2003). Similary, the supply of oxygen to organisms in warm environments at low altitudes may be higher than in cooler waters at higher altitudes with higher DO concentrations (Verberk *et al.* 2011). Despite these details, DO concentration is a key factor that controls habitat quality for aquatic life (Franklin 2014), although these ecophysiological considerations partly explain why criteria based on DO concentrations can only provide an indication of impacts to aquatic life.

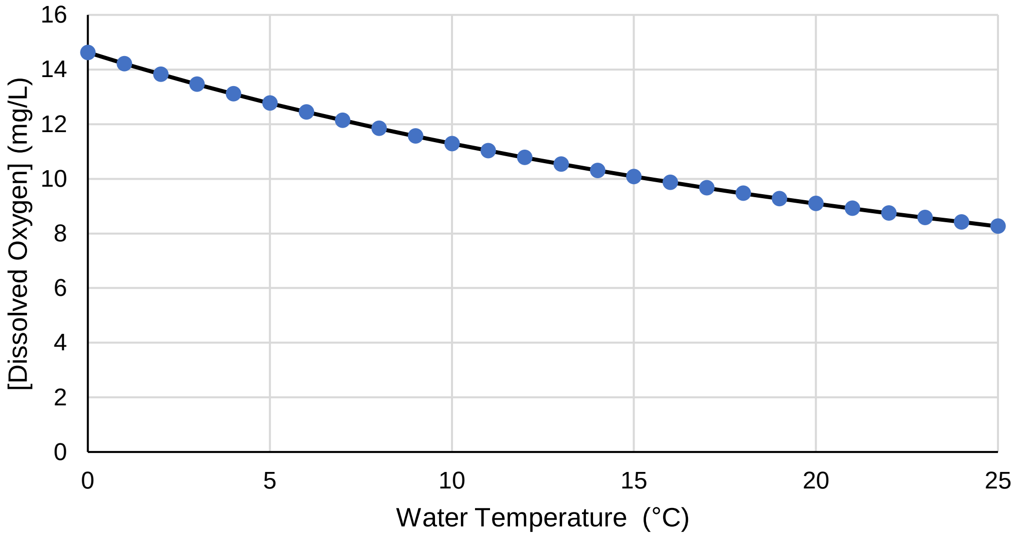

**Figure 1.** **Relationship between dissolved oxygen concentration and water temperature in freshwater, assuming 100% saturation. The relationship is based on equation 19.32 presented by Chapra (2014), sourced from APHA (1999).**

### 2.1.2 Relative Influence of Factors that Control Dissolved Oxygen

Based on studying streams in temperate USA, Garvey *et al.* (2007) proposed a hierarchy of key factors that control DO dynamics in streams (Figure 2). Season provides an overarching control on DO, principally due to the effect of season on temperature, which in turn affects oxygen solubility (Figure 1), photosynthesis by primary producers, and respiration by autotrophs. Seasonal changes to light availability can also exert a major control on stream metabolism at higher latitudes (Bernhardt *et al.* 2022).

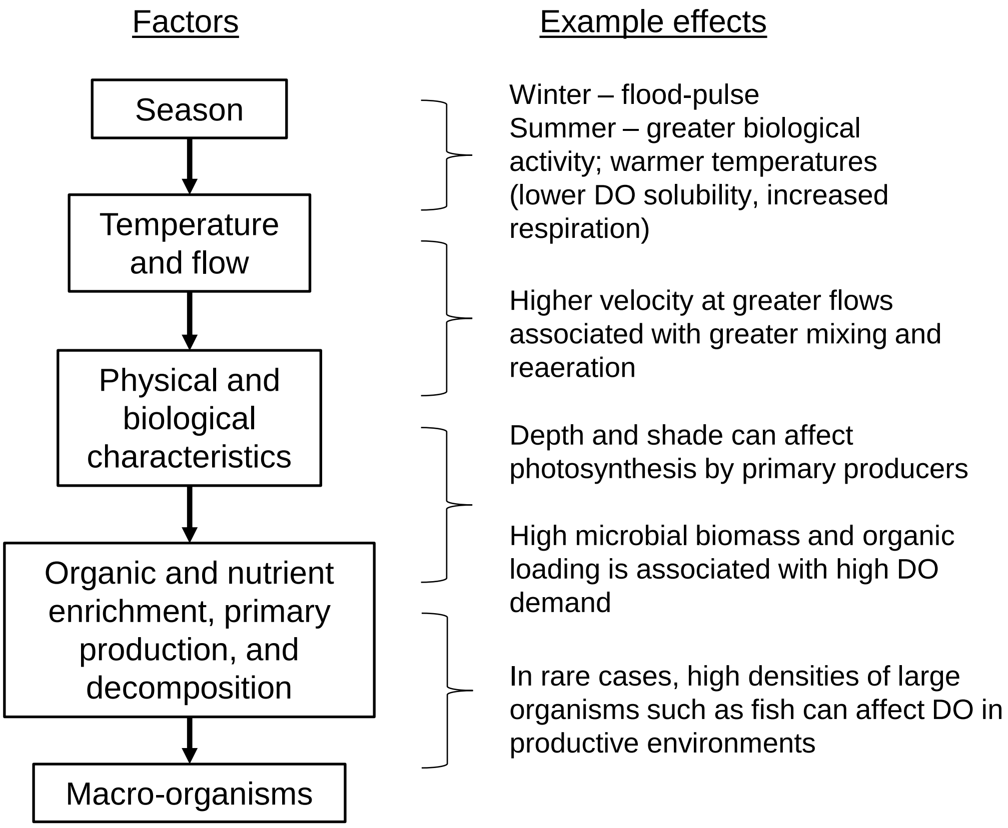

**Figure 2. Key factors that affect dissolved oxygen (DO) in freshwaters. Redrawn with modifications from Garvey *et al.* (2007).**

Changes in rates of photosynthesis and respiration (by fauna and plants) throughout the day contribute to diurnal fluctuations in DO, which mean that DO measurements are sensitive to the time of day when sampling occurs, underscoring the value of collecting near-continuous measurements using in situ sensors. Blaszczak *et al.* (2023) conducted a global review of hypoxia in rivers in 93 countries. The authors showed that infrequent hypoxia in rivers is more common than had been assumed prior to more widespread collection of high frequency data using sensors, with the most frequent duration of hypoxia being 1–6 hours, and maximum water temperature the best predictor of hypoxia of the 13 predictor variables analysed. Based on their analysis, the start of hypoxic conditions most frequently occurs between 05:00 h and 08:00 h at the end of night-time when photosynthesis does not occur, whereas the end of hypoxic conditions most frequently occurs between 13:00 h and 15:00 h when photosynthetic rates are generally maximal. In coastal areas, tidal intrusion of estuarine water with variable DO concentrations can also contribute to diurnal fluctuations in DO concentration, particularly in low gradient streams where the spatial extent of the tidal influence is greatest and reaeration rates are low (Wilding *et al.* 2012). In lakes, diurnal changes in DO concentrations of several mg/L in the surface mixed layer can occur due to factors such as solar heating, reaeration caused by wind, and phytoplankton photosynthesis, with diurnal variability greatest in shallow productive lakes (Tasnim *et al.* 2021).

After season, water temperature and flow condition (Figure 2) were the second-most important factors that control riverine DO conditions, based on Garvey *et al.* (2007; although it is recognised that water temperature and flow typically covary with season). Increased water temperatures increase metabolic oxygen demand and respiration (Kalff 2002), as well as reduce oxygen solubility (Figure 1), whereas flow conditions exert an important control on reaeration in streams (Eq. 1). When considering the relationship between discharge and reaeration, it is necessary to recognise the different influences of depth and velocity, i.e., reaeration from turbulent mixing generally increases with velocity but decreases with depth (Cox 2003a). This relationship means that, for rivers with equivalent discharge, reaeration is typically higher in shallow fast-flowing rivers, than in deep, slow rivers, e.g. low gradient or many impounded rivers.

High gradient streams with high velocity and turbulent flow rarely experience hypoxia due to high reaeration rates (Garvey *et al.* 2007). By contrast, hypoxia is more prevalent in low gradient and low velocity streams, e.g., a study of 78 sites in eight catchments in France showed that hypoxia was most likely to occur in streams with low gradient during periods of high temperature and low flow (Diamond *et al.* 2023). Streams with low gradient and low velocity are abundant in lowland areas of the Waikato such as the Waikato River floodplain, where the presence of streams that flow into and from riverine lakes presents added complexity, meaning that DO conditions in many waterways in the floodplain can be influenced by processes in a combination of lotic and lentic ecosystems upstream. The role of stream gradient was further elucidated by Blaszczak *et al.* (2023), who showed that the probability of riverine hypoxia increased with increasing temperature, yet the probability was highest overall in low gradient streams and lowest in high gradient streams. Furthermore, Blaszczak *et al.* (2023) showed that these relationships were moderated by river size (the probability of hypoxia decreased with increasing river size), meaning that the probability of hypoxia was greatest overall in small low-gradient rivers with high temperatures, and lowest overall in large high-gradient rivers with low temperatures.

