V

APPENDIX V

Pit Lake Limnology Assessment (Hydronumerics)

Project Martha

Martha Phase 4 Pit Extension

Pit Lake Limnology

Scoping Study of Water Quality – Nutrients and Primary Production

Final Report

22 May 2018

Prepared for Oceana Gold (NZ) Limited

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NOTICE

DISCLAIMER

EXECUTIVE SUMMARY

This report provides a high-level assessment of the likely water quality in the Phase 4 Martha Pit Lake (MPL) based on hydrodynamic modelling results (Hydronumerics, 2018) and available data for pit lake inputs. The analysis is focused on dissolved oxygen, nutrients and algal production.

Dissolved oxygen concentrations in MPL will respond directly to the mixing and stratification, with near-saturation concentrations in the epilimnion most of the time because of the mixing of atmospheric oxygen from the surface. Dissolved oxygen in the water below the epilimnion will become seasonally de-oxygenated and potentially anoxic due to the lack of replenishment from the surface. These waters will be re-oxygenated briefly during winter mixing, but the depth of re-oxygenation will range from shallow (approximately 50 to 60 m deep) to just above the monimolimnion, depending on the extent of winter mixing. The monimolimnion (below approximately 930 m RL) is likely to remain persistently anoxic.

Provided there is sufficient nutrient availability highest algal production will occur in spring and summer in response to the warmer temperatures that favour growth. Light limitation in the epilimnion is unlikely given the clarity of the river waters and settling of suspended solids, except in the event of significant algal production.

The river water and the pit-wall run-off are significant nutrient inputs into MPL and it is most likely that the extent of primary production during filling will be limited by the availability of phosphorus in the source waters. During filling (and immediately after) the nutrient concentrations of the inputs are high enough to suggest productivity that is consistent with a eutrophic to supertrophic lake (under the classification for NZ lakes provided by Burns et al. 2000). However, the true bioavailability of the phosphorus is not known. For example, the external sources of phosphorus may be (or become) bound to the suspended sediments and settle to the bed.

After filling, the internal cycling of nutrients is likely to become the dominant process with both physical and biogeochemical mechanisms controlling nutrient availability in the epilimnion. Loss of nitrogen from the lake is likely to occur due to denitrification in the anoxic waters and this may lead to a shift towards nitrogen limitation, therefore increasing the potential risk of cyanobacteria growth. The depleted oxygen concentrations in the hypolimnion, and associated sediment release of nutrients into the hypolimnion, followed by the subsequent entrainment of these nutrient-enriched waters into the epilimnion during mixing will be an important sequence of processes that control nutrient availability in the photic zone after filling. As a result, nutrient availability in the epilimnion is likely to become irregular, given the changes in the depth of winter mixing and the associated changes in the extent of entrainment of nutrient-enriched waters. This may produce years that are significantly more productive than others, particularly when mixing occurs after an extended period of hypolimnetic nutrient enrichment.

The complexities of the nutrient cycles and the unknown rates of oxygen depletion and nutrient release from the sediments, make it difficult to accurately predict post-filling primary production, other than to note that it is likely to initially reduce after the filling period.

Including provisions for a littoral zone in the mine closure planning that allows for the establishment of macrophyte beds and riparian vegetation will have overall benefits for lake water quality. Nutrient enrichment may provide a means to promote natural lake processes if MPL evolves to become unproductive. It may also be a means to increase the TN:TP ratio and reduce cyanobacteria risk. Ongoing monitoring of nutrients and primary production during and after filling will be important to improve long-term predictions of water quality in MPL and inform management practices into the future.

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1 Project Overview

1.1 Martha Phase 4 Pit Lake

1.1.1 Location

Part of the consent process to extend mining activities at Waihi provides for rehabilitation of the Martha Pit Phase 4. Rehabilitation includes filling the Martha Pit to create a pit lake (the Martha Pit Lake – hereafter referred to as MPL) that is to provide recreation benefits to the local community.

A regional depiction of the open pit (to be rehabilitated as MPL) in relation to the town of Waihi and associated mining activities is provided in Figure 1.1.

Figure 1.1 Regional view of the Martha Pit and related mining infrastructure (Source: Google Earth).

1.1.2 Bathymetry

At the completion of the Martha Pit Phase 4 cutback the pit shell characteristics will be:

- Floor level of approximately 875 m RL;
- Depth of approximately 275 m;
- Length (NE to SW) of approximately 950 m;
- Breadth (NW to SE) of approximately 715 m;
- Surface area of approximately 51 ha; and
- Total volume of approximately 43 million m^3.

A contour diagram of the pit is provided in Figure 1.2.

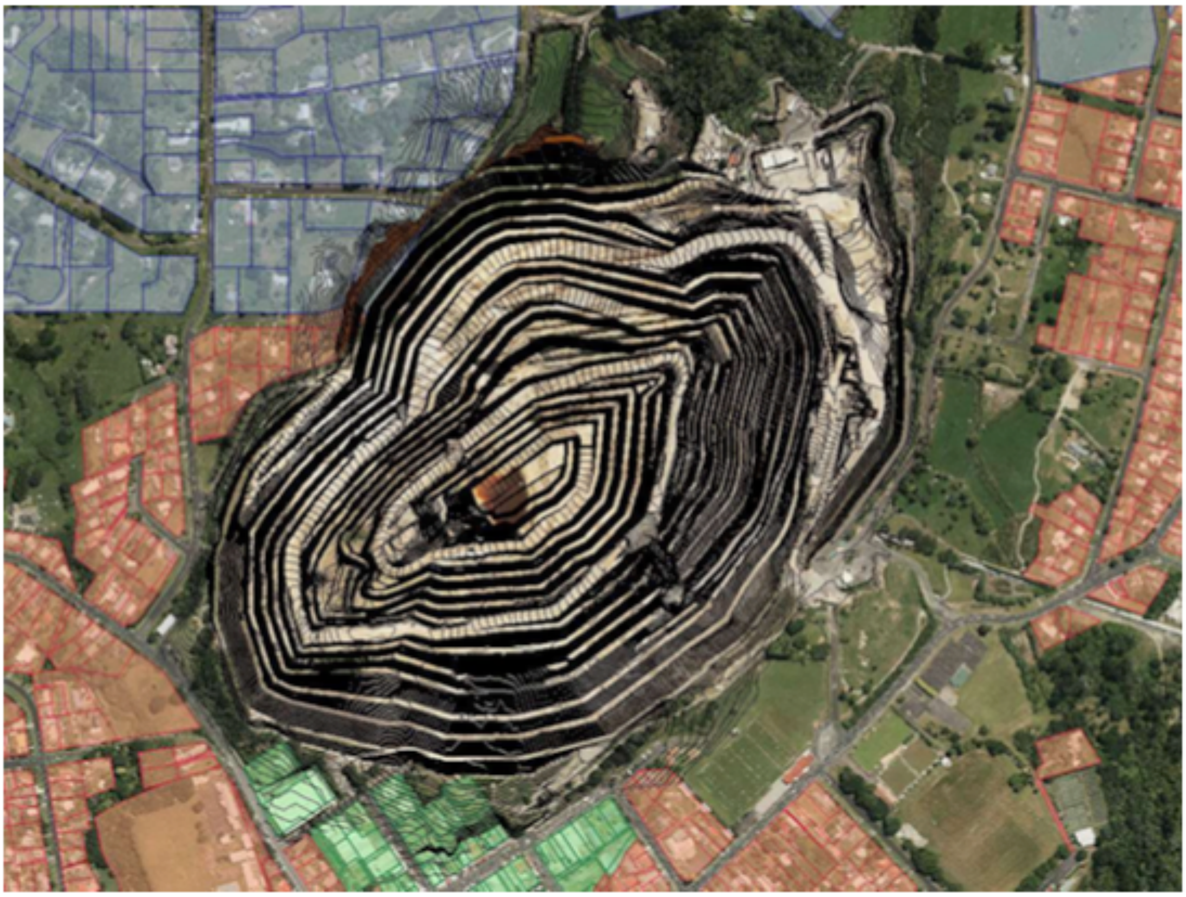

Figure 1.2 Martha Pit contours and surrounding township (Ocean Gold, 2017a).

1.1.3 Meteorology

Meteorological conditions at and near to the Martha mine pit are recorded at Waihi mine site, Golden Valley to the east, and Tauranga Airport to the south.

The meteorological conditions at Waihi consist of a humid-maritime climate with average annual precipitation of about 2 m that exceeds evaporation by approximately three-fold. Winds are frequently strong (in excess of 10 m/s) and there is only a moderate variation between minimum and maximum temperatures (average of 10 degrees difference between winter and summer). Average summer daily temperatures peak at approximately 25 ^{o}C, during winter they peak at approximately 15 ^{o}C. Daily minimum temperatures are approximately 10^{o}C in summer and below zero in winter.

1.2 Study Objectives

Hydronumerics was contracted by Oceana Gold (NZ) Limited to undertake a high-level assessment of the likely water quality in the Phase 4 Martha Pit Lake (MPL) based on hydrodynamic modelling results (Hydronumerics 2018) and available data for pit lake inputs. This works package did not include additional modelling, and focused on estimates of nutrients and algal production. This technical report has been compiled to support a resource consent application.

It is important to note that this study has been restricted to assessing the likely characteristics of MPL in terms of dissolved oxygen, nutrients and primary production by algae and does not include an assessment other chemical constituents such as pH, metal concentrations, alkalinity and hardness.

2 Water Quality in Pit Lakes

2.1 Overview

The limnology of pit lakes is influenced by a range of physical and biogeochemical processes that govern the quality of in-situ waters and water that is released into downstream environments. Predicting nutrient abundance and primary production in MPL needs to take into account the spectrum of processes that are typically considered in the limnology of lakes and reservoirs. For mine pit lakes an emphasis is often given to assessing the impacts of geochemical processes on water quality that relate to the site hydrology and mineralogy. Given the intended end-use of MPL as a recreational water body it is also important to consider the potential behaviour of dissolved oxygen, nutrients and algae.

