Ruataniwha Water Storage Scheme

Characterisation of Makaroro reservoir water quality

Prepared for Hawkes Bay Regional Investment Company Limited

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Contents

Tables

Figures

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Executive Summary

As part of the feasibility study for the proposed Ruataniwha Water Storage Scheme, NIWA was commissioned by the Hawke's Bay Regional Council to provide an assessment of the likely water quality in and discharged from the proposed Makaroro reservoir to be constructed on the Makaroro River upstream of Burnt Bridge. Subsequent to the production of that Feasibility Study Report, the proposed operating regime was changed to Scenario 3-28M which is described in the Project Description Report. The Feasibility Study Report has been updated in light of those changes, in order that it might form part of the assessment of environmental effects to support any resources consent applications being made by the Hawke's Bay Regional Investment Company (HBRIC).

The assessment of water quality effects in this report is based on the proposed Ruataniwha Water Storage Scheme (the Scheme) as described in the report prepared by Tonkin and Taylor Limited entitled Ruataniwha Water Storage Scheme: Project Description, (dated March 2013), referred to in this report as the Project Description (PD).

Potential effects

The major effect of constructing a dam on the Makaroro River will be a change in flow regime in the river below the dam from a natural high-low response to rainfall events to a more regulated flow without extreme flood events. The use of the Makaroro reservoir, that forms behind the dam, as a water supply for the proposed Ruataniwha Water Storage Scheme will cause changes in the water level in the reservoir and different flow patterns in the downstream river, as defined in the PD.

The water in the Makaroro reservoir will have a theoretical mean residence time of about 164 days, based on the full volume of 90 million m^3 and a proposed mean annual discharge of 6.342 m^3 s^{-1} (Tonkin & Taylor data provided for the Feasibility Study). This residence time will delay the movement of sediment down the river channel by causing the heavier rocks, gravel and sand to deposit at the inflow end of the reservoir and allowing sufficient time for the finer particles to settle to the lake bed as the water moves the 6 km downstream to the dam wall and outtake structures. This will substantially reduce the sediment load and produce higher clarity water downstream of the dam.

The residence time will also allow the surface waters in the lake to become warmer than the inflow river in winter and consequently the downstream river will be slightly warmer than it would naturally be without the reservoir. Conversely, in summer the water temperature in the reservoir will be cooler than the midday temperatures in the inflow river but warmer than the night time river temperatures. This "thermal damping" will result in less variability in temperature than would otherwise occur in the river downstream of the dam.

Assessment undertaken

The assessment undertaken required characterisation of the predicted water quality in the proposed Makaroro reservoir including:

1. expected physico-chemical characteristics of the water within, and discharged from the reservoir
2. suitability of reservoir water quality for aquatic life, recreation and other uses

3. effects of removing vs. retaining vegetation within reservoir extent
4. other considerations/recommendations regarding future dam site management before, during and after dam establishment, and
5. further investigations/information that may be required to characterise reservoir water quality.

To achieve this, the proposed reservoir was modelled using the coupled hydrodynamic-ecological model DYRESM-CAEDYM to simulate hydrological, hydrodynamic and water quality for several operating regimes. Expected bathymetry of the completed reservoir and flow data in the Makaroro River were provided by Tonkin and Taylor Limited. Meteorological and climate data were obtained from 5 of NIWA's Virtual Climate Network Stations (VCNS) over the reservoir site and catchment, as well as national Meteorological climate stations at Dannevirke and the Takapau Plains. Water quality data for the Makaroro River were obtained from the NIWA National Rivers Water Quality Network (NRWQN) monitoring site at Burnt Bridge. Additional parameters used in the model were obtained from literature values and other studies producing similar simulations. These data were applied to the DYRESM-CAEDYM model which was run with a daily step interval for the 5-year period 2000 to 2005.

Because the Makaroro reservoir does not exist, the model was unable to be calibrated against empirical observations using statistical measures of model performance. Rather, the calibration for sensitive parameters during the setup of the model was based on a combination of expert knowledge, coefficients from other model applications, and values from literature. Consequently, predictions and assessments use best scientific practice based on the available data provided.

Assumptions made in the modelling include no changes to landuse in the catchment that would increase nutrient loads to the Makaroro River and reservoir and that land clearance for production forestry and other activities would be managed to keep sediment erosion to a minimum.

Initial model scenarios used operating regimes where a mean flow of around 6 $m^3 s^{-1}$ was drawn from outtake valves set at either 455.5 m relative level (RL) (upper) or 426 m RL (lower) with additional compensation water of about 1.23 $m^3 s^{-1}$ being drawn from the toe of the dam at 395 m RL. These modelling results indicated that the upper and lower outtake levels resulted in selective draw-induced stratification at the draw depth. Water quality above the draw depth was generally good but below the draw depth the water quality was poor, and would become anoxic for extended periods. It was concluded that selective draw from as deep in the lake as possible would greatly improve the water quality in the reservoir.