Temperature and flow can further interact with other physical (e.g., depth) and biological (e.g., plant community) stream characteristics (Figure 2) that can affect DO via processes such as photosynthesis and respiration. In terms of respiration, plankton and microorganisms in the sediment exert the most important controls on DO (Miranda *et al.* 2001), most notably in lakes, where decomposition of organic matter in benthic and suspended sediments in bottom waters (hypolimnia) causes oxygen depletion during stratified periods in all but the least productive lakes (Viner 1989; Burns 1995). For a given physical stream template, variability in loading of inorganic nutrients and organic carbon can strongly affect DO dynamics (Figure 2). Inorganic nutrients can stimulate primary productivity (increasing diel variability in DO) and additions of inorganic nitrogen (ammonium and nitrite) can cause oxygen depletion due to nitrification, while organic carbon addition promotes respiration by heterotrophs (Chapra 2014). Notably, episodic high loading of organic material to lowland rivers caused by direct transport of organic material to the river in floodwater, or due to pooling of floodwater in the floodplain and associated plant senescence, can cause a type of hypoxic event termed a ‘blackwater event’ (Kerr *et al.* 2013). Such events occur naturally in some systems, although intensive land management practices, hydrological modification , and climate change can increase the risk of blackwater events (Whitworth *et al.* 2012; Kerr *et al.* 2013). For example, increased air temperatures are associated with increases to the rate at which hypoxia develops when pasture is flooded (Vithana *et al.* 2019). Furthermore, hypoxic blackwater events are associated with long periods of inundation during warm periods that occur after a prolonged period of dry conditions that allows organic carbon to accumulate on the floodplain (Howitt *et al.* 2007; Kerr *et al.* 2013). Drivers of blackwater events are considered further in Section 2.2 below.

Prior to anthropogenic land drainage, it is likely that periodic wetting and drying throughout floodplain habitats would have naturally affected aquatic DO concentrations in lowland areas of the Waikato region due to variable fluxes of dissolved organic carbon (DOC) from intermittently flooded floodplain habitats. Such lowland floodplain habitats are abundant in the northern part of the region, where gently sloped catchments drain to the lower Waikato River and connected waterbodies such as riverine lakes, which can be particularly susceptible to hypoxia due to high organic matter loading. Fluxes of organic material are affected by background variability in soil organic content and the Waikato has some of the largest areas of organic soils nationally (Hewitt *et al.* 2021). Drainage from peatlands such as those at Kopuatai and Whangamarino wetlands contains high concentrations of DOC (Moore and Clarkson 2007), which can increase DO consumption in association with respiration of DOC by microorganisms (Rixen *et al.* 2010; Dalzell *et al.* 2011). Thus, inundation of peat soils by floodwaters that subseqently become hypoxic and drain to freshwaters presents a particular challenge for feshwater management in the Waikato. This challenge has implications for restoration projects. Increasing floodplain connectivity is a priority for the river restoration community in New Zealand due to the range of associated ecological benefits (Abell *et al.* 2023); however, the potential for increases to lateral connectivity in floodplains to increase the risk of blackwater events needs to be considered during restoration planning, as considered further in Section 5. Another soil characteristics that can influence background spatial variability in oxygen demand is the presence of acid sulphate soils in some parts of the Waikato (Lee *et al.* 1987), which can exacerbate oxygen consumption due to pyrite oxidation (Bronswijk *et al.* 1993).

Finally, large-bodied animals increase biological oxygen demand via respiration. However, it is unusual for the density of macro-organisms to be sufficiently high to cause measurable effects on DO, and therefore this factor is only influential in rare cases, such as where there are dense proliferations of invasive mussels (Garvey *et al.* 2007) or spawning salmon (Sergeant *et al.* 2023). In the Waikato, high densities of invasive cyprinid fish in some eutrophic lakes (Tempero *et al.* 2019) will add to the biological oxygen demand, although associated effects on DO are likely to be minor compared to the sediment oxygen demand associated with organic sediments in productive waterbodies.

## 2.2 Anthropogenic Drivers of Hypoxic Events

Multiple anthropogenic drivers interact with the factors described above to affect the frequency, duration, and magnitude of hypoxic events in freshwaters, as described in Table 1 and shown on Figure 3. Most of the anthropogenic drivers in Table 1 are intrinsically linked to urbanisation and agricultural land-use intensification, which are associated with impairment of water quality generally, including increased DO demand (Prasad *et al.* 2014; Larned *et al.* 2020). Eutrophication is likely to have been a key driver of hypoxic events in the Waikato in the period since extensive land development has occurred, although increased water temperatures and possibly flooding associated with climate change may become increasingly influential in the future. Drivers may act synergistically, e.g., water abstraction may interact with increased water temperatures associated with climate change to exacerbate the potential for hypoxic events in the region during the summer.

As discussed further in Section 4, models can be valuable for parsing the influence of individual anthropogenic drivers, and for predicting how changes in key drivers could affect hypoxic event characteristics in the future. For example, Lajaunie-Salla *et al.* (2018) used a three-dimensional hydro-biogeochemical model to examine the effects of four potential drivers of hypoxia in the tidal reach of the Garonne River (France) over the remainder of this century. Increased water temperature, decreased summer flow, and increased population were all predicted to exacerbate hypoxia during at least certain times of the year, although sea level rise (hypothesised to increase oxygen consumption in submerged tidal flats) had no clear effect on hypoxia in model simulations.

Globally, there is evidence that the frequency and magnitude of hypoxic events is increasing in lakes (Carey 2023), but not necessarily in river systems (Blaszczak *et al.* 2023). This discrepancy may reflect that lakes are more susceptible to hypoxia due to reduced mixing of bottom waters during stratification, lower reaeration rates, and potentially greater within-system (autochthonous) phytoplankton growth that provides a source of labile carbon to fuel respiration by bacteria (Jane *et al.* 2021). Note though that these characteristics of lakes overlap with those of large river systems, which can similarly stratify temporarily, experience low reaeration rates, and exhibit high autochthonous production (including from rooted macrophytes) that contributes to oxygen consumption following plant senescence.

**Table 1. Key anthropogenic drivers of hypoxic events in freshwaters.**

| Driver | Description | Relevance to the Waikato |
|---|---|---|
| Climate change | Increased water temperature can increase rates of primary productivity, respiration, and decomposition, thus increasing diel variability in dissolved oxygen (DO) (Kalff 2002; Rabalais *et al.* 2010). On balance, the rate of increase in DO consumption with increasing temperature is greater than that of DO reaeration processes, causing the net result that warmer water is less able to assimilate inputs of organic material (Chapra *et al.* 2021).<br>Heavy rainfall that causes inundation of floodplains can be a major driver of hypoxic events, particularly in floodplains that are forested or have extensive wetlands, and therefore contain large quantities of organic material (Kerr *et al.* 2013). Floodwaters and associated organic matter can then drain to connected waterbodies, causing hypoxic events. Storm events can also cause direct influx to surface waters of organic material and groundwater with low DO, whereas drying and rewetting events associated with greater hydrological extremes can exacerbate hypoxia (Whitworth *et al.* 2014; Leigh *et al.* 2015; Diamond *et al.* 2023). Conversely, droughts can increase the availability of litter on floodplains, exacerbating blackwater events during subsequent flooding (Kerr *et al.* 2013).<br>In lakes, increased water temperatures prolong and strengthen stratification, causing greater DO consumption in bottom waters (Woolway *et al.* 2021). | Air temperatures are projected to increase in the Waikato, e.g., annual mean temperatures are projected to be 0.7–1.1°C warmer by 2040 than in 1995 (Ministry for the Environment 2018). Warmer temperatures are likely to cause more persistent thermal stratification in lakes in the summer, including in lowland riverine and peat lakes connected to the Waikato River.<br>Changes to the frequency of storms are expected to be small relative to interannual variability, although some increase in storm intensity is predicted (Ministry for the Environment 2018). |
| Eutrophication | Inputs of nutrients promote aquatic productivity, increasing diel variations in DO concentrations and the potential for hypoxia in areas where respiration and decomposition processes dominate, supported by carbon associated with increased primary producer biomass (Carpenter *et al.* 1998; Mallin *et al.* 2006; Rixen *et al.* 2010). Consequently, eutrophication associated with increased anthropogenic pressure has been identified as the main driver of hypoxia in freshwater ecosystems over the last 300 years (Jenny *et al.* 2016). | Eutrophication associated with agricultural land-use intensification has been a key cause of water quality decline in the Waikato Region (Chapman 1996; Collier *et al.* 2019). Addressing water quality degradation has been a focus for managers in the region, although ongoing eutrophication is still a concern, and a particular challenge is to address eutrophication in shallow lakes partly caused by internal cycling of legacy nutrients associated with historical loading from the catchment (Hamilton *et al.* 2010). |