As a background to this report we refer the reader to Hydronumerics (2018) for a description of the expected physical limnology of MPL and to AECOM (2018) for an analysis of predicted water chemistry. The findings documented in these reports have been used in this assessment.

2.2 Background

2.2.1 Dissolved Oxygen

Vertical distribution of the dissolved oxygen (DO) concentration in pit lakes (and most lakes and reservoirs in general) is in part controlled by the physical limnology, and most importantly the cycles of vertical stratification and mixing. During stratification DO concentrations evolve differently within the vertically stratified layers, depending on the comparative rates of DO renewal and depletion. During the warmer months in thermally stratified holomictic lakes (i.e. lakes that completely mix from top to bottom at least once per year) the hypolimnion is physically isolated from the mixing processes that supply DO in the upper surface mixed layer (epilimnion) waters. If there is sufficient chemical and/or biological oxygen demand in the hypolimnion and poor replenishment by vertical mixing or the intrusion of inflows, the DO concentration in the hypolimnion will deplete. If the strength of the oxygen demand is high enough and the duration of stratification long enough, the hypolimnion may become anoxic at some stage during the stratification period.

In contrast to the hypolimnion, the rate of oxygen depletion in the epilimnion is typically less than the rates of oxygen renewal from the sum of atmospheric exchange, and algal and submerged macrophyte photosynthesis during daylight hours. Well-oxygenated water just below the surface is frequently mixed throughout the epilimnion during mixing events that are driven by wind and convective processes. In lakes with high photosynthetic activity near the surface the epilimnion may become supersaturated with oxygen during daylight hours (Boland and Griffiths, 1995). During the night, when photosynthesis stops, respiration will reduce epilimnetic DO. With the exception of high oxygen demand under quiescent conditions, it is atypical for epilimnion waters to experience extended periods of oxygen depletion, owing to frequent atmospheric exchange from mixing. Extended de-oxygenation may occur during periods of extremely high oxygen demand, such as the decomposition of large loads of organic matter and microbial degradation of labile organics in flooded littoral zones, which has been observed in newly filled water bodies or during refill of drawn-down reservoirs (Gunnison et al. 1980).

For lakes with a hypolimnetic oxygen demand, vertical DO profiles in the intermediate waters of the metalimnion typically consists of a strong oxygen gradient (an oxycline) that ranges from near-saturation at the bottom of the epilimnion to depleted concentrations, and potentially anoxia, in the waters at the top of the hypolimnion. The specific structure of the metalimnetic DO profile will change gradually over time as the epilimnion deepens in the cooler months, and also intermittently in response to mixing events and/or intrusions of inflows that entrain higher DO waters into the metalimnion (e.g. localized storms etc.). However, complete erosion of the oxycline is usually not observed until late autumn or winter when the thermal stratification is dismantled and waters that are oxygenated near the surface circulate throughout the depth of the water column.

For meromictic lakes (i.e. lakes that do not mix to the bottom) the monimolimnion at the bottom may remain anoxic indefinitely due to the ongoing presence of the density stratification that prevents complete mixing of the lake. For oligomictic lakes (i.e. lakes that mix to the bottom only occasionally and not every winter), anoxia in the hypolimnion may persist for many years, but the lake will at some time experience deep mixing during highly energetic conditions (such as storms), which re-oxygenate the bottom waters.

The extent of oxygen depletion in the bottom waters, and the duration of the depletion, will be a significant factor in the alteration of the lake chemistry. Permanent change in redox conditions in the bottom waters may lead to the development of a chemocline at the top of the monimolimnion. For an oligomictic lake, strong gradients in the chemistry may also develop over extended periods (possibly many years) of stratification. For holomictic lakes, the frequency of complete mixing (every winter) may reduce the strength of the chemocline, but this will depend on the rates of site-specific biogeochemical reactions that respond to seasonal anoxia. Among the numerous chemical changes that may take place in oxygen-depleted waters, the release of mineralised nutrients from anoxic lake sediments is often a critical part of the nutrient cycle in stratified lakes.

There are numerous reported observations of hypolimnetic oxygen depletion in mine pit lakes (e.g. Dowling 2004, Doyle and Runnels 1997; Levy et al. 1997; and Yusta and España 2013) that note the development of strong oxygen gradients during stratification. Doyle and Runnels (1997) provide a clear example of temperature, conductivity and DO profiles in the deep meromictic Gunnar pit lake (Figure 2.1). These illustrations show seasonal temperature stratification near the surface, permanent salinity stratification at depth and oxygen depletion and renewal in response to the changes in the thermal stratification. This includes re-oxygenation to 60 m during the autumn-winter months (see November in profiles in Figure 2.1) but permanent near-anoxic conditions below. Observations in other pit lakes (e.g. Boland and Padovan 2002) show that when productivity is low (and hence hypolimnetic oxygen demand weak) significant oxygen concentrations can remain in the deeper waters all year round.

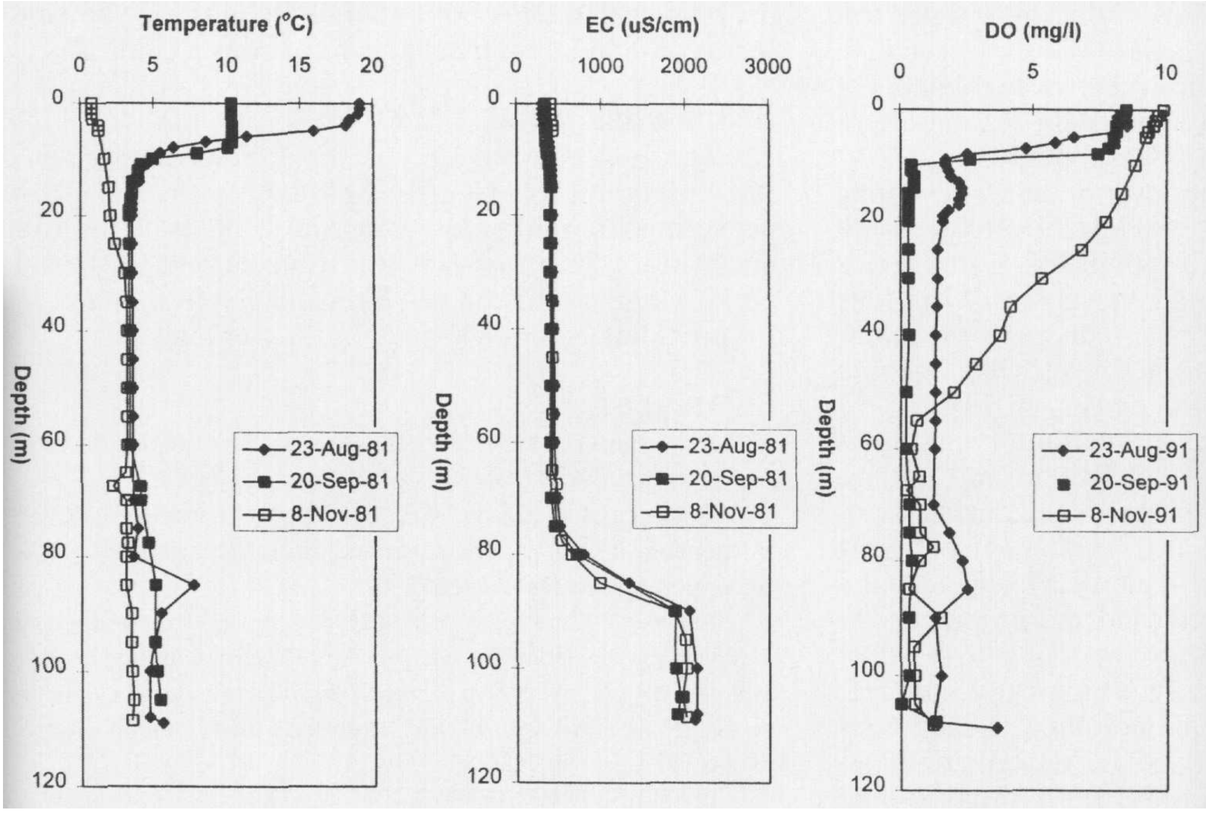

Figure 2.1 Observed profiles of temperature, conductivity and DO concentrations in Gunnar pit lake (cited in Doyle and Runnels, 1997 – reproduced from Tones, 1982).

2.3 Nutrients

2.3.1 Nitrogen

The basic components of the nitrogen (N) cycle within a lake are illustrated in Figure 2.2. The cycle is complex and consists of numerous fluxes between water-column and sediment pools of inorganic and organic nitrogen. Inorganic nitrogen consists of dissolved forms - nitrate NO_3^- (and, under reducing conditions, nitrite NO_2^-) and ammonium, NH_4^- – and particulate inorganic nitrogen. Organic forms consist of particulate and dissolved sources that are either labile (i.e. easily broken down) or refractory (i.e. difficult to break-down such as woody plant material), and nitrogen that is contained within the biota, which includes benthic plants (e.g. macrophytes), algae and higher organisms.

Sources and sinks into and out of the in-lake nitrogen cycle include external inflows, atmospheric deposition and loss (primarily loss to the atmosphere as N_2 gas though the process of denitrification) and N-fixation by primary producers that draw atmospheric nitrogen into the cycle. Importantly, the nitrogen cycle relies on a range of different conditions that are necessary to support biogeochemical processes. This includes well-oxygenated water and/or sediment zones for the process of nitrification to produce NO_3^-, and oxygen-depleted zones for the generation of NH_4^- through ammonification. Somes (2013) provides a simplistic schematic that demonstrates the requirement for oxic and anoxic conditions in the open ocean for the completion of the stages of the nitrogen cycle within the water column. The same principles apply to deep lakes with the exception that there is a far greater emphasis on processes occurring at the sediment-water interface when compared to the open ocean. Because the fluxes in the nitrogen cycle depend on microbially mediated processes undertaken by decomposers and nitrogen fixing, nitrifying and denitrifying bacteria, the nitrogen cycle requires an established microbial community within the lake sediments.