This was tested with three new model scenarios:

- **M1**: main draw depth set at 405 m RL (allows 10 m deep sediment accumulation below the draw depth)
- **M2**: main draw depth set at 443 m RL (has 48 m water depth below the draw depth), and
- **M3**: minimum base flow of 1.228 $m^3 s^{-1}$ drawn from 405 m RL and the remainder, about 5.1 $m^3 s^{-1}$ being drawn from the 443 m RL outtake.

Results of assessment

The presence of organic matter remaining within the reservoir extent at the time of construction was found to cause oxygen depletion due to natural decomposition processes for several years after the reservoir is first filled. As the organic matter was consumed over time, the extent of the oxygen depletion reduced. While there was a small reduction in the time required to reduce the oxygen depletion by removing the vegetation within the reservoir extent before filling, the costs of removing the vegetation would be great and there would be areas of the reservoir extent where it would be impractical.

Additional considerations were the management of the reservoir catchment to eliminate unnecessary soil erosion due to land slippage following land clearance and future logging operations for production forest.

In general, modelling showed that the water quality in the Makaroro reservoir was likely to be similar to water quality of the inflow water although biogeochemical processes that occur naturally in lakes may change the relative concentrations of some parameters. Seasonal changes followed the natural cycles found in other deep lakes with the water column being fully mixed and well oxygenated in winter but thermally stratified during summer. The depth of stratification was strongly affected by the draw depth with oxygen depletion in the bottom waters, unless an aeration system was used.

- Scenario **M1** produced the best water quality with less than 0.25% of the volume of the reservoir (when full) becoming anoxic. Aeration may be required in some years with this scenario.
- Scenario **M2** produced the worst water quality with an estimated 21% of the total lake volume becoming anoxic during summer stratification. Because of the large volume of stagnant water below the draw-induced stratification depth, the modelling indicated that under this scenario the reservoir may not mix in some years. This would compound the issues of nutrient release from the sediments in the bottom waters and could stimulate substantial algal blooms in the year when the reservoir water column did mix. Aeration would be required with this scenario.
- Scenario **M3** produced an intermediate water quality with anoxia below the 405 m RL outtake (as in scenario M1) and progressive oxygen depletion below the 443 m RL outtake eventually becoming anoxic by mid-summer in some years. Aeration would be required with this scenario.

The M1 scenario model showed that nutrient concentrations were likely to be low in the upper water column during summer but were likely to increase following winter mixing, and were likely to support a low level of phytoplankton (free floating algae) in the upper water column in spring. With low phytoplankton levels and low suspended solids concentrations from sediment, the water clarity was likely to be high. Overall, the expectation was for the Makaroro reservoir to have a trophic level classification of oligotrophic to mesotrophic.

Under the M1 scenario:

- The physico-chemical characteristics of the water within, and discharged from, the reservoir Makaroro reservoir would be high.
- The water quality in the reservoir would be suitable for aquatic life, recreation and other uses. Under scenario 2, a substantial part of the lake would be unsuitable for some aquatic life due to anoxia.
- The effects of removing vs. retaining vegetation within reservoir extent had only a small effect on the oxygen depletion in the reservoir in the first few years after filling. Retaining the vegetation would provide valuable habitat for aquatic biota including fish and koura. The costs associated with removing the vegetation may be prohibitive assuming the vegetation could be removed completely.

Suggested approach for identified effects

The Feasibility Study modelling found that scenario M1 produced the best water quality in the lake with the least oxygen depletion in the bottom of the reservoir. Consequently, Scenario M1 is the recommended option for the Makaroro reservoir operation regime.

It is also recognised that there are likely to be a few years after first filling when the bottom waters will develop anoxia, before the reservoir stabilises. It is recommended that an aeration system be installed in the bottom of the reservoir near the dam wall to provide water column mixing and reduce the effect of or prevent anoxia.

The water quality in the reservoir is dependent on the quality of water entering the reservoir. Sediment is a major pollutant of freshwater as is nutrient runoff from farming. It is recommended that management strategies are developed for the reservoir catchment to reduce the incidence of erosion that could exacerbate sediment accumulation in the reservoir, and to control landuse changes, including farming intensification, that could enhance nutrient runoff into the Makaroro River and the reservoir.

It is recommended that a routine monitoring programme be designed and implemented on the Makaroro reservoir to facilitate adaptive management strategies for the reservoir. Of critical importance is the monitoring of temperature and dissolved oxygen (DO) at all depths in the reservoir water column in order to manage the aeration system and thereby keep the DO concentration above the minimum required for fish, i.e., 5 mg/L. A recommended aeration activation threshold and monitoring regime for the aeration system is provided in this report.

It is also important to have a monitoring programme that will provide basic water quality information on the water in the reservoir in order to assess trophic condition and change over time. Without this type of information it is not possible to detect changes in the reservoir water quality that will allow management strategies to be developed and implemented in a timely manner.