| Driver | Description | Relevance to the Waikato |
|---|---|---|
| | Eutrophication and climate change can act synergistically to exacerbate hypoxia, particularly in lakes (Me *et al.* 2018). | Managing loads of organic matter and nutrients from urban areas is likely to be an increasing concern as urbanisation continues in the region. |
| Water abstraction/ diversion | Reduction of flow due to water use or water storage can exacerbate hypoxia by reducing reaeration rates and increasing DO consumption due to longer water residence time (Pardo and García 2016). Reduced flows can also promote thermal stratification in river pools (Buxton *et al.* 2022), exacerbating hypoxia in isolated bottom waters. | Water abstraction and diversion is widespread in the Waikato (Chapman 1996). Stopbanks in the Waikato River floodplain can exacerbate hypoxia by holding water on the floodplain before it is returned to the mainstem (Pingram *et al.* 2021).The potential for increased drought risk (Ministry for the Environment 2018; Bevans and Koh 2022) and greater water demand associated with urbanisation and agriculture potentially mean that hypoxia associated with low flows will become an increasing concern. Vertical thermal stratification may be a feature in low velocity areas of the Waikato River. |
| Deforestation and land drainage | Forest harvesting, particularly on organic rich soils, can lead to reduced DO in freshwaters due to mobilisation of organic carbon associated with organic sediments and brash material (O'Driscoll *et al.* 2016). Increased drainage can increase inputs of dissolved organic carbon (DOC) to receiving waters, increasing DO consumption (Rixen *et al.* 2010; Dalzell *et al.* 2011), as well as exacerbate oxidation rates in acid sulphate soils (Bronswijk et al. 1993). | High DOC concentrations are present in water draining important peatland areas in the Waikato such as Koputai, Torehape, and Whangamarino (Moore and Clarkson 2007). More generally, land clearance and wetland drainage have historically been widespread in the Waikato to support agricultural intensification (Collier *et al.* 2019). |
| Fire | Fire leaves organic debris on the landscape that can enter waterbodies in debris flows following heavy rainfall, increasing DO demand. For example, bushfire has been one of several drivers of blackwater events in the Murray-Darling basin, Australia (Beavis *et al.* 2023). | There is potential for climate change to exacerbate fire risk in the Waikato, although less so than for other regions in New Zealand (Pearce *et al.* 2011). |

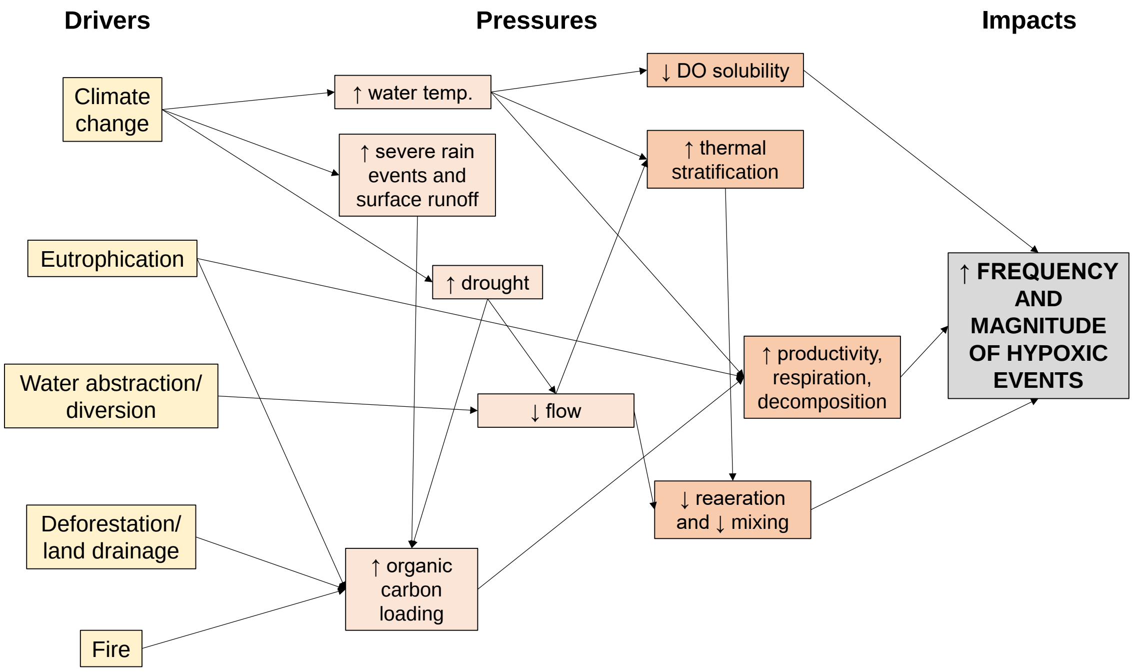

**Figure 3.** **Pathways of effect by which anthropogenic drivers affect the frequency and severity of hypoxic events.**

# 3 Ecological Effects of Hypoxia

***Key Points***

- ***The concentration of DO is a master variable that indicates the ecological state of a waterbody.***
- ***Hypoxia can cause a range of adverse physiological (e.g., reduced growth) and behavioural (e.g., reduced feeding) effects on fish and invertebrates. Direct effects on microorganisms are less-well studied although hypoxic events are linked to changes in microbial community composition in aquatic ecosystems.***
- ***The cumulative effects of hypoxia on fauna and flora can cause broad-scale adverse effects on aquatic ecosystems, requiring high restoration effort and long timescales (e.g., years to decades) to address.***

Concentrations of DO vary naturally in time and space, with perennial or periodic hypoxia a natural feature of aquatic ecosystems such as wetlands and productive ponds. However, increases to the magnitude, frequency, duration, and spatial extent of hypoxic events due to anthropogenic drivers (Table 1) can have major indirect and direct ecological effects. This section summarises ecological effects of hypoxia on biota.

Physiologically, effects on fish are reviewed in a general context by Pollock *et al.* (2007) and in a New Zealand context by Franklin (2014). Literature summarised by those authors shows that reduced DO supply typically causes increased gill ventilation, reduced swimming capability, retarded embryo development, reduced growth, and, following severe exposure, death. Native fish species in New Zealand exhibit a range of tolerance to hypoxia. For example, Dean and Richardson (1999) exposed seven native and one non-native species to DO of 1 mg/L for 48-hours. All individuals of the following five species died in the experiments: banded kokopu (*Galaxias fasciatus*), juvenile torrentfish (*Cheimarrichthys fosteri*), common smelt (*Retropinna retropinna*), juvenile common bully (*Gobiomorphus cotidianus*), and rainbow trout (*Oncorhynchus mykiss*) trout. By contrast, all shortfinned and longfinned elvers (*Anguilla australis* and *A. dieffenbachii*) survived in their experiments, whereas a subset of the adult and juvenile inanga (*Galaxias maculatus*) and adult common bully (*Gobiomorphus cotidianus*) individuals survived. Juvenile rainbow trout was the only species that suffered mortality when exposed to DO concentration of 3 mg/L, and no mortality occurred for the 5 mg/L treatment. As indicated by those experimental results, early life stages of fish are typically more sensitive to hypoxia than adults.

Related to these physiological effects, hypoxia can induce a range of behavioural responses in fish including aquatic surface respiration, reduced feeding, reduced overall activity, reduced parental care, and reduced ability to avoid predators (Chapman and Mckenzie 2009). Changes to physiology and behaviour can ultimately cause broader ecological changes, and differences among species in how tolerant they are to hypoxia can affect fish community composition. Of particular relevance to the Waikato, it is notable that invasive cyprinids such as common carp (*Cyprinus carpio*) and tench (*Tinca tinca*) that are widespread in the region (Collier and Grainger 2015) are highly tolerant of low DO supply (Franklin 2014). Thus, an increase in hypoxia is likely to support colonisation and proliferation by invasive fish as some native species are displaced

(Pingram *et al.* 2021). Such an effect may be associated with a positive feedback cycle as bioturbation by benthivorous fish such as carp increases suspended sediment concentrations (Peterson *et al.* 2022), thus further increasing biochemical oxygen demand in the water column.