In addition to the ecological setting, physical disconnects between the components of the nitrogen cycle may disrupt fluxes and lead to temporary or permanent sinks. This is the case in stratified lakes where a lack of vertical mixing means that primary producers in the epilimnion may be physically disconnected from available sources of nitrogen in the hypolimnion that arise though decomposition of organic nitrogen deposited on the bed. This disconnect may be permanent, in the case of a meromictic lake, or temporary, in the case of holomictic and oligomictic lakes. This may, for example, lead to pooling of NH_4-N and/or NH_3-N in the anoxic hypolimnion, and N-limitation in the epilimnion. During complete or partial mixing events, these disconnects in the cycle are potentially very rapidly 'repaired', which may trigger a spike in productively as nutrient availability is rapidly restored.

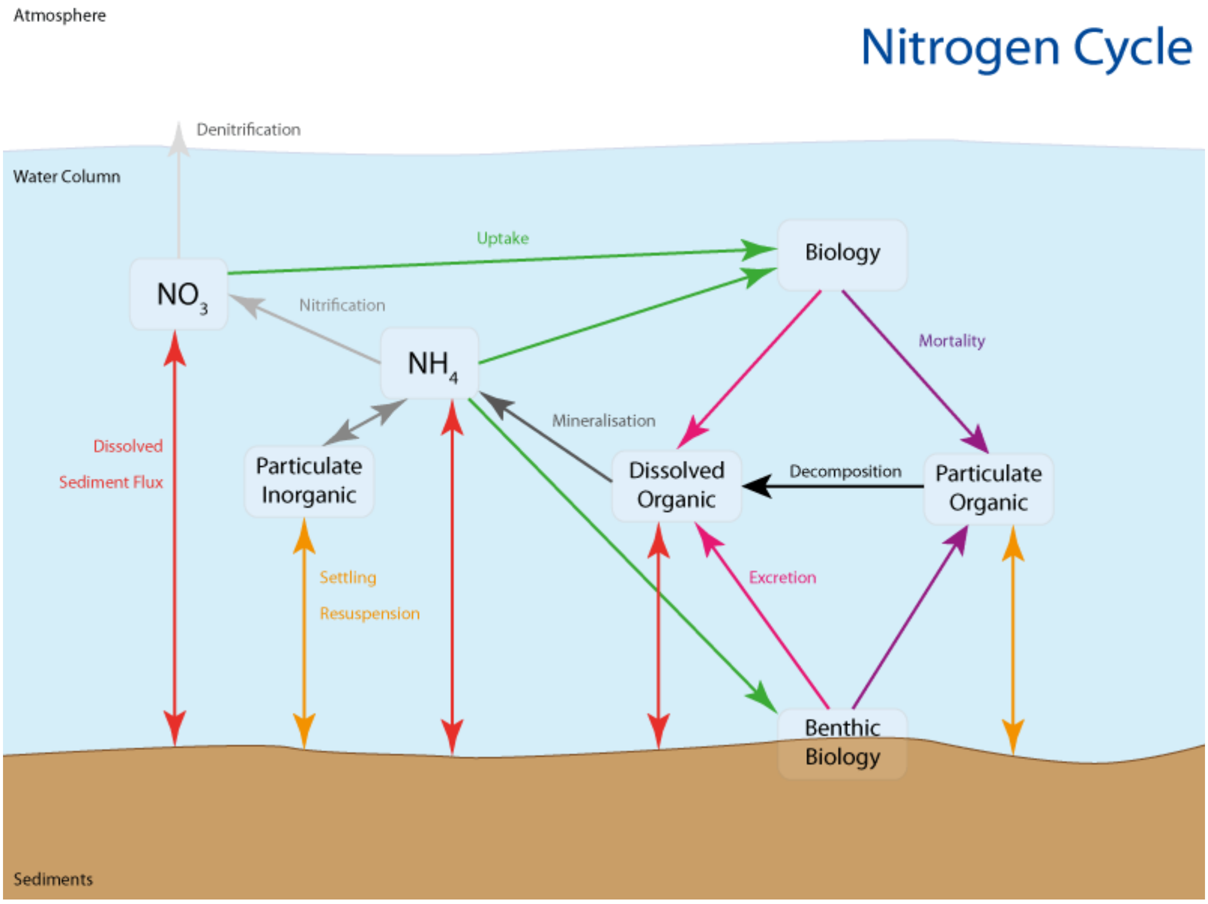

Figure 2.2 Schematic of nitrogen cycle in a lake.

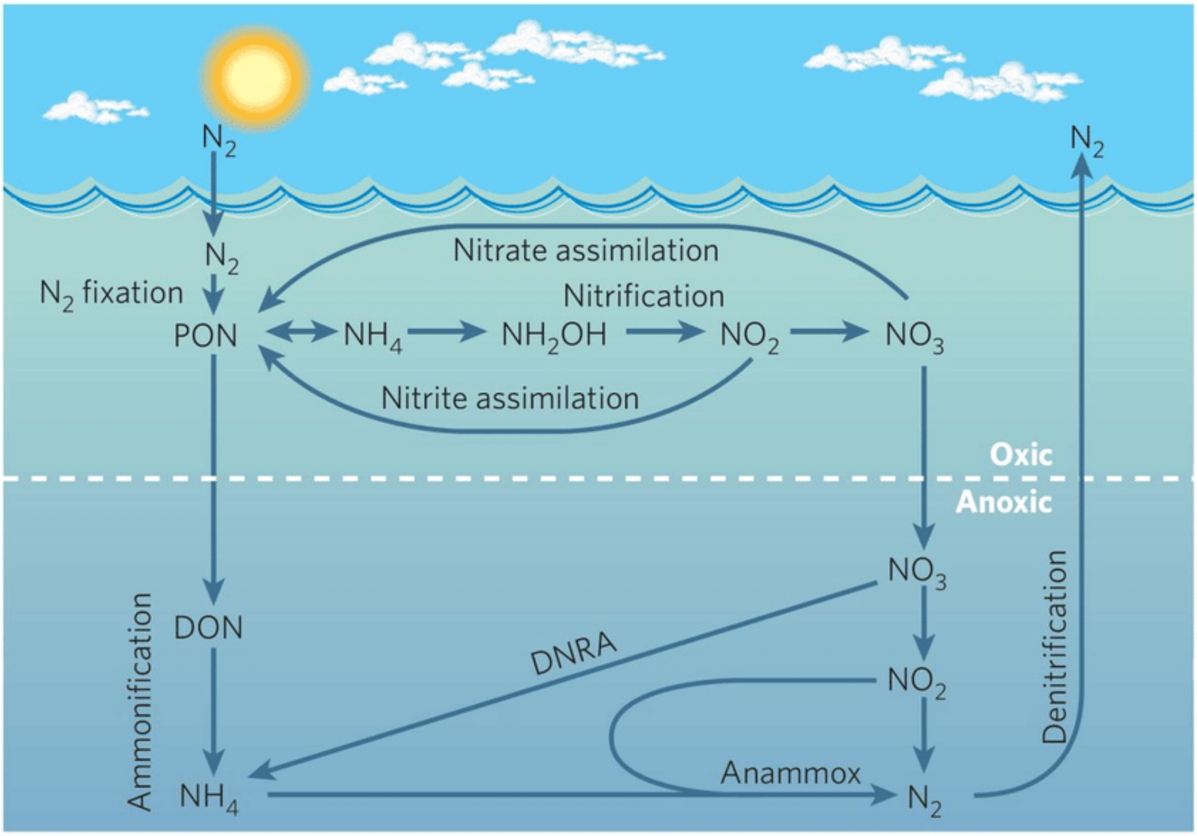

Figure 2.3 Cycling of nitrogen in the open ocean (Somes, 2013). PON refers to particulate organic nitrogen.

2.3.2 *Phosphorus*

Figure 2.4 illustrates the phosphorus (P) cycle in lakes, which is somewhat less complicated that the nitrogen cycle. The phosphorus cycle consists of sediment and water-column constituents that are inorganic – orthophosphate (PO_4^{3-}, i.e. reactive phosphates) and particulate-bound inorganic phosphorus, and dissolved and particulate organic forms, plus internal phosphorus stored in benthic and waterborne biota. External loads include inflows, atmospheric deposition, anthropogenic inputs and internal loading that may come from the release of sediment-bound phosphorus in the bed. There are numerous lake-specific factors involved in the process of sediment release of phosphorus, including the redox sensitive mobilization from the anoxic zone (a few millimetres or centimetres below the sediment surface) and microbial processes (Søndergaard et al. 2003). This may lead to the accumulation of inorganic phosphorus in the anoxic hypolimnion waters during stratification.

In many terrestrial freshwater bodies phosphorus is the limiting nutrient for primary production. This is related to the availability being constrained to the rate of external inflows and the rate of internal loading (from the lake sediments). For deep lakes that experience seasonal stratification and phosphorus deficiency in the epilimnion, the entrainment of phosphorus enriched hypolimnetic waters into the photic zone near the surface during mixing events is a critical mechanism that generates and supports primary production.