While the Feasibility Study found that scenario M1 produced the best water quality and was therefore the recommended option, subsequent hydrological modelling produced a new operating regime (Scenario 3-28M) defined in the Project Description Report (Tonkin & Taylor May 2013). Scenario 3-28M will allow water levels in the proposed Makaroro reservoir to be lower more often than in scenario M1 in most years. However, the lower levels indicated from the Scenario 3-28M modelling are well within the range of water levels modelled for Scenario M1. Consequently, provided the main draw depth for water is kept as deep as possible in the reservoir, nominally at 405 m RL, the change in operating regime is unlikely to have more than a minor effect on the lake water quality and thus the quality of the water discharged to the downstream river. Further hydrological modelling was undertaken following the release of the Final Draft (March 2013) suite of documents, which superseded scenario 3-28M described above. The outcomes of this modelling with regards to lake level behaviour are presented in Figure 3.6a of the Final PD report (Tonkin & Taylor, May 2013). Visual examination of this plot indicates very minor differences with the 3-28M scenario described above, and the conclusions drawn above in relation to the 3-28M scenario are also valid for this latest scenario described in May 2013 Project description report.

1 Introduction

The assessment of water quality effects in this report is based on the proposed Ruataniwha Water Storage Scheme (the Scheme) as described in the report prepared by Tonkin and Taylor Limited entitled Ruataniwha Water Storage Scheme: Project Description, (dated May 2013), referred to in this report as the Project Description (PD).

The Hawke's Bay Regional Investment Company Limited Ltd (HBRIC Ltd) is seeking resource consents under the Resource Management Act for an irrigation water reservoir on the Makaroro River and the associated supply distribution as the Ruataniwha Water Storage Scheme ("the Scheme"). The Makaroro reservoir would consist of a high (83 m) dam built upstream of Burnt Bridge (Makaroro Road) and would include a small hydro-electric power station. As part of the Scheme, a number of technical and scientific investigations have been initiated. This study aims at defining the "Water quality of reservoir water and its potential effects on the downstream environment".

HBRIC Ltd requires characterisation of the predicted water quality in the proposed Makaroro reservoir including:

1. expected physico-chemical characteristics of the water within, and discharged from the reservoir
2. suitability of reservoir water quality for aquatic life, recreation and other uses
3. effects of removing vs. retaining vegetation within reservoir extent
4. other considerations/recommendations regarding future dam site management before, during and after dam establishment, and
5. further investigations/information that may be required to characterise reservoir water quality.

1.1 Background

Water quality in reservoirs is closely related to the intended water use. The quality of the water in the reservoir and released from the reservoir affects other environmental inhabitants such as fish and wildlife, and can impact or impair water use. Water quality considerations can vary widely since a host of descriptors can be used to characterize water quality. Temperature and dissolved oxygen (DO) are of primary interest for most reservoirs since temperature regulates biotic growth rates and life stages and defines fishery habitat (warm-, cool-, or cold-water), and oxygen is necessary to sustain aquatic life. Turbidity is of considerable interest because of the effects on light transmission and water clarity. Nutrient enrichment receives frequent attention since it fuels primary productivity that can lead to oxygen depletion and taste and odour problems. Consequently, water quality is an important consideration for new reservoir construction and the design of structural features such as depth of draw, compensation water outtake design and the operational parameters.

Consideration needs to be given to both in-reservoir and release water quality. For many years, selective withdrawal (e.g., Casamitjana et al. 2003) has been used to control release temperature to meet downstream targets set for selected species by fishery resource agencies. Selective withdrawal can provide a relatively effective means of controlling release temperature, especially for deep stratified reservoirs, but it is not as effective for controlling multiple water quality variables in the release. In recent years there has been a shift to an emphasis on techniques that can be implemented within the catchment, in-reservoir, and within or immediately downstream of the release structure to augment the benefits of selective draw.

This report provides a prediction of the probable water quality in the proposed Makaroro reservoir and in the water released from the reservoir based on best science practice.

1.2 Scope

1.2.1 Physico-chemical characteristics

The water quality in the new reservoir will have many of the characteristics of the source water and some characteristics may change due to specific biogeochemical processes that occur in standing (lakes and reservoirs) versus flowing (rivers) water. Consequently, the physico-chemical characteristics cover a broad range of parameters including, but not limited to water temperature, pH, colour, clarity, particulate organic matter, BOD, ammoniacal nitrogen, dissolved inorganic nitrogen, dissolved reactive phosphorus, total phosphorus and total nitrogen. Predictions and assessments use best scientific practice based on the available data provided.

1.2.2 Suitability of water quality for aquatic life and recreation

The formation of the Makaroro reservoir will replace previous river pool and riffle system habitats with reservoir habitats that range from near-shore reservoir bed (littoral zone) where there is sufficient light for plant growth to deeper bare reservoir bed (profundal zone) where there is insufficient light for plant growth, as well as the open water column (pelagic zone).

The keys to aquatic life are dissolved oxygen and habitat. Newly filled reservoirs commonly experience oxygen depletion in the bottom waters in the first five years of operation, due to the short-term decay of submerged vegetation. This is also pertinent to the question of whether to remove or retain vegetation within reservoir extent. Deep reservoirs will thermally stratify (form a warm surface layer over a colder bottom layer) in summer exacerbating bottom water dissolved oxygen depletion. Where all of the oxygen is consumed by decomposition processes, the bottom water becomes anoxic and is not suitable for aquatic life e.g., fish, crustaceans and aquatic insects (invertebrates). The extent of bottom water oxygen depletion can be estimated based on knowledge of the organic load left in the reservoir at the time of filling.