For aquatic invertebrates, physiological effects of a decline in DO supply include increased respiration rates, reduced reproductive success, reduced growth, and reduced feeding rates (Galic *et al.* 2019). Hypoxia has also been linked to increased susceptibility to disease in invertebrates (Mydlarz *et al.* 2006), suppression of the emergence of zooplankton from benthic sediments (Ning *et al.* 2015), and reduced invertebrate drift (Connolly *et al.* 2004). Many invertebrate groups are intolerant of hypoxia (e.g., mayflies, stoneflies) and thus reduced DO supply leads to greater abundance of taxa that are more tolerant of hypoxia such as non-biting midges (Connolly *et al.* 2004; de Haas and Kraak 2008), potentially causing substantial changes to invertebrate community composition. Overall, reduced DO supply is associated with lower macroinvertebrate richness in freshwaters (Boulton *et al.* 1997; Croijmans *et al.* 2021).

Hypoxia can adversely affect macrophytes due to root anaerobic stress caused by sediment anoxia (Lemoine *et al.* 2012). The occurrence of hypoxia can also affect the bacterial community composition in freshwaters, although effects on bacteria have been studied less than effects on higher organisms. In a study of a hypoxic event following a cyanobacteria bloom in a large shallow lake in China, researchers showed that bacterial groups such as *Clostridium* (facultative anaerobes that can be pathogenic) proliferated at the onset of hypoxia and decreased as DO concentrations subsequently increased (Li *et al.* 2012). Similarly, DO was identified as the key driver of bacterial community composition in the Pearl Estuary in China (Liu *et al.* 2015), whereas chemical oxygen demand was shown to be a key environmental driver of bacterial community composition in a eutrophic lake (Shao *et al.* 2021).

The cumulative outcome of such effects on a wide range of taxa can be broad changes to aquatic food webs in ecosystems that include streams (Canning and Death 2021), spring-fed pools (Lukas *et al.* 2021), lakes (Vanderploeg *et al.* 2009), and estuaries (Baird *et al.* 2004). Restoring degraded aquatic ecosystems that have shifted to a state with frequent hypoxic events can be challenging, with long recovery timelines (e.g., decades for estuarine systems) and a time lag between recovery of improved DO conditions and recovery of the biotic community (Steckbauer *et al.* 2011).

Aside from the ecological effects described above, hypoxia can have important broader effects on water quality due to the role of oxygen in controlling redox processes. As such, hypoxia is associated with increased concentrations of dissolved fractions of redox sensitive metals such as iron (Jaiswal and Pandey 2020), release of dissolved nutrients including phosphate from benthic sediments (Søndergaard *et al.* 2003), mercury methylation, and taste and odour problems in potable water sources (Preece *et al.* 2019). This role of DO as a master variable has led DO to be described as “the best “vital sign” of a waterbody’s ecosystem health” (Chapra *et al.* 2021).

# 4 Forecasting

***Key Points***

- ***Broadly, three approaches are identified and reviewed to forecast DO concentrations: 1) regression-based approaches, 2) process-based simulation models, and 3) machine learning and artificial intelligence approaches.***
- ***Data requirements (quantity, detail) can be summarised as follows: process-based simulation models > machine learning and artificial intelligence approaches > regression-based approaches.***
- ***Regression-based approaches are relatively simple and can be used to predict DO at low spatiotemporal resolution based on measurements of variables such as river stage and water temperature for the system of interest.***
- ***Process-based simulation models are best suited for evaluating management strategies based on scenario analysis. There are numerous examples of such models being used to inform longer term planning based on analysis of scenarios of land use and/or climate change. In particular, detailed work has been undertaken in the Murray-Darling catchment (Australia) to develop coupled catchment–aquatic process-based models to better manage blackwater events; these models could potentially be used as a basis to develop modelling approaches for the lower Waikato River floodplain. Such models are resource intensive to develop and require detailed and extensive input data for variables that include bathymetry/topography, discharge, meteorology, and water quality. However, with diligence, process-based simulation models can be applied to assess scenarios that differ from historical and existing monitored conditions, thereby providing insights into the effects of hypothetical management actions and extreme events.***
- ***Machine learning and artificial intelligence approaches increasingly hold promise for providing short to medium term (hours to ~1 week) forecasts based on measurements of variables such as discharge, air temperature and antecedent DO concentrations. However, there is limited evidence that such forecasting systems are yet being routinely used by managers as part of day-to-day operations.***

## 4.1 Overview

The section focuses on using models in combination with monitoring data to forecast hypoxic events in the short (hours to days) to medium (weeks to months) term to inform management. However, it should be recognized that models can be used more broadly to understand ecosystem functioning (e.g., to quantify the relative importance of DO sources/sinks in a waterbody) or to evaluate the effects of hypothetical management scenarios. An example of the latter includes the modelling study of peat and riverine lakes in the Waikato by Lehmann *et al.* (2017), who used a one-dimensional lake ecosystem model to evaluate the effects of catchment and in-lake management interventions on lake water quality generally, including DO characteristics.

Broadly, modelling approaches that were reviewed can be categorized as 1) regression-based approaches, 2) process-based simulation models, and 3) machine learning and artificial intelligence approaches. These three approaches are summarised in Table 2 and discussed individually below with reference to case studies described in Table 3.

Data requirements for each modelling approach vary, as indicated by the 'Key Predictor Variables for Forecasting' column in Table 3. Data requirements are greatest for process-based simulation models (Section 4.3), which require detailed information for the system of interest for variables that include bathymetry, discharge, tributary/upstream water quality (e.g., water temperature and nutrient concentrations), key primary producer communities (e.g., phytoplankton/macrophyte biomass and community composition), meteorology and benthic substrate characteristics (e.g., carbon content). Multiple years of meteorology, hydrology, and water quality data are typically required for process-based models, with measurements or estimates required at daily or sub-daily intervals. Data requirements are more modest for the two empirical approaches (Section 4.2 and 4.4), although machine learning and artificial intelligence methods require large quantities of data to develop models, with data ideally collected at high frequency (e.g., sub-hourly using sensors) for a minimum of one year and during a representative range of climatic and hydrological conditions. Key predictor variables associated with the two empirical approaches are DO concentrations, discharge, and air temperature, although there is scope to potentially improve model accuracy by considering indicators of organic carbon fluxes such as rainfall or, potentially, high-frequency measurements of fluorescent dissolved organic matter, e.g., collected at ~hourly frequency using sensors deployed in waterways that drain peat soils.

## 4.2 Regression-Based Approaches

The first category of models (regression-based approaches) relates to the use of relatively simple empirical models to predict hypoxia characteristics based on system-specific relationships. Examples are regression models used to predict early summer and late summer anoxic volume in Chesapeake Bay (Table 3). Specifically, early summer anoxic volume is predicted based on total nitrogen loads in January to April, tributary flow in May, average sea level the previous year, and wind conditions in spring (an indicator of mixing); late summer anoxic volume is predicted based simply on total nitrogen loads in January to May (Testa *et al.* 2017). Advantages of these models are that they have proven to be accurate at the intended spatial and temporal bounds; they are computationally and mathematically simple; and they make good use of a large historical dataset (Testa *et al.* 2017). Disadvantages are that such approaches only consider a minority of key predictor variables, suitable predictions can only be made within the ranges of observed data, and the models provide predictions with low spatiotemporal resolution (Testa *et al.* 2017).

Another example of the application of regression-based approaches is provided by Harvey *et al.* (2011), who developed regression models to predict DO at monthly, weekly, and daily timescales based on river stage and water temperature. In turn, water temperature was predicted separately based on stage and air temperature. The authors developed separate linear and exponential decay regression models for four rivers in Newfoundland (Canada). High diurnal variability in hourly DO measurements presented a challenge for model development, and models that predicted average DO concentrations were more accurate than models that predicted minimum or maximum concentrations. Similarly, models that predicted DO metrics at weekly or monthly timescales were more accurate than models that predicted DO at daily timescales, although the models generally performed well, e.g., adjusted $r^2$ values for the exponential models to predict mean DO were 0.80–0.94 for monthly predictions and 0.68–0.91 for daily predictions. However, despite the seemingly good model performance, the models do not have clear value for forecasting episodic hypoxic events as they do not explicitly account for other predictor variables such as organic matter loading.

For the purpose of this review, this category of modelling approach is considered to also include more advanced inferential statistical methods that are distinct from the methods considered in Section 4.4. For example, Pasco *et al.* (2016) describe the use of principal component analysis and general additive models to parse the relative influence of floodplain inundation metrics, water temperature, and water chemistry variables on hypoxia in water on the floodplain of a tributary of the Mississippi River, USA. Their study identified thresholds based on temperature and river stage that managers can use to inform floodplain management to reduce the probability of system-wide hypoxia, as described further in Table 3. Such an approach could be applied to inform management of hypoxia in floodplains of other large river such as the Waikato River, providing multiple years of hydrology and water quality data are available for analysis.