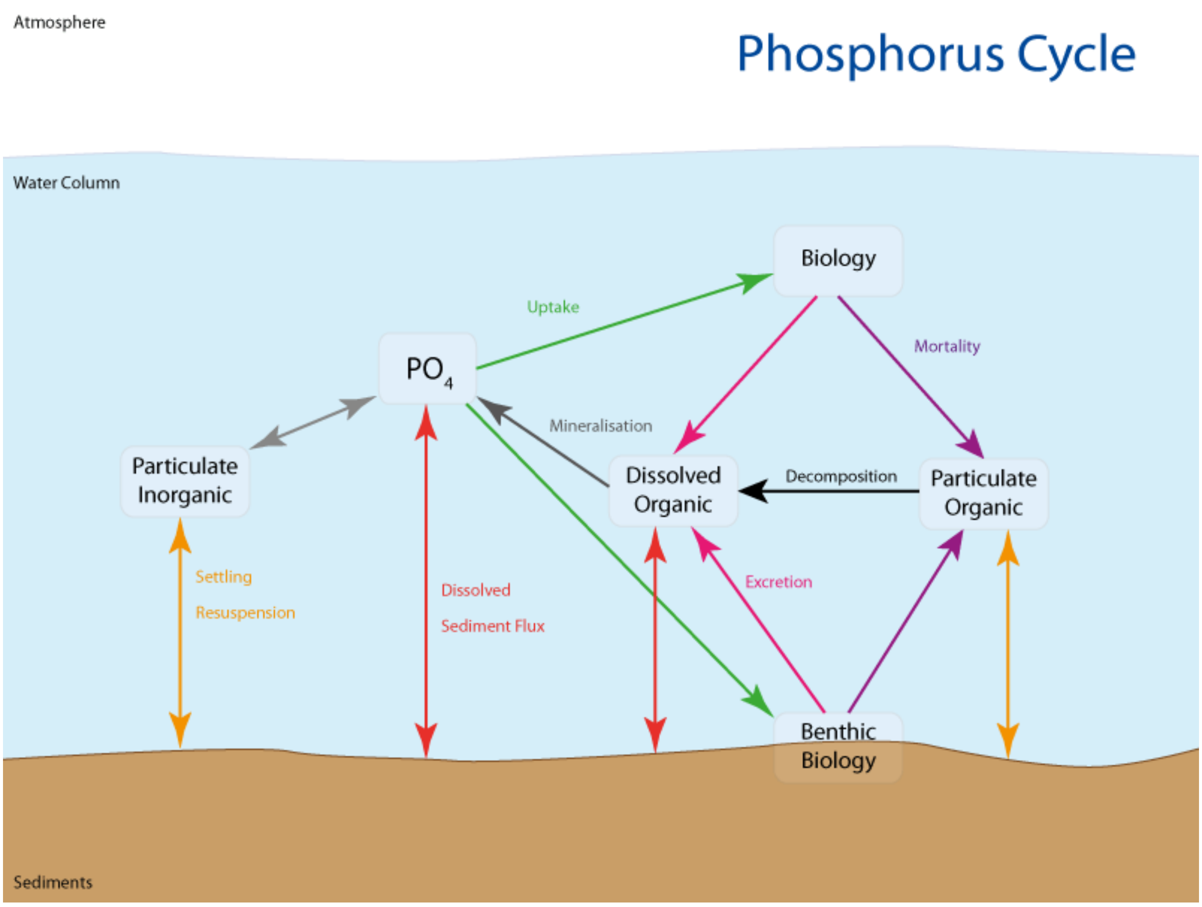

Figure 2.4 Schematic of phosphorus cycle in lakes.

2.3.3 *Nutrients in Pit Lakes*

There are two key factors that set newly filled pit lakes apart from other new water bodies. Firstly, the drowned landscapes they fill are often barren and potentially nutrient deficient. In contrast, newly formed reservoirs often inundate vegetated landscapes so that the nutrient composition of drowned vegetation provides a large initial enrichment to the water body. Secondly, the external inputs into mine pit lakes may also potentially be nutrient-poor, which is the case for pit lakes that are filled from small local catchments in the adjacent mining landscape or by rainfall and groundwater. In contrast, direct run-off or diverted river flow that is impacted by urban or rural activities is in many cases nutrient enriched, with the level of enrichment depending on the land use activities in the catchment.

As a consequence there may be a very limited initial nutrient pool in most young pit lakes, so they are nutrient poor (i.e. oligotrophic), with nutrient-limited production of algae and macrophytes (Soni et al. 2014). Blancette and Lund (2016) report that large inputs of nutrients are often required to support primary production in pit lakes, although eutrophication may be a risk in pH-neutral pit lakes. However, the effects may not be sustained after nutrient addition ceases, in part because the often-acidic conditions of pit lakes that may further reduce nutrient availability. Salmon et al. (2008) observed that under mildly acidic conditions the sorption of phosphorus to mineral surfaces is enhanced so that phosphorus-mineral interaction is likely to limit primary production. The authors note that Al and Fe mineral precipitates can scavenge phosphorus from the water column, however, only the latter re-releases phosphorus under reductive anoxia, which may occur in the hypolimnion. Although acidic pit lakes often have adequate concentrations of nitrogen, the nitrogen predominantly exists as ammonia due to limited nitrification at low pH (Nixdorf et al. 2001, cited in Kumar et al. 2016). Yusta and España (2013) observed oligotrophic pit lake water quality with relatively stable total nitrogen, where in summer nitrates dominate in the shallow oxygenated zone and ammonium was the predominant species observed in the deep anoxic zone. They further report that the cycle of nitrification and ammonification disappeared in winter and only nitrates were observed.

Shultze et al. (2010) reported on more than 40 pit lakes in the central German lignite-mining district. The authors found that phosphorus concentrations were typically low, even in the case when river water with TP concentrations of over 100 µg/L was used to fill the pit. This is because the phosphorus was adsorbed onto the surfaces of iron precipitates and buried in the sediments. The authors also observed that despite some pits being filled with nitrate-bearing river water, after the filling period the in-lake concentrations of nitrate were typically low. Rapid removal of nitrate by primary production and denitrification in the anoxic lake sediments were postulated as the key mechanisms of removal. Despite typically well-oxygenated water in the pit lakes (with the exception of permanent anoxia in the monimolimnion of meromictic lakes), denitrification occurs because of the anoxic conditions that are typically observed in pit lake sediments (Shultze et al. 2010). As a consequence of the limited availability of nutrients the concentrations of chlorophyll-a observed by Shultze et al. (2010) were also small (88% of pit lakes had Chl-a < 4 µg/L), with the exception of eutrophication in one lake that was used to intermittently store river water over a period of decades.

2.4 Primary Production

The availability of nitrogen and phosphorus is required for the growth of primary producers including macrophytes and phytoplankton. Whilst macrophytes can utilise nutrients in the substrate, phytoplankton are reliant on availability of nutrients within the water column. A simple approach to nutrient limitation is to assess the atomic ratio of N:P and compare this to the ‘Redfield Ratio’ of C:N:P = 106:16:1 (Redfield 1958; Guildford and Hecky 2000). Under environmental conditions in which the ratio N:P > 16, phosphorus is considered the limiting nutrient for phytoplankton growth. When the ratio N:P < 16, the system is considered nitrogen deficient and potentially at risk of cyanobacterial (i.e. blue-green algae) dominance because of the ability of many cyanobacteria species to fix atmosphere nitrogen and hence overcome the inherent nitrogen deficiency.

In addition to the nutrient availability, growth (via photosynthesis) is dependent on available sunlight and water temperature. Water clarity will determine the depth in the water column over which photosynthesis can occur before becoming light limited – the so-called photic depth. The photic depth can be estimated as the depth to which 1% of incident light at the surface penetrates; following Beer-Lambert law, this yields $4.61/K_d$, where K_d is the Photosynthetically Active Radiation (PAR) light extinction coefficient (Kirk 1983). For low K_d, lake waters have high clarity, whereas for high K_d, clarity is poor. K_d is increased by elevated turbidity caused by suspended sediments, biota and particulate organics that absorb available PAR.

In a well-mixed epilimnion, the depth to which phytoplankton are observed may be considerably deeper if frequent circulation of the epilimnion ensures adequate cumulative daytime exposure to sunlight closer to the surface. For fixed plants in the littoral zone the euphotic depth is indicative of the extent of benthic growth down the slope of the lake shore. In deep steep-sided lakes, such as pit lakes, the areal extent of substrate with suitable light for littoral growth may be very small, when compared to lakes with gentle sloping banks and/or shallow overall depth.

Other limitations on the growth of aquatic plants include temperature (which typically manifests as distinct seasonal cycles of growth in mid-latitude lakes), pH and potential toxicity (such as high Cu concentrations), with some limitations applying to the growth of specific types of flora, such as the requirement of silica for the growth of diatoms. In the case of pH and toxicity, there are species-specific ranges for tolerance, outside of which growth may be prohibitive or loss may occur. The success of both macrophytes and algae may also be limited directly by the physical characteristics, which may include the frequency and extent of inundation and drying, vigorous mixing, and water currents and bottom stress.

When conditions are favourable for growth, the composition of the community that is successful will depend on the competitive advantage offered by individual adaptions to the physical and biogeochemical conditions, and the presence of an inoculum that triggers initial growth. One important adaptation that allows specific species (such as many types of cyanobacteria) to overcome nitrogen limitation is the ability to fix atmospheric nitrogen, which gives these species a distinct advantage in nitrogen-poor waters.

3 Martha Pit Lake

3.1 Stratification and Mixing

The predicted limnological behaviour of MPL consisted of strong seasonal stratification in the warmer months, followed by winter mixing that erodes the thermal stratification (see Figure 3.1 and Figure 3.2). In the first 5 years after filling the winter mixing extends more than 150 m below the surface. After this period a density gradient from high TDS groundwater inflow into the bottom of the pit extends higher into the water column and restricts the depth of winter mixing. After the initial 5 years and in years with warmer autumn and winter months, the extent of winter mixing is less than 100 m, and typically less than 75 m. Mixing to the full depth of the pit lake was not predicted because of the development of the density gradient (pycnocline) between the overlying pit water and high TDS groundwater that enters at depth (see Figure 3.3). We refer the reader to Hydronumerics (2018) for further details regarding the predicted mixing and stratification.

Modelling results show that during the peak of summer stratification between January and February the epilimnion is 5 to 10 m deep and with temperatures of 23 to 27 ^{o}C. The temperature gradients in the metalimnion extend 20 to 25 m below the epilimnion, reaching down to 12 to 13 ^{o}C. In the hypolimnion temperature gradients are very weak with temperature differences of less than 1 ^{o}C spanning over the bottom 150 m. In the autumn months the surface temperatures cool and the epilimnion deepens until the temperature gradients erode almost completely. The water cools to between 12 and 13 ^{o}C in mid-winter and in the spring, temperature gradients build again back towards peak summer stratification.