For this Sub-study, those estimates have been made using best scientific knowledge and the coupled hydrodynamic-ecological model DYRESM-CAEDYM[1].

Where the water level fluctuates due to draw-down for irrigation in summer, permanent littoral habitat is lost and wind-wave erosion of the exposed bed can lead to high turbidity (low clarity). These and other associated affects, such as accessibility of the water, can affect recreational use of the reservoir. Low water levels may also expose submerged vegetation with drowned trees creating hazards for boating, fishing and swimming. Changes in water level will also be considered in the modelling.

[1] DYRESM_CAEDYM was developed at the Centre for Water Research, University of Western Australia.

1.2.3 Recommendations of future dam site management

These have been limited to the design of a monitoring programme for the reservoir/dam and advice on the use of aeration systems or “selective draw” techniques to manage the quality of the water discharged from the reservoir.

During the evaluation of the initial model scenarios, it became apparent that significant improvements in water column oxygen concentrations could be obtained by having the selective draw depth for the discharge water as low as practical in the reservoir. A recommendation in the draft report for this scenario to be modelled was adopted. For expedience, the results of that supplementary modelling have been included in this report rather than being presented in a separate report. The supplementary modelling is presented as a separate section. All modelling scenarios are considered in the summary and conclusions.

Further use of the DYRESM-CAEDYM modelling is recommended if major changes to the reservoir design or operational parameters are considered or predictions around climate change effects are required.

Figure 1-1: Erosion in the Ruahine Ranges. The steep slopes are easily eroded in heavy rain. [Photo: Max Gibbs].

2 Methods

2.1 Site

The proposed Makaroro reservoir (Figure 2-1) will be located on the Makaroro River about 10 km upstream of the NIWA National Rivers Water Quality Network (NRWQN) monitoring site at Burnt Bridge (Makaroro Road), in the foothills of the Ruahine Ranges (Figure 2-2). When full the reservoir will have a crest elevation of 469.3 m above sea level (mRL), a depth of 70.4 m, a surface area of approximately 3.6 x 10^6 m^2 (360 ha) and a volume of approximately 90 x 10^6 m^3 (Tonkin & Taylor data). The 6.5 km of river bed to be inundated comprises braided gravel banks with islands of vegetation including scrub and willow holding a thin layer of organic soil and silt. The river banks have larger trees including remnant beech forest, pine and eucalyptus as well as pasture on the south side (Figure 2-3). Although essentially a "ribbon" lake, the shoreline of the proposed reservoir will be dendritic with side arms extending into two large valleys off the main river channel.