## 4.3 Process-Based Simulation Models

The second category of models (process-based simulation models) relates to more complex models implemented using software that includes mathematical descriptions of key processes that control DO (and usually other water quality variables), typically based on either ordinary or partial differential equations. Thus, an advantage of this approach is that key processes that affect DO (e.g., advection, photosynthesis, respiration) are represented mechanistically in the models. That is, , important processes are explicitly described using equations that represent the physical and biogeochemical mechanisms involved, rather than being based on statistical relationships that are unreliable for scenarios with different conditions from those under which empirical data were collected. This mechanistic basis means that the models can be used to evaluate the influence of a wide range of variables, and potentially evaluate scenarios that differ from previously observed conditions, providing models are applied diligently. Excellent background to the architecture and equations that underpin such models is provided by Cox (2003a) with specific reference to lowland rivers, and by Chapra (2014) more generally. Specific examples of process-based water quality models that can be used to simulate DO in rivers include QUAL2E, MIKE-11, and WASP (Cox 2003b; Kannel *et al.* 2011), whereas examples of models applicable to lakes include PCLake (applicable to shallow lakes), CAEDYM (when coupled to a hydrodynamic model), and GLM-AED (Soares and Calijuri 2021). Specific examples of process-based models applied to simulate DO in freshwaters in the Waikato include DYRESM-CAEDYM applied to shallow lakes (Lehmann *et al.* 2017), whereas the three-dimensional hydrodynamic model DELFT3D-FLOW has been applied to evaluate īnanga (*Galaxias maculatus*) habitat in the lower Waikato River (Jones and Hamilton 2014). The latter model application focused on modelling water temperature, salinity, and stage (i.e., not DO), but the authors noted that their existing model of the Waikato River estuary could be coupled with an ecological and water quality model such as Delft-WAQ, which could simulate DO. The choice of model needs to be considered carefully depending on system characteristics and study objectives; in their review of open-source models for simulating DO in rivers and streams, Kannel *et al.* (2011) concluded that “Not a single model could serve all [of the] wide range of functionalities required and thus, the choice of a model depends upon time, cost and a specific application”.

There are many examples in the literature of the use of process-based models to evaluate the effects of scenarios on DO in freshwaters – one example is the study of the Garonne River (Lajaunie-Salla *et al.* 2018) discussed in Section 2.2. However, such examples do not generally relate to providing regular forecasts of hypoxic events in the short to medium term, which is the focus of this review. Instead, such models are typically used as part of discrete studies to inform longer term planning by simulating a range of scenarios related to aspects such as land-use intensification or climate change. Challenges to using process-based simulation models for more routine forecasting tasks include the need for high computing power, and the high effort and expertise required to prepare model forcing data and process/interpret results. As modelling processes become more sophisticated and efficient, use of complex process-based models for regular forecasting is expected to become more feasible, and Testa *et al.* (2017) note that, for managing Chesapeake Bay, a "forecast product using some version of a mechanistic biogeochemical model is imminent".

One of the most sophisticated examples of applying process-based modelling systems for predicting hypoxic events in freshwaters is the development of an integrated river-floodplain model in the Murray-Darling catchment (Howitt *et al.* 2007; Whitworth and Baldwin 2016; Mosley *et al.* 2021). The modelling approach has developed over time and more recently comprises the eWater Source modelling platform, which can be used with a freely available "plugin" to the eWater Source platform to simulate DO and DOC (DODOC Model), described by Mosley *et al.* (2021). The DODOC Model simulates transport and transformation processes in coupled river-floodplain(s), including the accumulation of organic litter and subsequent leaching of DOC, which contributes to DO consumption. The DODOC Model has been used to simulate flow management scenarios that were designed to develop management strategies to avoid or mitigate blackwater events. The coupled DODOC Model can simulate long-term (years to decades) scenarios over river reaches >100-km-long to provide insights into managing hypoxia in lowland floodplains. Model validation has demonstrated good model performance, and, with sufficient effort (e.g., to refine parameter values), the model could potentially be applied to systems outside of Australia such as the lower Waikato River floodplain. As for other process-based simulation models, this modelling system is best suited to evaluating management strategies with scenario analysis, rather than forecasting hypoxic events in the short to medium term.

## 4.4 Machine Learning and Artificial Intelligence Approaches

The third category of models (machine learning and artificial intelligence approaches) is the most recently developed and relates to using data-driven modelling in conjunction with data collected at high frequency to derive predictions of DO, e.g., at hourly resolution. Examples of specific modelling techniques include artificial neural networks, adaptive neuro-fuzzy inference systems, gene expression programming, quantile regression forest machine learning, and support vector machine models (Kisi *et al.* 2013; Ji *et al.* 2017; Ahmed and Lin 2021; Dehghani *et al.* 2022). Such methods can effectively "mine" large datasets to predict DO concentrations over timescales of approximately hours to a week, based on predictor variables such as antecedent DO concentrations, specific conductivity, water temperature, stage, precipitation, and nutrient concentrations. Examples of jurisdictions where such approaches have been applied include South Korea (Kim *et al.* 2021), China (Ji *et al.* 2017), and the USA (Heddam 2016), as described in Table 3. In a sense, the approach can be considered a much more sophisticated application of the empirical regression-based approaches described in Section 4.2, which leverages recent developments in computing systems and data analysis methods.

Unlike process-based models, the approach does not require detailed information about biophysical characteristics of the system that can only be obtained with field studies or laboratory tests. The associated reduced requirement for input data for a large number of predictor variables and model parameters therefore makes this approach better suited than process-based models for generating routine short-term forecasts. Despite this advantage, it was not clear from the references reviewed that such forecasting systems have advanced from the development stage to the stage of being routinely used by managers as part of day-to-day operations, although this uncertainty may reflect bias in the literature towards focusing on research to develop models, rather than describing management applications.

Good model performance was reported in multiple studies, e.g., Heddam (2016) reports Pearson's r values of 0.91–0.98 and 0.79–0.92 respectively for predictions of DO at two monitoring stations on the Klamath River (USA), based on forecasting intervals of 1–7 days. However, a disadvantage of this category of models is that they are not suited for predicting conditions that are outside of the bounds of the data used to train the models and care needs to be taken to avoid model overfitting. If only a small number of variables are used to make predictions, then the model will have limited capability to make forecasts during dynamic periods, e.g., following floods. Stajkowski *et al.* (2020) used a machine learning method to forecast DO concentration in a tributary to Lake Ontario, Canada, with the goal to "develop a user-friendly model for the practitioners to easily assess the health of urban streams and avoid the challenging problems associated with the application of more complex multiparameter models". The resulting model (stochastic autoregressive integrated moving average model) was relatively simple and provided accurate predictions of daily average DO concentrations with a forecasting interval assumed to be 1 day (this aspect was unclear). However, an apparent disadvantage of this model is that DO is solely predicted based on antecedent DO conditions (i.e., it is autoregressive), and therefore the model seems unsuited to make accurate forecasts several days or more in advance, or to forecast DO under changing environmental conditions. Process-based simulation models (Section 4.3) are generally better suited for scenario analysis than this category of models because the mechanistic nature of process-based models means they are better-suited to predict conditions outside of the bounds of the conditions used to develop and calibrate the model.

**Table 2. Summary of broad categories of forecasting tools reviewed.**

| Category | Description | Data Requirements | Advantages | Disadvantages | Examples |
|---|---|---|---|---|---|
| Regression-based approaches | Relatively simple empirical models to predict hypoxia based on system-specific relationships | Relatively low; example predictor variables are water temperature and stage | - Can be accurate within intended (usually coarse) spatial and temporal bounds<br>- Computationally and mathematically simple; easy to interpret<br>- Can make good use of large historical datasets<br>- Can be used to identify intuitive management thresholds | - Suitable predictions can only be made within the ranges of observed data<br>- Only considers a small number of predictor variables<br>- Generally unsuitable for scenario analysis<br>- Low spatial resolution, e.g., relationships apply to a single site. | - Predict summer anoxic volume in Chesapeake Bay (Testa *et al.* 2017)<br>- Predict DO in Newfoundland rivers based on water temperature and stage (Harvey *et al.* 2011). |
| Process based simulation models | Complex models that incorporate mathematical descriptions of key processes that control DO | Extensive data required to characterise biophysical conditions and parameters that control hydrological and biogeochemical processes | - Highly flexible; can be applied to a range of ecosystems<br>- Can make predictions for dynamic conditions that have not been previously observed<br>- Suitable for scenario analysis to inform planning<br>- Can provide predictions at high temporal and spatial resolution | - Models are complex and resource intensive to apply, requiring large datasets and an expert team<br>- High computational/resource demands mean models are not well-suited for routine forecasting | - DO and DOC modelling in the Murray-Darling (Mosley *et al.* 2021)<br>- Modelling drivers of hypoxic events in the Garonne River (Lajaunie-Salla *et al.* 2018)<br>- Developing total maximum daily load targets in Chesapeake Bay (Testa *et al.* 2017) |
| Machine learning and artificial intelligence approaches | Data-driven modelling used with high-frequency monitoring data | Moderate data requirements: methods require large and high frequency (e.g., hourly) datasets, although accurate models can be developed with a small number of predictor variables that are routinely measured | - Can be used to effectively analyse large existing datasets<br>- Demonstrated to be effective for making accurate forecasts in the short to medium term (hours to ~1 week)<br>- Good potential for automation<br>- Could inform short-term decisions, e.g., regarding managing floodgates | - Requires specialist analytical methods<br>- Relationships that underpin models may not be transparent and do not describe mechanistic processes<br>- Predictions are based on historical patterns; not well suited for scenario analysis | - 24-h forecasts of DO in urban streams in South Korea (Kim *et al.* 2021)<br>- Daily to weekly forecasts of DO in the Klamath River, USA (Heddam 2016) |