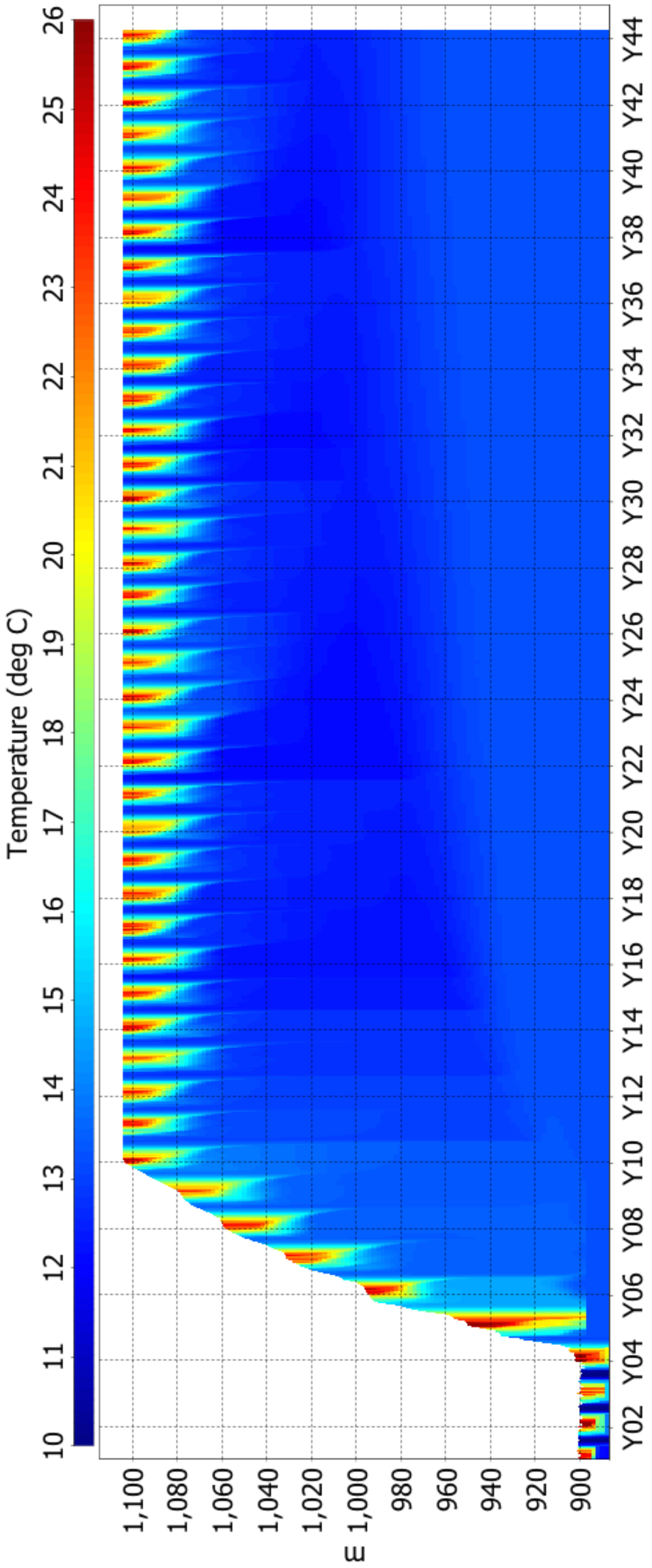

Figure 3.1 Simulated temperature for extended baseline simulation. Years (Y) denote the year of project.

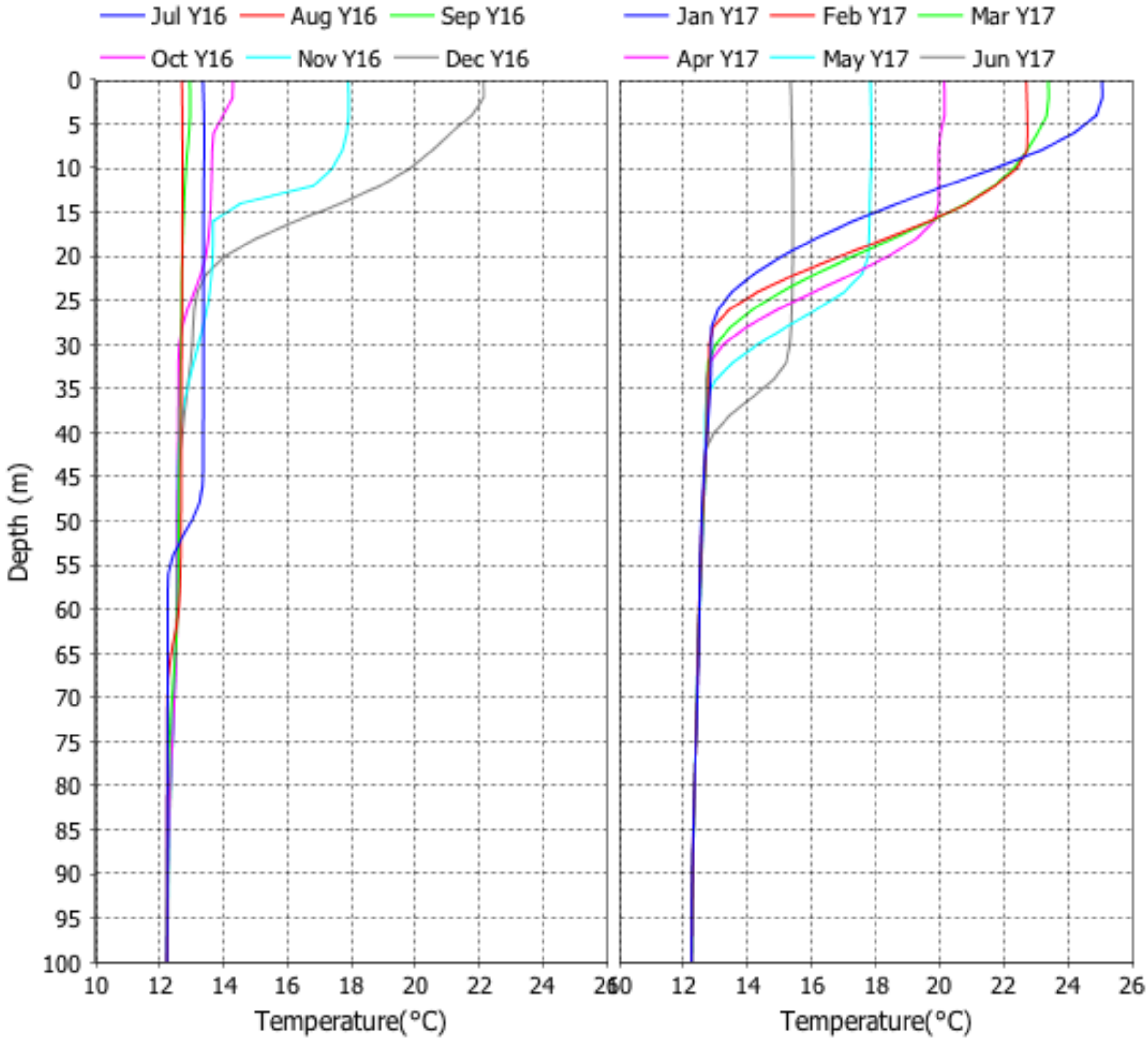

Figure 3.2 Example of simulated mid-month temperature profiles from July Y16 to June Y17.