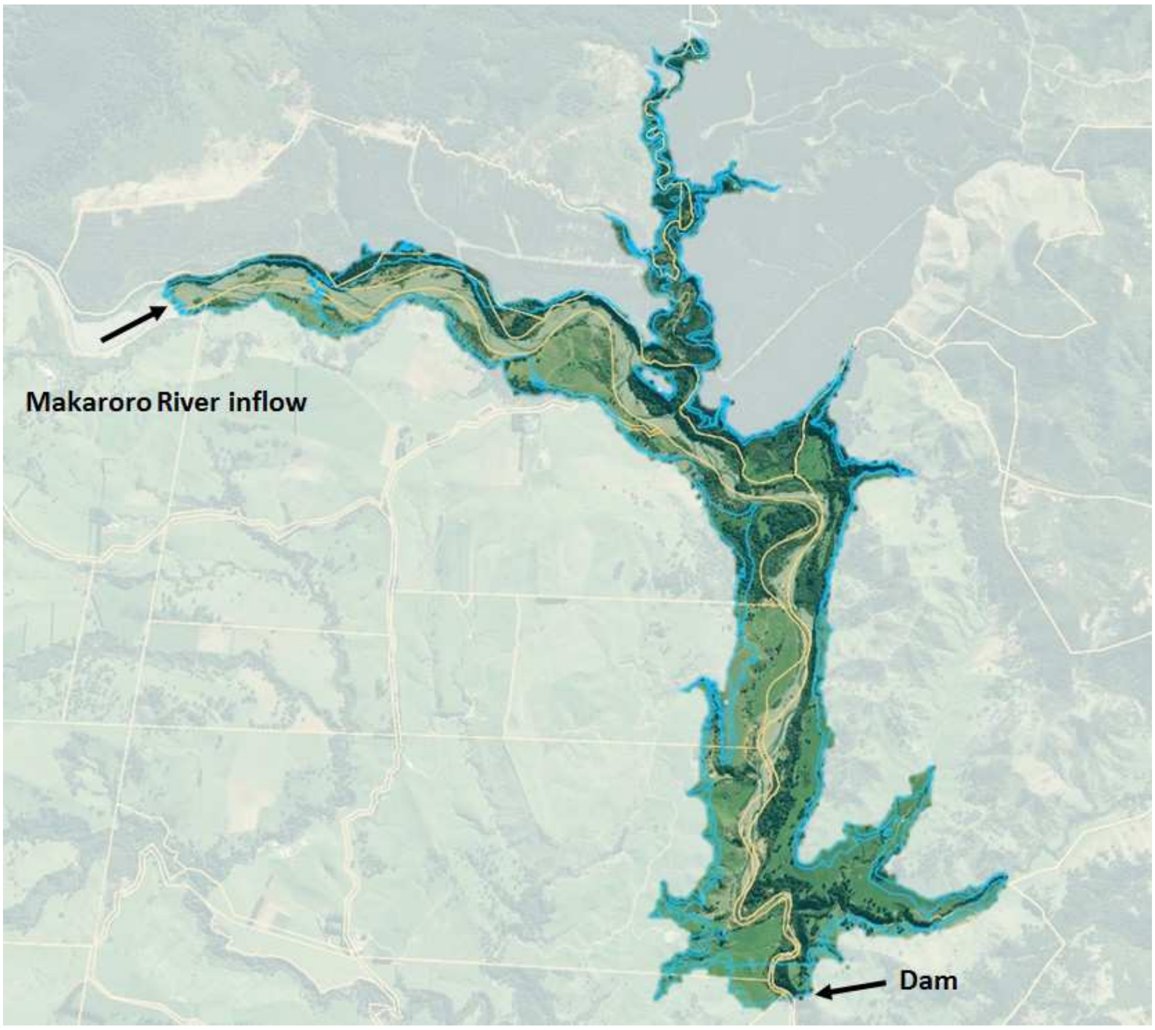


Figure 2-1: Proposed Makaroro Reservoir. The dam will flood about a 6.5 km long section of the Makaroro River channel producing a dendritic ribbon lake.

The land-use in the proposed reservoir's 12,000 ha catchment (Table 2-1) is diverse, with a high proportion (9055 ha) of native forest on the Ruahine Ranges to the north and west. The southern catchment is mainly rolling pasture (1450 ha) while much of the northern catchment is dominated by production forestry (725 ha).