**Table 3. Case studies of hypoxia forecasting systems.**

| Case Study | Ecosystem Type | Forecasting Method | Monitoring Methods | Key Predictor Variables for Forecasting | How are Forecasts Used by Managers? | Key Lessons and Relevance to Waikato |
|---|---|---|---|---|---|---|
| Chesapeake Bay, USA (Testa *et al.* 2017) | Large estuary (11,000 km$^2$) | Hypoxia forecasts have been provided for Chesapeake Bay since 2007. Three models are used to make forecasts of summer hypoxic and anoxic volumes based on conditions in Jan to May:<br>1. A mechanistic model based on the Streeter-Phelps oxygen sag model that uses Bayesian inference to predict July hypoxic volume ("Hypoxia Model")<br>2. Simple linear regression to predict the mid-July to Sept anoxic volume ("Late Summer Anoxia Model")<br>3. Multiple linear regression to predict the June to mid-July anoxic volume ("Early Summer Anoxia Model")<br>More complex coupled hydrodynamic-biogeochemical models have been used for scenario analysis but, unlike the models listed above, they have not been used for routine forecasting. | Hypoxic/anoxic volumes in bay estimated based on interpolation of dissolved oxygen (DO) concentrations from 30–35 stations.<br><br>Limited detail provided regarding monitoring nutrient loads in tributaries; discharge obtained from USGS NWIS; historical sea level data obtained from NOAA; wind data measured at the Patuxent Naval Air Station. | Hypoxia Model:<br>- Susquehanna River total nitrogen (TN) load (Jan-May)<br>- Initial DO deficit estimated from DO measurements<br>Late Summer Anoxic Model:<br>- Susquehanna River TN load (Jan-May)<br>Early Summer Anoxic Model:<br>- Susquehanna River and Potomac River TN loads (Jan-Apr)<br>- Combined Susquehanna River and Potomac River freshwater flow (May)<br>- Fraction of hours with southeast winds during March-May<br>- Annual average sea level (from prior year) | - Primary goal to "inform potential ecosystem users". Forecasts routinely receive media coverage.<br>- Raise public and political awareness of problem<br>- Increase scientific understanding of complex DO dynamics<br>- Inform decision making (further details not provided)<br>- Advising public policy debate<br><br>More complex coupled hydrodynamic-biogeochemical models have also been used to explore hypothetical nutrient-management scenarios and develop current total maximum daily load (TMDL) targets for nutrients. A "forecast product using some version of a mechanistic biogeochemical model is imminent". | This case study demonstrates that statistical and hybrid models can be used to accurately forecast summer hypoxia in a large estuary based on conditions in late winter and spring. Such models are less applicable to forecasting episodic hypoxic events in freshwater floodplains, where hypoxia is less seasonally and spatially predictable. |

| **Case Study** | **Ecosystem Type** | **Forecasting Method** | **Monitoring Methods** | **Key Predictor Variables for Forecasting** | **How are Forecasts Used by Managers?** | **Key Lessons and Relevance to Waikato** |
|---|---|---|---|---|---|---|
| Newfoundland Rivers, Canada (Harvey *et al.* 2011) | Four rivers in Newfoundland and Labrador, (Canada) spanning a wide range of catchment area (20–7,000 km$^2$) | Linear and exponential decay regression models | Hourly real time data collected at a single station in each river by a government agency | Water temperature and river stage | The authors present a plot to allow managers to determine water temperature and DO concentration based on air temperature, although it is unclear whether the models are used for forecasting | The models demonstrate the important influence of seasonal fluctuations in water temperature on DO. However, the models seem to have limited value for forecasting hypoxic events as they do not account for other predictors such as organic matter loading. |
| Atchafalaya River, Louisiana, USA (Pasco *et al.* 2016) | A large (5,000 km$^2$) regulated floodplain system; largest tributary of the Mississippi River | - Principal component analysis (PCA) was used to distil seven flood metrics<br>- General additive models (GAMs) were used to model the percentage of hypoxic observations for each biweekly sampling event | - Flood metrics calculated using stage data collected at stations maintained by USGS<br>- Surface DO measured biweekly in six areas for 5–12 years | Flood metrics analysed with PCA:<br>- Flood start date<br>- Flood end date<br>- Flood days<br>- Low temperature days<br>- High temperature days<br>- Days of falling flood<br>- Maximum flood days | The analysis was not applied to provide forecasts, but the authors identify thresholds based on temperature and river stage that managers can use to inform floodplain management to reduce the probability of system-wide hypoxia. | The study reiterates the role of water temperature and flood extent/duration as major controls on hypoxia in lowland large river floodplains. The study also highlights the potential to |

| **Case Study** | **Ecosystem Type** | **Forecasting Method** | **Monitoring Methods** | **Key Predictor Variables for Forecasting** | **How are Forecasts Used by Managers?** | **Key Lessons and Relevance to Waikato** |
|---|---|---|---|---|---|---|
| | | | | Predictor variables in GAMs:<br>- Water temperature<br>- Estimated inundation level<br>Conductivity, pH, and turbidity did not improve the models.<br>Macrophyte biomass and dynamics were likely also influential, but there were insufficient data for modelling. | | analyse long term datasets to identify thresholds that can inform management. |
| Murray-Darling River, Australia – Blackwater Risk Assessment Tool (Howitt *et al.* 2007; Whitworth and Baldwin 2016) | Risk assessment tool developed for Eucalyptus floodplains in Australia, but could be modified for different vegetation types | The Blackwater Risk Assessment Tool (Whitworth and Baldwin 2016) forecasts DO and DOC concentrations in return water during inundation and was built upon the conceptual framework of an earlier blackwater prediction model (Howitt *et al.* 2007) but differs from the original in that it is not site specific and can be customized based on hydrology and vegetation type. | Limited detail provided regarding data collection; many input variables are themselves modelled based on existing/publicly available data (e.g., litter loads, DOC leaching, DOC consumption). | - Water temperature<br>- Inflow date<br>- Volume delivered to floodplain<br>- Duration of floodplain inflows<br>- Maximum floodplain outflow rate<br>- Inundation area<br>- Floodplain water transit time<br>- Discharge/flow rate<br>- Litter load (actual or estimated based on time since previous flood) | Models aim to explore effects of flood management options on the likelihood and impact of blackwater events during the flooding of Eucalyptus forest. The tool will also assess the risk of blackwater formation prior to water being allowed onto the floodplain. | Presents a process-based approach that could be applied elsewhere if sufficient effort is allocated, although see description below of the DODOC plugin for an updated model that is freely available |

| Case Study | Ecosystem Type | Forecasting Method | Monitoring Methods | Key Predictor Variables for Forecasting | How are Forecasts Used by Managers? | Key Lessons and Relevance to Waikato |
|---|---|---|---|---|---|---|
|  |  |  |  | - Dominant litter type<br>- DO concentration based on modelled consumption and reaeration variables (inflow, depth, and wind speed)<br>- DOC concentrations (based on modelled DOC leaching/ consumption) |  |  |
| Murray-Darling River, Australia: DODOC plugin model (Mosley *et al.* 2021) | Regulated reach of River Murray in South Australia (2,508 km long; study area included >100 km stretch). | The "DODOC plugin", developed for the eWater Source hydrological modelling software and predicts DO and DOC concentrations.<br>Daily time step is typically used (however software is capable of shorter and longer time steps). | Limited detail provided; the ranges used for configurable model parameters were based on previous research (e.g., leaf, bark, and twig decay rates, DOC release rates). | - Water temperature<br>- Reaeration processes (based on depth and wind speed)<br>- Rate of litter accumulation<br>- Degradable fraction of accumulating litter<br>- Floodplain area<br>- Floodplain elevation<br>- Quality of inflowing water | Developed to inform risk mitigation strategies for managed inundation events. | The freely available plugin model describes the strong relationship between DOC and DO. Although not described in the reference, this relationship indicates that high frequency measurements of fluorescent dissolved organic matter could be used as a predictor of DO, particularly in regions with peat |