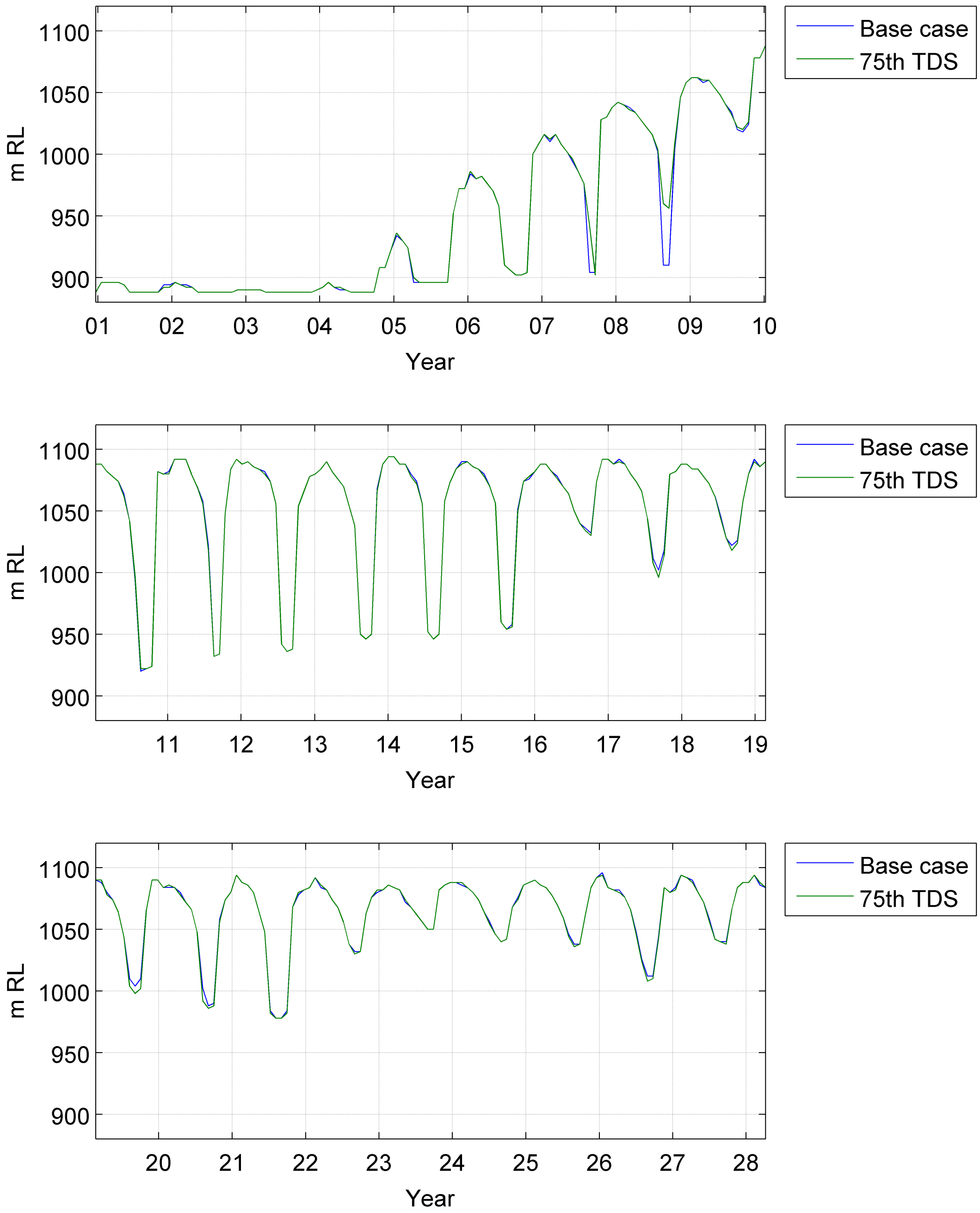

Figure 3.3 Simulated mixing depth for the base case simulation with 50th percentile TDS used for PAF run-off inflows (blue) and 75th percentile TDS used for PAF run-off.

3.2 Dissolved Oxygen

Dissolved oxygen (DO) was not modelled in the MPL physical modelling study; however, the likely behaviour can be deduced from the mixing and stratification predictions. Here, we examine the simulated mixing energy (Figure 3.4 and Figure 3.5) and retention time (Figure 3.6). The depth of the mixing energy is indicative of the extent to which oxygen transferred via exchange at the surface will be transported down into the water column. The results suggest that in the top 10 to 15 meters mixing is typically regular throughout the year, and the penetration of mixing energy is deeper over the cooler months, so that dissolved oxygen concentrations near the surface are likely to remain near saturation due to atmospheric exchange and mixing. There are however brief periods, when wind speeds are low (see for example Figure 3.5 in late-April and mid-September in Y23) and mixing does not penetrate below the surface few metres. If oxygen demand in the epilimnion waters is high enough, moderate DO depletion near the surface may occur during these quiescent periods, but is likely to be short-lived and followed by re-oxygenation in the next mixing event.

During winter mixing years after filling Y10 to Y14, oxygen (as indicated by the mixing depth) may be transported as deep as 930 m RL (174 m depth), but only in mid-winter and for a brief duration (see Figure 3.3). In the shallower mixing years that follow the oxygen replenishment may only be to approximately 1050 m RL (54 m deep). As a consequence, for much of the year there is likely to be no oxygen replenishment of the hypolimnetic waters and anoxia may result below the thermocline. When winter mixing does occur, in shallow mixing years the replenishment may be limited to the top 50 to 70 m so that there remains a large portion of the hypolimnion over which persistent anoxia may occur. In the waters below 930 m RL there is no top-down mixing so permanent anoxia is likely. The thickness of the anoxic bottom layer is also likely to increase over time as the groundwater contribution at the bottom of the pit continues, gradually lifting the density gradient higher into the water profile and reducing the depth of winter mixing.

The simulated retention time shows that after filling there is a continual ageing of the waters in the pit due to a lack of new source waters after river diversion stops, with the exception of renewal of groundwater at the bottom associated with the continual inflow of groundwater. During years of deep winter mixing after filling (see for example Y26) there is a sharp reduction in water age down to the extent of the mixing. This suggests that given the lack of inflows into MPL over the long term, the internal biogeochemical processes that impact dissolved oxygen at depth are likely to be dominant, with the exception of brief periods when winter partial mixing replenishes dissolved oxygen, although not to the bottom of the lake.

This prediction for DO dynamics in MPL is consistent with the observed hypolimnetic oxygen depletion seen in other mine pit lakes (e.g. Dowling 2004, Doyle and Runnels 1997, Levy et al. 1997 and Yusta and España 2013). It is however, difficult to predict the strength of the DO gradients and the extent of depletion in the hypolimnion without prior knowledge of the oxygen demand in the pit lake. For example Tones (1982) (Figure 2.1) observed sharp oxygen gradients at 10 m during the warmer months and a gradual decline from the surface to 60 m during the winter mixing period. Moreover, Boland and Padovan (2002) show that when productivity is low (and hence hypolimnetic oxygen demand weak) significant oxygen concentrations can remain in the deeper waters all year round. However, for MPL, in which multiple years of no oxygen replenishment to the deep waters is likely, permanent anoxia of the deep waters may develop. The oxygen gradient above these waters is harder to predict due to the complex interaction between rates of renewal (via mixing and potentially photosynthesis) and rates of depletion (via biogeochemical consumption that will occur in the intermediate waters).

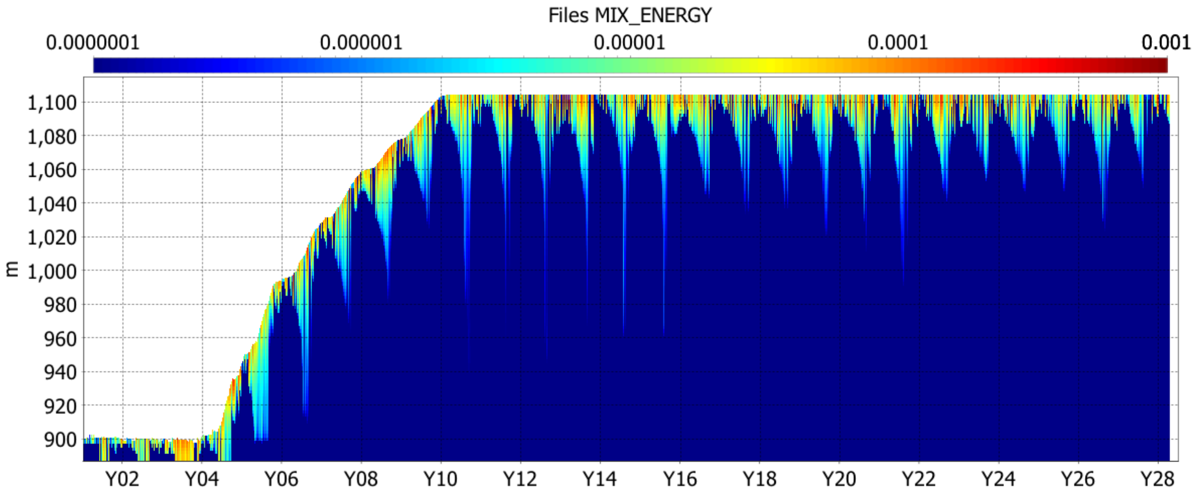

Figure 3.4 Simulated mixing energy (in units of dissipation, m^2s^{-1}) over the duration of the simulation.

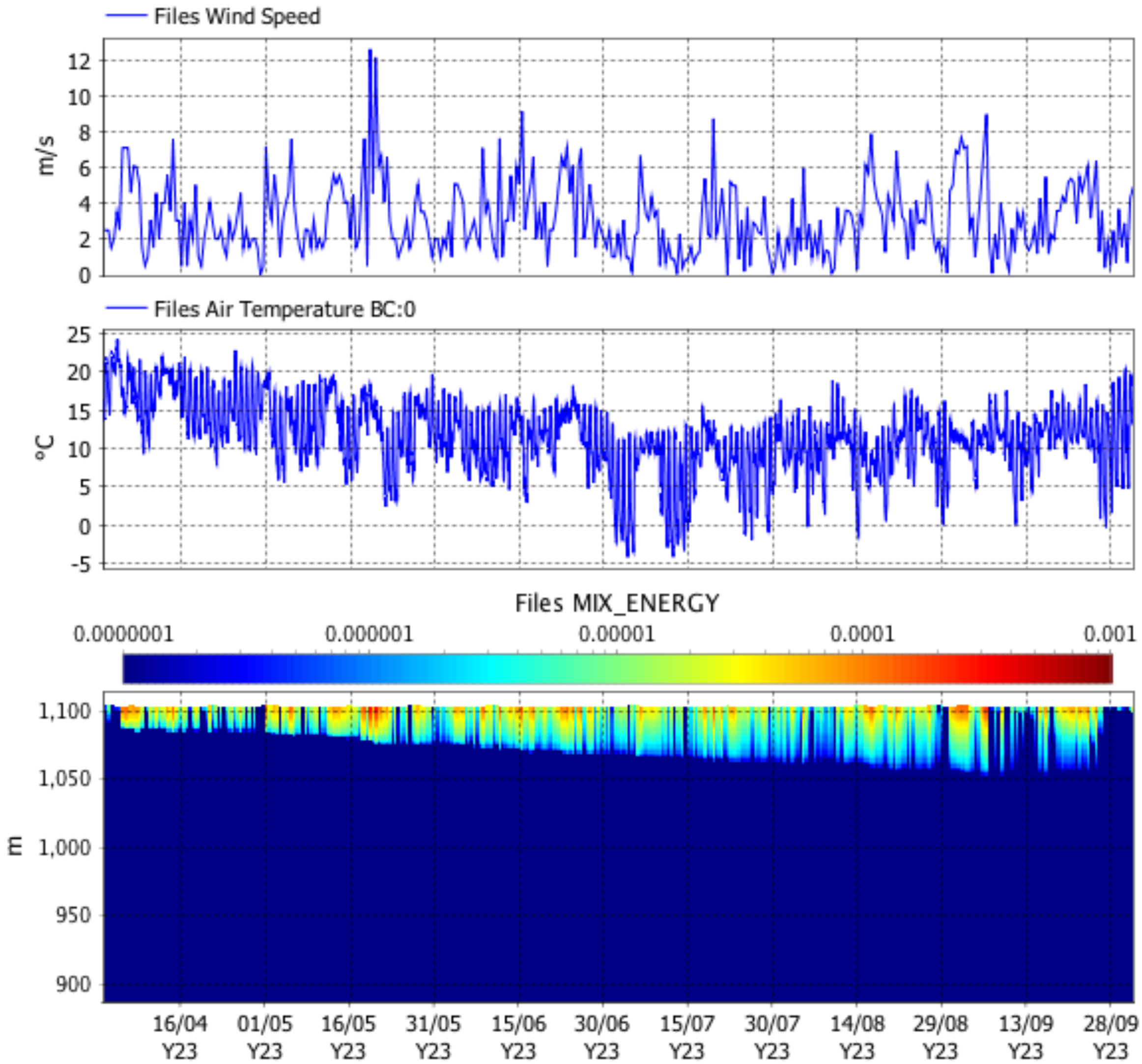

Figure 3.5 Wind speed (top panel), air temperature (middle panel) and simulated mixing energy (m^2s^{-1}) (bottom panel) from April to October Y23.