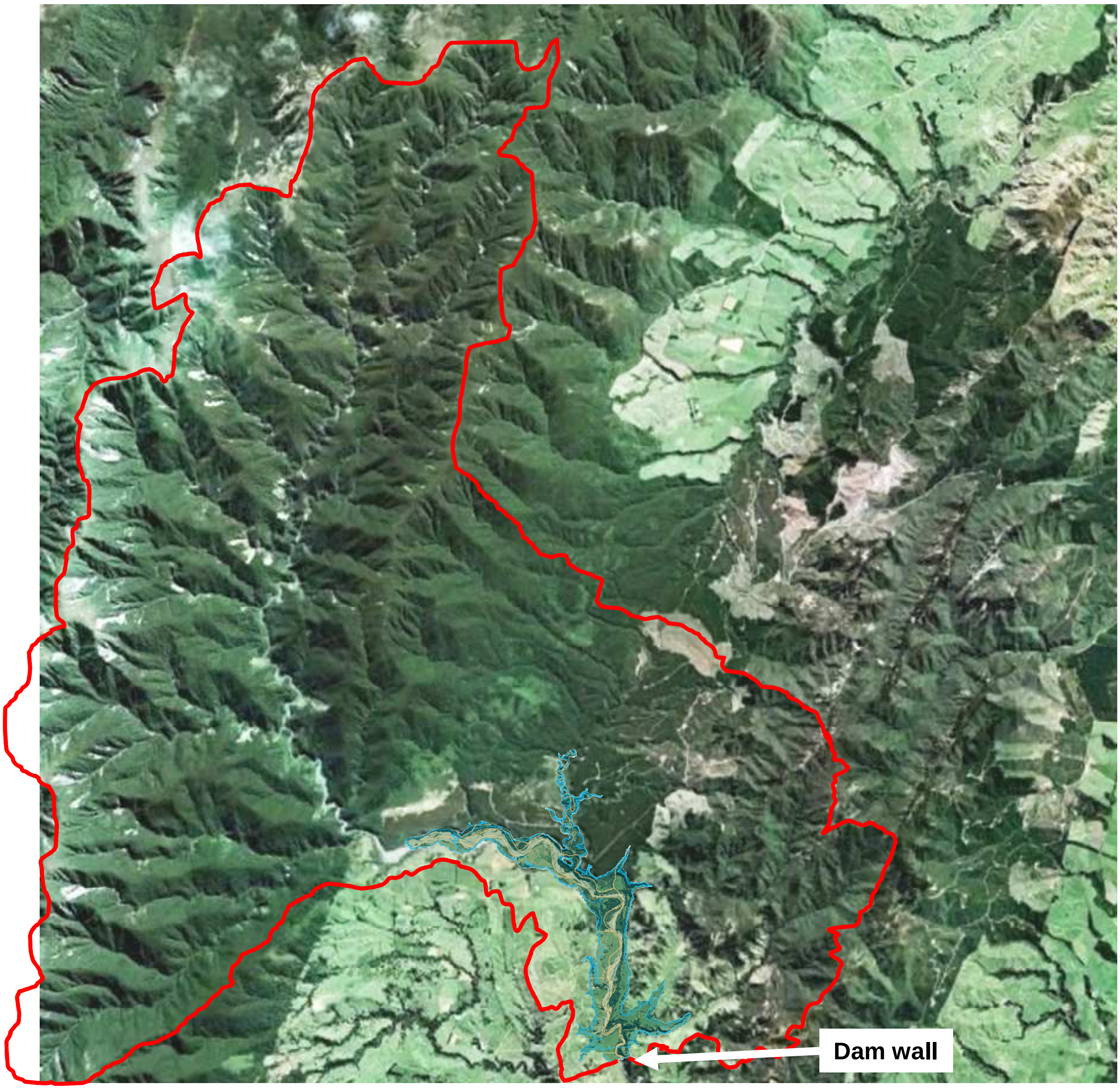


Figure 2-2: Catchment of the Makaroro reservoir. Outline (red) of the watershed boundary for the reservoir (blue overlay) and the location of the dam wall. [Image from Google Earth, 2006].

The Ruataniwha plains are a patchwork of diverse soils, ranging from heavy clays to gravels, from shallow to deep, and from waterlogged to excessively drained. The soils in the footprint of the proposed dam are similarly variable with the headwater streams draining the leached soils beneath native tussock and scrubland on steep rocky hillsides (522 ha). The steep hills of the catchment are highly erodible in heavy rain and there is an estimated 185 ha of landslides (Figure 1-1) which make up a large part of total erodible land in the catchment (260 ha) (2.1% of the catchment area), which are the most likely sources of suspended solids in periods of high rainfall.