| **Case Study** | **Ecosystem Type** | **Forecasting Method** | **Monitoring Methods** | **Key Predictor Variables for Forecasting** | **How are Forecasts Used by Managers?** | **Key Lessons and Relevance to Waikato** |
|---|---|---|---|---|---|---|
| | | | | | | rich soils, e.g., Whangamarino. |
| Han River watershed, South Korea (Kim *et al.* 2021) | Urban streams (32–36 km long) | Artificial neural network to make 24-h forecasts of hourly DO concentrations stations at the mouths of three tributaries. Predictions are based on measurements at separate stations upstream. | Automatic monitoring stations maintained by Seoul Metropolitan Government and deployed in each stream at the mouth and a second station ~2–5 km upstream. Key monitoring variables: DO, water temperature, pH, electrical conductivity, suspended solids, TN, total phosphorus (TP), total organic carbon (TOC), water level, precipitation. | - DO<br>- Water level<br>- Water temperature<br>- pH<br>- 24-h cumulative precipitation<br>- TP<br>- Time lags of 1–6 hours applied | Limited detail provided: the reference states that forecasts can provide “managers with useful information to give forewarnings and take timely actions in advance of hypoxic events”. | The study provides support for the concept of using data-driven modelling approaches with real time stream monitoring to derive short term (24-h) forecasts to inform management of streams. In principle, this concept could be applied to well monitored streams in the Waikato, particularly in urban areas. |
| Wen-Rui Tang River, China (Ji *et al.* 2017) | “Severely degraded” major river system in south-eastern China (watershed is 353 km$^2$) | Support vector machine (artificial intelligence model) was most effective of the four models tested. | Model inputs: 11 hydro-chemical variables. Variables were measured bimonthly at 8 sampling sites along the rural-suburban-urban portion of Wen- | All 11 hydro-chemical parameters used as model inputs; however, sensitivity analysis identified the following variables as being the most influential: | Concluded that organic pollution variables were most influential, and their reduction would be critical to improving water quality (i.e., increasing DO concentrations). Study recommended implementing best management practices to | Highlights value of considering indicators of organic pollution (e.g., ammonium) during forecasting, |

| Case Study | Ecosystem Type | Forecasting Method | Monitoring Methods | Key Predictor Variables for Forecasting | How are Forecasts Used by Managers? | Key Lessons and Relevance to Waikato |
|---|---|---|---|---|---|---|
|  |  |  | Rui Tang River from 2004 – 2008 (2 rural, 4 urban, 2 suburban).<br>Water quality parameters included: water temperature, pH, chemical oxygen demand index, 5-day biochemical oxygen demand, ammonium-nitrogen, petroleum, TP, cadmium-chemical oxygen demand index, fluoride, TN, electrical conductivity, and DO. | - Ammonium-nitrogen<br>- TN<br>- TP<br>- Oxygen demand parameters | decrease volume of urban pollutants reaching surface waters (e.g., improved wastewater treatment). | particularly in urban streams |
| Klamath River, Oregon, USA (Heddam 2016) | Large regulated and temperate river (423 km long) | The model was trained using historical DO data and forecasts DO concentrations between 24 hours ahead to 168 hours ahead (short- to long-term forecasting) and is called an "optimally pruned extreme learning machine (OP-ELM)" | DO concentration information collected from two USGS stations | Model inputs include the six antecedent DO concentrations (measured 5, 4, 3, 2, 1, and 0 hours prior to forecast) | The work is presented as an early warning system that can be used with minimal input data to manage hypoxia, although it is uncertain whether the model is yet used by managers | The study demonstrates that data driven analysis can be used to accurately predict hypoxia based on antecedent DO. In theory, such a system could be used to inform short-term decisions about operating flood/tidal gates. |

# 5 Mitigation

***Key Points***

- ***Three broad approaches to directly mitigate the risk of hypoxic events are identified and reviewed: 1) physical aeration of lake hypolimnia and rivers, 2) manipulating the sources of flow to augment hypoxic water with water of better quality, and 3) adaptively managing floodplain inundation to isolate hypoxic water from sensitive habitats and/or limit the accumulation of organic material on floodplains and manage the risk of future hypoxic events.***
- ***Physical aeration is an established method for small to medium sized deep lakes that stably stratify. Physical aeration techniques are less established for rivers than for lakes, although they have been used successfully in rivers, albeit with localised benefits. Capital and operational costs can be substantial for physical aeration methods.***
- ***Manipulating the sources of flow to augment hypoxic water with water of better quality can be highly successful (e.g., at intermittently closed and open coastal lagoons in New Zealand), although its success depends on the context. Notably, the technique requires a source of good quality water that can be diverted.***
- ***Managing return flows has potential to mitigate the risk of hypoxic events by limiting the build-up of carbon loads on floodplains, although successful implementation requires careful planning and assessment.***
- ***More generally, hypoxia is a symptom of eutrophication and therefore hypoxia risk can be reduced by enacting measures to manage eutrophication, notably by controlling external nutrient loads. Riparian planting to increase shade can also reduce hypoxia risk.***

The list of available options to avoid or directly mitigate hypoxic events in freshwaters is short. As summarised in Table 4, the basis for mitigation options is either to physically increase aeration, promote augmentation of hypoxic water with water of better quality, or to manage floodplain inundation to isolate hypoxic water from the most sensitive habitats and/or limit the accumulation of organic material on floodplains (Kerr *et al.* 2013; Whitworth *et al.* 2013), including drained wetlands. Successful implementation of all options requires careful planning to ensure they are well-tailored to the characteristics of the study system.

Physical aeration can be applied in both lakes and rivers. The technique is more common in lakes, where the method is likely most suitable due to the confined nature of lake basins and greater predictability in where and when hypoxia is likely to occur. Hypolimnetic aeration has been applied worldwide (Ashley 1985; Preece *et al.* 2019) and to a limited extent in deep lakes in New Zealand (Hickey and Gibbs 2009). The method is only suitable for lakes that stratify, and it can entail high capital and operational costs. In rivers, artificial mixing has been applied in the Murray-Darling basin in three ways: 1) using paddle wheels of a paddle boat or small aquaculture paddle wheels to create an oxygenated fish refuge, 2) mechanical aeration using pumps to increase flow to isolated pools in a creek, and 3) modifying water regulatory structures at an inlet to a creek so that water flows over 3-m-high falls (Whitworth *et al.* 2013). All three methods were considered effective as follows: 1) paddle wheel operation increased localised DO concentrations from 0.1–1.3 mg/L to 3.3 mg/L at a distance of 100 m from the paddle, with physiological improvements observed in fish suffering from hypoxia symptoms, 2) pumping promoted reaeration and increased DO concentrations within 4 days from <2 mg/L to >6 mg/L within a refuge pool 90 m downstream, and 3) turbulence at the modified falls caused a mean increase in DO concentration of 0.6 mg/L (Whitworth *et al.* 2013).

Manipulating the sources of flow to augment lower quality water with water of better quality is widely applied worldwide, although the feasibility depends greatly on system characteristics, notably the availability of a source of water of superior quality. In New Zealand, openings between several intermittently closed and open coastal lagoons and marine environments are controlled to manage water quality more generally (i.e., symptoms of eutrophication). For example, periodic managed openings at Waituna Lagoon in Southland (surface area = 7.2 $km^2$; mean depth = 1.6 m) provide stark improvements in water quality (Schallenberg *et al.* 2010; Jones *et al.* 2018). From the perspective of specifically managing blackwater events, delivering oxygenated augmentation flows has been effectively used in the Murray-Darling catchment (Whitworth *et al.* 2013; Watts *et al.* 2018), where the converse approach has also been proposed of diverting hypoxic water to shallow off-channel storage areas where it can be retained without causing significant environmental harm (Whitworth *et al.* 2013) (Table 4).

A similar approach that involves managing hydrological processes but is more proactive, is to adaptively manage environmental return flows from floodplains to rivers to periodically flush organic material and manage the risk of future hypoxic events. The premise of this method is that the availability of plant litter exerts a major control on the formation of hypoxia in periodically flooded habitats (Hladyz *et al.* 2011) and therefore periodically flushing organic material from floodplains can limit the potential for hypoxia to occur during subsequent flooding. Such an approach has been trialled using a before-after-control-impact study in a 27,000 ha area of the Murrumbidgee River in southeast Australia that comprises wetlands and *Eucalyptus camaldulensis* forested floodplain (Wolfenden *et al.* 2018). Some of the results of the study were inconclusive, but the study demonstrated that return flows could be managed to return organic material from the floodplain to the mainstem, without causing hypoxic events. Consequently, the authors concluded that managing return flows has potential to mitigate the risk of hypoxic events by reducing carbon loads on floodplains. Successful implementation of such an adaptive management strategy would require careful planning and assessment of trade-offs, e.g., with flood risk and agricultural production. Process-based simulation models (Section 4.3) could be used to complete scenario analysis to inform feasibility and refine adaptive management strategies, whereas data-driven forecasting based on high-frequency monitoring (Section 4.4) could inform effective implementation. More broadly, it is necessary to consider the potential for increased floodplain inundation to cause hypoxic events when undertaking projects to enhance lateral connectivity, which has been identified as a restoration objective for large river ecosystems in New Zealand generally (Abell *et al.* 2023) – similarly, modelling can have a valuable role in assessing ecological consequences of managing hydrology in large river floodplains.