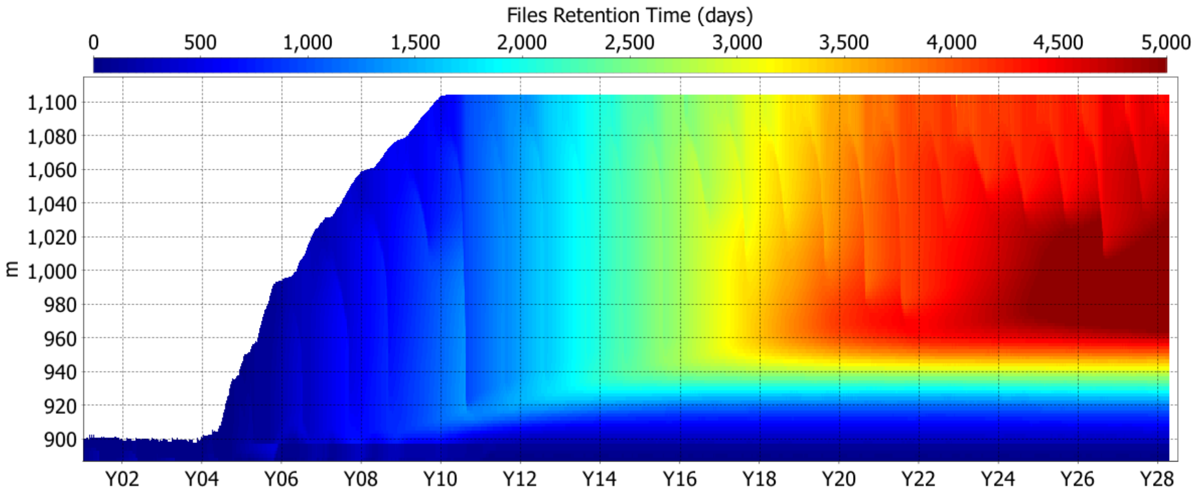

Figure 3.6 Simulated retention time (in days).

3.3 Primary Production

3.3.1 Light and Temperature Limitation

Temperature limitation of phytoplankton growth is likely in the epilimnion during the cooler months of the year, which is typical of temperate lakes with distinct seasonal temperature differences. Light limitation in the epilimnion may result from suspended sediments, algal growth, and organic substances that absorb light. However, water quality data suggests the river water has low turbidity (median of approximately 1 NTU) so that it is unlikely that the river water will inhibit the availability of light over the epilimnion depth.

The water quality data suggests a combined median TSS in excess of 100 mg/L for the pit-wall run-off. Whilst the high TSS of the run-off water may temporarily inhibit light availability immediately after run-off it is likely that settling of the particulate material will restore high clarity. Furthermore, the pit-wall run-off during the filling period contributes only a small fraction of the overall water in the pit, and over the filling period this fraction decreases as the walls are inundated. After filling, when the river diversion ceases, there is potentially greater influence on clarity from the pit-wall run-off TSS; however, it would be expected that pit-wall weathering and rehabilitation will negate some of the TSS input. It is therefore likely that water clarity will respond to primary production in the lake and less so to external inputs. This is discussed further in Chapter 0.

There is also the potential for light limitation when the water level in the pit is low during filling (compared to the when full) because of the extended periods over which the pit lake surface will be in the shadow of the pit walls.

3.3.2 Nutrient Availability

We first discuss nutrient availability in the filling stages, when river water is the dominant external source of input into the pit lake and for which there is available data. As time passes after filling, the internal nutrient sources and sinks are likely to become more dominant. This is discussed further in Section 3.3.4.

During filling, nutrient availability in the water of MPL will be dictated by the external sources that are dominated by the Ohinemuri River, with addition from groundwater, pit-wall run-off and rainfall. The observed nutrient concentrations for each of the external sources has been summarised in Table 3.1 below and for the epilimnion of MPL during the summer in the filling (i.e. with river diversion) period.

External nitrogen input into the epilimnion is dominated by the high proportion of high concentration river water, most of which exists as nitrate and nitrite (NO_x-N). The residual is associated with organic nitrogen inputs from the river water.

External input streams of phosphorus are low in concentration with the exception of the pit-wall run-off, with high P concentrations expected from runoff over the fresh PAF portion of the pit wall (median TP of 2.8 mg/L) and post-mineralised portion of the pit wall (median TP of 0.15 mg/L). These are important sources of P into the pit lake given the low P concentrations in the remainder of the contributing waters.

It is reasonable to assume that in comparison to the external sources the internal contributions of N and P will be small in the filling and early post-filling stages. However, the long-term chemical mobility of nutrients within the pit-wall mineralogy or from deposition of allochthonous sources under sub-aqueous and anoxic conditions will be important in the long term nutrient dynamics. At this stage these mechanism are not well understood and difficult to quantify.

Based on the values shown in Table 3.1 the TN:TP ratio in the epilimnion of MPL in summer during filling is estimated to be approximately 18. This suggests a nutrient balance close to the Redfield Ratio of 16 and only slightly above values that indicate N-deficiency and potential 'high risk' of cyanobacteria growth. The TN:TP ratio therefore indicates that there is a potential risk of cyanobacteria growth in MPL.

Table 3.1 Fraction of contribution and median concentrations of N and P sources in the epilimnion during filling.

Source	**Contribution to Epilimnion (fraction)** [1]	**N (mg/L)**			**P (mg/L)**	
		NOx-N	**NH4-N**	**TN**	**FRP**	**TP**
River	0.80	0.535	0.01	0.735[2]	0.0052	0.015
Groundwater	0	0.07	0.13	0.2	N/A	0.01
Run-off[3]	0.19	0.018	0.015	0.033	N/A	0.35
Rainfall	0.037	0.04	0	0.02	N/A	0
Epilimnion		0.45	0.011	0.61		0.077

Notes: [1] AECOM (2018), Scenario A.

[2] TKN + NO_x from Ohinemuri River (site OH3) monitoring data (i.e. includes organic N)

[3] Volume weighted medium values from combined pit-wall run-off data

3.3.3 Trophic Level

Based on the New Zealand Ministry for the Environment published "*Protocol for Monitoring Trophic Level in New Zealand Lake and Reservoirs*" (Burns et al. 2000) the expected trophic level index of MPL can be determined. For an epilimnetic TP concentration of 0.077 mg/L the trophic level index for TP is 5.7, with a classification of supertrophic. For available TN in the epilimnion of 0.61 mg/L the trophic level index for TN is 4.8, with a classification of eutrophic.

From the averaging approach presented by Burns et al. (2000) and applied for the known variables of TN and TP the trophic level of MPL is estimated as 5.2, which suggests a classification (in terms of nutrients) at the boundary between eutrophic and supertrophic. Burns et al. (2000) suggest a eutrophic classification is associated with annual average Chl-a concentrations of 5 to 12 μg/L and Secchi depths of 1.1 to 2.8 m. For the supertrophic classification the Chl-a concentrations range from 12 to 31 μg/L and the Secchi depths from 1.1 down to 0.4 m.

Land Air Water Aotearoa (LAWA, see https://www.lawa.org.nz) publishes an online inventory of trophic status of lakes throughout New Zealand using the classifications described in Burns et al. (2000) and based on observations of total nitrogen, total phosphorous, water clarity, and chlorophyll-*a*. Under the description of classifications a eutrophic lake is described as being "*green and murky, with higher amounts of nutrients and algae"*. In the Bay of Plenty region an example of a eutrophic lake is Lake Rotorua. Over the last decade at a near-central site in Lake Rotorua, epilimnion TP has been observed to exceed 0.05 mg/L and TN more than 0.5 mg/L, with Chl-a periodically exceeding 30 μg/L. Whilst the TP and TN concentrations in Lake Rotorua are comparable to the estimates presented in Table 3.1, it is unlikely that a similar trophic status will be observed (or at worst sustained) in MPL, for the reasons explained below.

After filling in MPL, and based on the Redfield Ratio calculation, the abundance of available P is likely to determine the productivity of MPL. The calculated concentration of TP in the epilimnion is significantly increased by the small volume but high concentration run-off from the post-mineralised and fresh PAF portions of the pit wall. However the true bioavailability of this P is not known, and so the expected P-limitation for algal growth may be more pronounced than suggested by the TP concentrations determined from the mass balance. Assessments of the pit wall run-off water quality, and in particular from the pit-wall zones that generate high-P concentrations also show high TSS concentrations in the run-off. This indicates the potential for a large portion of the TP to in fact be particulate-bound, in which case it is not readily available for phytoplankton uptake and will also likely settle with the particulates and undergo burial in the pit lake sediments. Although the predicted circum-neutral pH of MPL (AECOM, 2018) does not suggest there will be enhanced sorption of phosphorus to mineral surfaces seen in acidic lakes (e.g. Salmon et al. 2008), the external sources of P may already be sediment bound and settle quickly to the bottom. Moreover, clay-bound P may undergo rapid settlement due to the clay particles being complexed by hardness (divalent cations, particularly Ca and Mg). Furthermore, there are changes that are likely to take place over time and reduce nutrient availability in the long term (see 3.3.4 below).