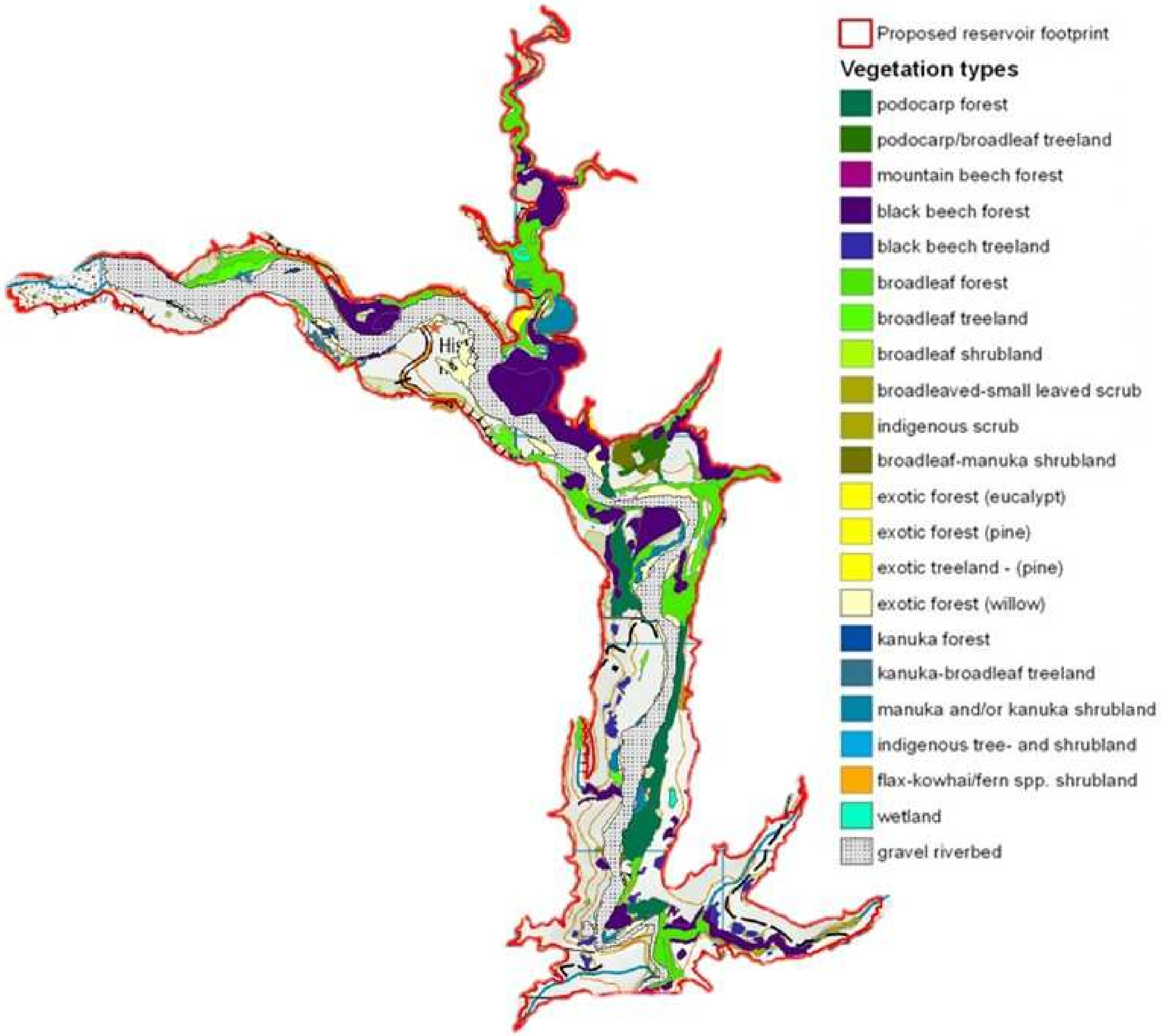


Figure 2-3: Makaroro reservoir vegetation map. The proposed dam will flood a broad range of vegetation in the river channel and on the banks and hill side slopes above the river channel. Vegetation data extracted from a map by Kessel and Associates Ltd, 31 September 2011.

Table 2-1: Land-use classes for the Makaroro reservoir catchment. These data provided by Tonkin & Taylor from the New Zealand Land cover database (LCDB2).

Land-use Description	Area [ha]	Land-use Description	Area [ha]
Indigenous Forest	7176.6	Tall Tussock Grassland	235.9
Broadleaved Indigenous Hardwoods	628.9	Sub Alpine Shrubland	244.5
Deciduous Hardwoods	9.6	Gorse and Broom	3.3
Manuka and or Kanuka	1239.9	Lake and Pond	3.2
Pine Forest - Closed Canopy	106.8	Herbaceous Freshwater Vegetation	5.9
Pine Forest - Open Canopy	275.5	Alpine Gravel and Rock	41.2
Forest Harvested	338.7	River and Lakeshore Gravel and Rock	137.3
Other Exotic Forest	3.7	River	1.9
Major Shelterbelts	0.6	Landslide	184.6
High Producing Exotic Grassland	1453.3		
Low Producing Grassland	10.4	Total catchment area	12101.8

2.2 Prediction of the water quality

Prediction of the water quality in the proposed reservoir is difficult and uses the concept of developing a hind-case model based on historical data to predict the likely conditions in the reservoir in the future, to best scientific practice. The use of the DYRESM-CAEDYM model allows prediction of water quality in the newly filled reservoir and the probable changes in that water quality over the next 5 year time period.

Geomorphic data for the proposed reservoir was provided by the Scheme engineers. These data included the hypsographic contours of the proposed reservoir, configuration of the dam and outlet structures and operational flow regime. Prior to commencing this study, advice provided to the Scheme engineers by NIWA was that the dam should have two outlet valves – one at the deepest point and the other higher in the water column. The elevations of these intake valves given on the proposed dam plans were 426 mRL (lower) and 455.5 mRL (upper) with an additional compensation water valve from the toe of the dam at 395 mRL. These draw depths were considered in the modelling of the reservoir water quality, with the primary draw depth being at 426 mRL i.e., about 29 m above the reservoir bed at the dam.

2.2.1 Inflow water characteristics

The Makaroro River at Burnt Bridge (Makaroro Road), about 10 km kilometres downstream of the proposed dam site, is one of the NRWQN monitoring site and has >20 years of monthly monitoring data. This database provides the physical and biogeochemical characteristics of inflow water to the proposed reservoir (Table 2-2). Because the land between the proposed reservoir and the Burnt Bridge monitoring site is mostly agricultural land, it will have a small impact on that water quality. Consequently, the water quality data at Burnt Bridge is probably a lower quality estimate of what will actually flow into the dam.

Features of interest in these data are the relatively low soluble nutrient concentrations for ammonium (NH_4-N), nitrate (NO_3-N) and dissolved reactive phosphorus (DRP) but higher concentrations for total nitrogen (TN) and total phosphorus (TP). The differences between the soluble nutrient and total nutrient concentrations will be due to dissolved organic and particulate components for which there are no data.

While the calcium values are indicative of some lime in the catchment, they could also be associated with marine sediments on the uplifting eastern side of the Ruahine Ranges.

Table 2-2: Physical and biogeochemical characteristics of the Makaroro River. This is the source water inflow to the proposed reservoir. (Data from the NRWQN site HV1 database).

Parameter	Unit	Makaroro River at Burnt Bridge Mean	Range
Water clarity - black disk	m	2.5	0.02–12.1
Turbidity	NTU	18.4	0.22–480
Temperature	°C	11.2	4.0–19.7
Dissolved oxygen	%-saturation	99.2	90.0–121.4
Specific Conductance	$\mu S\ cm^{-1}$	96.7	57.3–143
pH		7.77	7.36–8.57
Total ammonia-N	$mg\ N\ m^{-3}$	3	0–33
Nitrate + nitrite	$mg\ N\ m^{-3}$	71	1–314
Total nitrogen	$mg\ N\ m^{-3}$	119	11–598
Dissolved reactive phosphorus	$mg\ P\ m^{-3}$	5.2	0.7–18.4
Total phosphorus	$mg\ P\ m^{-3}$	36	2–907
Calcium (n = 12)	$g\ Ca\ m^{-3}$	11.8	9.2–14.3
Magnesium (n = 12)	$g\ Mg\ m^{-3}$	1.7	1.42–1.92
Sodium (n = 12)	$g\ Na\ m^{-3}$	4.9	4.1–6.5
Potassium (n = 12)	$g\ K\ m^{-3}$	0.65	0.43–0.92
Alkalinity	$g\ CaCO_3\ m^{-3}$	31	26.5–35.5
Chloride	$g\ Cl\ m^{-3}$	3.5	2.3–4.6
Sulphate	$g\ SO_4\text{-}S\ m^{-3}$	9.2	6.5–14.5
BOD	$g\ O\ m^{-3}$	0.24	0–1
Total Coliforms / 100 ml	MPN	474	61.6–2755
E. Coli/100 ml	MPN	32.1	1.0–272.3