More generally, hypoxia is a symptom of eutrophication and therefore actions designed to manage eutrophication – notably controlling nutrient loads from catchments to waterways – can also reduce hypoxia risk, albeit less directly. Management actions to control eutrophication are reviewed elsewhere in relation to streams (e.g., McDowell *et al.* 2009), large rivers (e.g., Abell *et al.* 2023), and lakes (e.g., Hickey and Gibbs 2009; Abell *et al.* 2022). The reviews pertaining to lakes include discussion of in-lake measures (e.g., dredging and sediment capping) that can reduce sediment oxygen demand.

Additionally, actions that ameliorate the occurrence of high water temperatures can mitigate hypoxia risk due to the inverse relationship between water temperature and DO concentrations (Figure 1). Notably, riparian planting to increase shade has been shown to increase dissolved oxygen concentrations in small lowland streams in New Zealand (Collins *et al.* 2013) and elsewhere (Orzetti *et al.* 2010).

**Table 4. Mitigation options to directly mitigate hypoxia risk.**

| Mitigation Option | Ecosystem | Description | Challenges | Relevance to Waikato | References |
|---|---|---|---|---|---|
| Hypolimetic aeration | Deeper lakes that stably stratify | Entails pumping air/oxygen directly to the bottom waters of stratified lakes to directly address hypoxia and associated nutrient release from bottom sediments. Aeration can also be used to disrupt lake stratification and increase dissolved oxygen (DO) via mixing with surface waters. | • Only suitable for deeper lakes that stably stratify in the summer, i.e., monomictic lakes in the Waikato<br>• Predominantly a tool to address internal nutrient loading and associated eutrophication, rather than a direct response to hypoxic events<br>• High capital costs<br>• Maintenance and operational costs that are ongoing<br>• Best suited for smaller lakes and reservoirs | Faithful et al (2005) reviewed the suitability of hypolimnetic aeration for Waikato peat lakes and concluded that the method would likely be ineffective due to the shallow characteristics of the lakes.<br>The method would be better suited to deeper lakes, where addressing hypolimnetic hypoxia is a key priority. The method has been applied to at least one reservoir in Auckland (Hickey and Gibbs 2009). | Ashley (1985); Bormans *et al.* (2016); Hickey and Gibbs (2009) |
| Physical aeration of rivers | Rivers | Mechanical aeration enhances the diffusion of oxygen into water by increasing the surface area to volume ratio of water bodies, typically through turbulence. Paddle wheels, pumps, and regulatory structures that manipulate flow (i.e., create waterfalls) have been used in the Murray River and associated waterbodies (Australia); increases in DO concentrations were observed in all cases. | • Persistence of increased DO depends on decomposition rate; therefore, benefits may be short-lived or limited in spatial coverage<br>• Moderate to high capital costs<br>• Maintenance and operational costs may be ongoing (particularly when equipment such as pumps or paddle wheels are used). | Could potentially be applied in the lower Waikato River catchment to provide temporary refuge during hypoxic events at important rearing habitats for native fish | Whitworth *et al.* (2013) |

| | | | | | |
|---|---|---|---|---|---|
| Augmentation flows | Rivers and lakes | Entails delivering well-oxygenated water to hypoxic water systems, achieved by the diverting well-oxygenated water into hypoxic channels or by increasing the discharge at upstream regulatory structures.<br>These strategies were monitored in the Murray-Darling catchment, Australia (Whitworth *et al.* 2013):<br>1. In the Wakool River, when augmentation flow was delivered through an irrigation escape from the Mulwala canal;<br>2. In the Murrumbidgee River, at the confluence with the Murray River (containing oxygenated water), and;<br>3. In the lower reach of the Murrumbidgee River, following releases from upstream regulatory structures (Maude and Redbank weirs).<br>Increases in DO concentration were observed at augmentation inflow locations, suggesting they can provide refuges and help maintain connectivity with oxygenated waters upstream. DO increases were also observed following releases from the Maude and Redbank weirs. | • Persistence of increased DO depends on decomposition rate; therefore, benefits are generally short-lived (and/or spatially limited) due to the high DO demand in hypoxic water.<br>• Efficacy partly depends on the quality of augmentation water.<br>• Strategy could exacerbate flooding if not properly managed.<br>• When increasing discharge at upstream regulatory structures, it is difficult to assess the degree of benefit due to the limited ability to measure volumes and quality of augmentation water and hypoxic water. | Could be applied in the lower Waikato River catchment based on managing flood/tidal gates and other regulation structures, although the feasibility will depend on the availability of suitable source water. Realtime monitoring systems would be advantageous to inform operations. | Kerr *et al.* (2013); Whitworth *et al.* (2013); Watts *et al.* (2018). |

| | | | | | |
|---|---|---|---|---|---|
| Diversion of hypoxic water to shallow off-channel storages | Large river floodplains | Hypoxic blackwater can be diverted into large lake or wetland systems adjacent to river channels if the diversion is expected to cause a net ecological benefit. Has been suggested as an initial intervention measure in the Murray-Darling catchment, although it is uncertain whether the technique has been applied. | • Requires presence of off-channel storage area with suitable capacity, as well as water diversion infrastructure<br>• Careful assessment is required to ensure that adverse effects of containing hypoxic water in receiving habitats are outweighed by the benefits of reducing hypoxia in the source environment | Could potentially be applied in the lower Waikato River floodplain by storing water in riverine lakes, although further assessment is necessary to assess ecological effects and evaluate costs and benefits | Whitworth *et al.* (2013) |
| Adaptive management of return flows | Wetlands and rivers | Entails the recurring and controlled delivery of wetland water to floodplain rivers to re-establish the natural connectivity of floodplain ecosystems. This strategy aims to decrease the amount of leachable DOC on floodplains and thus minimize the risk of future blackwater events. Two return flow events were implemented along the Murrumbidgee River (Australia) at the Wynburn Escape. However, due to the mechanism through which this method aimed to minimize the risk of blackwater events, it was difficult to evaluate the success of this strategy (i.e., increases in DO concentration following the two events were not anticipated). However, the authors conclude that managing return flows may be a useful tool to mitigate the risk of blackwater events. | • The benefits of this strategy to DO concentrations will not be immediate.<br>• Strategy can only be implemented when there is no risk of causing a hypoxic event in the receiving system; therefore, the scale and frequency of return flows will be limited.<br>• Increasing DOC can cause water supply challenges (potential visual, odour, and taste concerns), particularly for drinking water sources. | Could potentially be applied in the lower Waikato River floodplain by using existing or additional water management infrastructure. However, such an approach would require careful planning and assessment; scenario analysis using modelling could inform the feasibility and help to evaluate trade-offs, e.g., with agricultural productivity. | Wolfenden *et al.* (2018) |

# 6 Conclusion

Dissolved oxygen can be considered a master variable that exerts a fundamental control on the ecological quality of freshwaters and their associated capacity to support aquatic life, potable water uses, and cultural values. Developing effective tools and strategies to manage hypoxia in the region’s freshwaters has been identified as a priority by Waikato Regional Council. This review can inform regional policy for managing environmental risks to freshwaters associated with hypoxia by synthesising lessons from elsewhere in the context of the biophysical and environmental management characteristics of the Waikato.

This review has addressed four questions relating to causes of hypoxia (Section 2), potential effects on freshwater ecosystems (Section 3), modelling tools to forecast hypoxic events (Section 4), and options to avoid or mitigate hypoxic events (Section 5). Examples of forecasting tools and mitigation options that have been successfully applied in other jurisdictions have been identified (Table 2; Table 3). With careful evaluation and development, management approaches that have been successfully applied elsewhere (Table 4) could be modified for use in the Waikato region, although substantial planning and investment may be required to successfully adapt and apply approaches to suit the biophysical, political, and social characteristics of the region. Nonetheless, multiple drivers (Table 1) have potential to increase the frequency and severity of hypoxic events in the Waikato region, supporting an imperative to prioritise the continued development of tools, management responses, and policies to effectively manage the risk of hypoxic events in the region’s freshwaters.

As a next step, Waikato Regional Council could use the information in this review to guide the development of plans to manage the risk of hypoxic events in systems of highest priority. Forecasting, monitoring, and mitigation measures for individual systems will depend on local management objectives and interests; therefore, such planning may be best undertaken at the waterbody or sub-catchment scale.

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