3.3.4 Changes Over Time

After the mine pit is filled the availability of nutrients for primary production is likely to depend more on internal cycling of nutrients than on the external sources. This is because the nutrient input from river water (mostly nitrogen) will cease and there will also likely be a reduction in phosphorus inputs from pit-wall run-off over time. The phosphorus reduction will be in part from an inundation of a portion of the run-off area as the lake fills but also associated with the likely reduction in P-generation from leaching and scouring over time that may be further reduced by rehabilitation of the pit walls. In the absence of potential new nutrient sources associated with the rehabilitated lake and surrounds, internal nutrient cycling will eventually control nutrient availability.

Whilst there will be some nitrogen and phosphorus lost in the released water, the process of denitrification in the anoxic water and sediments may be a significant additional loss mechanism for nitrogen, as was observed by Shultze et al. (2010) in pit lakes initially filled with nitrate-bearing river waters. The recycling of nutrients that settle into the depths of the lake, either bound to particles or part of biota, will require a combination of chemical mobilisation from the sediments and physical mixing to entrain back into the photic zone. For the latter process, loss to the monimolimnion (i.e. the deep unmixed portion of the pit lake) is likely to be near-permanent or at least re-release from the monimolimnion will occur at very slow diffusion rates due to the lack of turbulent mixing. It has been observed in other pit lakes that the monimolimnion formed by the intruding saline groundwater acts as sinks for phosphorus and other contaminants (Schultze and Boehrer, 2008).

For the former process of mobilisation from the sediments, the predicted occurrence of anoxia in the sediments suggests that some flux of nutrients from the sediments will result from changes in redox conditions; however, both the rate of de-oxygenation and the rate of sediment release will depend on complex geochemical processes and is therefore difficult to predict. Because of the predicted irregularity of deep mixing (and therefore the likelihood of periods of extended nutrient release from the sediments under anoxic conditions) there may be an irregularity in the annual availability of nutrients from recycling within the pit lake. Deep mixing (to the top of the monimolimnion) after long periods of permanent stratification may lead to higher nutrient availability than in shallower mixing years, resulting in increased productivity.

Importantly, because there is likely to be a higher portion of phosphorus retained in the pit-lake, as opposed to nitrogen that may be lost through denitrification, the observed TN:TP ratio may decrease over time. This is also a potential outcome if the sediment release of phosphorus from the pit walls is high compared to internal nitrogen release from settled detritus. A reduced TN:TP ratio may lead to nitrogen deficiency, thus increasing the risk of cyanobacteria dominance.

It is therefore likely that over time the TN and TP will decrease and the availability of these nutrients will become increasingly dependent on internal biogeochemical cycling and the physical mixing processes that support internal fluxes of nutrients. With the decreased availability of nutrients the trophic status will decrease accordingly as the system becomes less productive. With the reduction in the availability of nutrients the trophic index will also reduce, potentially to the classification of mesotrophic lake (described by LAWA as "the *lake has moderate levels of nutrients and algae"*), such as Lake Okareka. Increased nutrient scarcity that results from a lack of internal cycling may result in further lowering of the trophic status to an oligotrophic lake classification (described by LAWA as "the *lake is clear and blue, with low levels of nutrients and algae"*), such as Lake Okataina.

3.4 Assumptions and Uncertainty

There are a number of assumptions that have been made in this assessment. The first is that the pit water quality does not contain significant concentrations of toxins that may limit primary production. The potential effects of toxicity on algal growth and other aquatic life in MPL are, at this stage of the project, not well understood. For example, recent derivations of new ANZECC water quality guidelines for copper and zinc (NIWA, 2017) indicate a 95% species protection guideline value of 1.2 µg/L for copper, which is significantly lower than the concentrations predicted after filling in MPL (AECOM, 2018). Moreover, species sensitivity distribution from the copper toxicity data spanned 4 orders of magnitude and indicated sensitivity at far lower concentration of 0.3 µg/L for green algae *Chlorella* sp. Similarly, the projected concentrations of zinc (AECOM, 2018) are likely to be higher than the revised toxicity guideline for 95% species protection of 3 µg/L. Potential toxicity in the lake waters may therefore inhibit colonisation by sensitive species.

The second key assumption is that there will be no additional long-term sources of nutrients into the pit-lake after the filling period. Additional sources may include, for example, diffuse or point source discharges associated with rehabilitation of lake surrounds, catchment drainage and augmented inflow supply. Thirdly, it has been assumed that the MPL's intended recreational end-use will not have a significant impact on the biogeochemical processes that govern the nutrient availability and primary production.

Aside from the uncertainties associated with the predicted physical setting (see Hydronumerics, 2018), there is large uncertainty regarding the nutrient cycling within the pit-lake given the complexity of the mechanisms and the required biogeochemical conditions, in particular for microbially mediated processes.

3.5 Monitoring, Management and Mitigation

It is not possible to accurately predict the complexities of the limnology that will result in MPL given the unique nature of all lakes. The knowledge required for successful management and addressing the uncertainties can only be properly addressed by ongoing monitoring during and after filling and adaptive management in response to the information collected. This will provide the information necessary to develop a more detailed understanding of the long-term nutrient availability and trends in primary production in the context of the broader ecology.

At a high-level there are a number of basic considerations that are likely to lead to improved outcomes for MPL. Including provisions for a littoral zone that allows for the establishment of macrophyte beds and riparian vegetation will have benefits for lake water quality. These include improved nutrient cycling, potential fish habitats and refugia, and bank stabilisation to reduce turbidity. Littoral macrophytes will, along with algae in the open lake areas, also increase the photosynthetic activity (in daylight hours) and assist the generation of increased concentrations of bicarbonate in the lake and hence its capacity to buffer acidity. The establishment of littoral habitats requires a physical setting on the lake edges that allows for sufficient light for growth of submerged plants. In addition, a stable water level (i.e. without periods of inundation and draw-down) will assist with the success of the littoral plants.

If MPL develops as an unproductive (and potentially acidic) lake, nutrient enrichment could be considered to stimulate algal growth and alkalinity generating processes, which can buffer acidity generation and promote natural lake processes. Kumar et al. (2016) suggests that even in acidic pit lakes with carefully planned enrichment, once there is enough autochthonous generation of nutrients to drive the natural biogeochemical processes, these pit lakes may slowly emulate their natural counterparts and become regionally representative functional aquatic ecosystems. Furthermore, enrichment with nitrogen-rich sources that are low in phosphorous may provide and mechanism to increase the TN:TP ratio and reduce the potential risk of cyanobacteria dominance.

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4 Summary

In summary, the following limnological water quality attributes can be expected for the Martha Phase 4 pit lake:

- Dissolved oxygen concentrations will respond directly to the mixing and stratification, whereby:
    - DO concentrations in the epilimnion are near-saturation concentrations most of the time because of the mixing of atmospheric oxygen from the surface. There may be periods of epilimnetic quiescence when exchange slows and oxygen concentrations fall, but they are likely to be short-lived given the high frequency of wind events;
    - DO in the water below the epilimnion will become seasonally de-oxygenated and potentially anoxic due to the lack of replenishment from the surface. These waters will be re-oxygenated briefly during winter mixing, but the depth of re-oxygenation will range from shallow (approximately 50 to 60 m deep) to just above the monimolimnion, depending on the extent of winter mixing; and
    - The monimolimnion is likely to remain persistently anoxic.
- There is likely to be a seasonal pattern of primary production. Provided there is sufficient nutrient availability highest production will occur in spring and summer in response to the warmer temperatures that favour growth;
- Light limitation in the epilimnion is not likely given the clarity of the river waters and settling of suspended solids, except in the event of significant algal production;
- The river water and the pit-wall run-off are significant external inputs into the available nutrient pool in the epilimnion during filling;
- It is most likely that the extent of primary production during filling will be limited by the availability of phosphorus in the source waters;
- During filling the nutrient availability is sufficient to suggest productivity consistent with a eutrophic to supertrophic lake (under the classification for NZ lakes provided by Burns et al. 2000), with annual average Chl-a concentrations between 5 to 31 μg/L;
- After filling, the internal cycling of nutrients is likely to become a dominant process with both physical and biogeochemical mechanisms controlling nutrient availability in the epilimnion. This may reduce the trophic status (and following observations in other pit lakes) to potentially oligotrophic with low productivity;
- After filling, loss of nitrogen from the lake due to denitrification in the anoxic waters may lead to a shift towards nitrogen limitation, therefore increasing the potential risk of cyanobacteria growth;
- The depleted oxygen concentrations in the hypolimnion and associated sediment release of nutrients into the hypolimnion followed by the subsequent entrainment of these nutrient enriched waters into the epilimnion during mixing will be an important sequence of processes that control nutrient availability in the photic zone after filling;
- Nutrient availability in the epilimnion is therefore likely to be irregular, given the changes in the depth of winter mixing and the associated changes in the extent of entrainment of nutrient-enriched waters. This may in turn lead to years that are significantly more productive than others, particularly when mixing occurs after an extended period of hypolimnetic nutrient enrichment;

- Given the complexity of the nutrient cycles and the unknown rates of oxygen depletion and nutrient release from the sediments, it is difficult to predict post-filling primary production, other than to note that it is likely to initially reduce from the filling period;
- Including provisions for a littoral zone in the mine closure planning that allows for the establishment of macrophyte beds and riparian vegetation will have overall benefits for lake water quality;
- Nutrient enrichment may provide a means to promote natural lake processes if MPL evolves to the nutrient deficient. It may also be a means to increase the TN:TP ratio and reduce cyanobacteria risk; and
- Ongoing monitoring of nutrients and primary production will be important to improve long-term predictions of MPL water quality and inform management practices into the future.

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