2.2.2 Model

For this assessment, the model of choice was the one dimensional (1-D) dynamic reservoir model DYRESM coupled with the aquatic ecological model CAEDYM (developed at the Centre for Water Research, The University of Western Australia). DYRESM resolves the vertical distribution of temperature, density and vertical mixing processes in lakes and reservoirs while CAEDYM simulates time-varying fluxes that regulate the biogeochemical variables including nutrient species nitrogen (N) and phosphorus (P), dissolved oxygen (DO) and phytoplankton biomass.

The DYRESM model was developed for geometrically simple reservoirs and lakes where it is reasonable to assume that lateral extrapolation from the 1-D modelling point is valid. However, the Makaroro reservoir is a long narrow reservoir with several side arms and constrained bathymetry around the inlets which means that, while it is valid to extrapolate along the length of the main channel (there will be minimal horizontal variability in this part of the reservoir), extrapolation into the side arms may not be valid. The bathymetry constraints will affect the validity of the near bottom results towards the inflow end of the reservoir. For this application, DYRESM-CAEDYM is used to provide a prediction of likely future condition and water quality in a non-existing reservoir. Consequently, the model is unable to be calibrated against empirical observations using statistical measures of model performance. Rather, the calibration for sensitive parameters during the setup of the model (McBride et al. 2011) was based on a combination of expert knowledge, coefficients from other model applications, and values from literature.

These limitations mean there is a level of uncertainty for the results presented. The level of risk associated with that uncertainty is tempered with practical experience and knowledge of how lakes and rivers of similar morphometry behave over the seasonal cycle. Consequently, the interpretations provided are best estimates produced in accordance with best scientific practice and the risk is likely to be low.

Use of the DYRESM-CAEDYM model is a specialised task which was sub-contracted to Limnotrack Ltd (McBride et al. 2011). The period from July 2000 to June 2005 was simulated in 1-day steps in order to assess the thermal structure of the Makaroro reservoir water column during and after reservoir filling. The simulation included the chemical and biological attributes of the reservoir and the outflow water. The filling time was assessed both starting in winter and starting in summer using data from the year 2000.

For convenience, the Limnotrack modelling reports for the initial scenario and the supplementary modelling have been attached to this report as appendices.

2.2.3 Historical data

The successful use of the DYRESM-CAEDYM model relies on the quality of the data input. Flow data was provided to all parties involved in the Scheme by Tonkin & Taylor to ensure the same information was used for all assessments.

Historical river monitoring data in the Makaroro River was obtained from the NRWQN monitoring site HV1 at Burnt Bridge (Makaroro Road) about 10 km kilometres downstream of the proposed dam site. Additional meteorological and climate data were obtained from 5 of NIWA’s Virtual Climate Network Stations (VCNS) over the reservoir site and catchment, as well as national Meteorological climate stations at Dannevirke and the Takapau Plains.

Details of these data are contained in the Limnotrack modelling report (McBride et al. 2011) and a copy of the data files is provided on a CDROM disc.

2.2.4 Soil sampling

Data not available from historical records were the soil characteristics in the reservoir footprint. Representative samples of 8 different land-uses soils from within the proposed reservoir footprint were collected on the 17 November 2011. The fresh soil samples were separated by depth into the surface 2 cm and the next 5 cm below. The samples were weighed, dried and sub-samples were combusted at 450˚C to determine organic matter content by loss on ignition (LOI). Separate aliquots of the dried samples were analysed for total nitrogen (TN) and total carbon (TC) on a Thermofinnigan CHN analyser in the NIWA laboratory at Hamilton. Total recoverable phosphorus (TP) and total recoverable iron (TFe) were determined by ICP-Mass Spectrometry after acid digestion in R.J. Hill Laboratories.

The soil sample data was provided to Limnotrack Ltd to use in the modelling for assessing the effects of soil decomposition on the water quality in the proposed reservoir.

2.3 Characterisation of the Makaroro reservoir water

Ecological assessment and assessment of the suitability of the reservoir water quality for aquatic life, recreation and other uses, conform to best scientific practices, best scientific knowledge and the results from the DYRESM-CAEDYM model. This “desktop” study includes an overview of the predicted water quality in the Makaroro reservoir at long term equilibrium and the changes that are likely to occur over the first 5 years of reservoir operation.

A literature search was used to assist interpretation or illustrate specific points.

3 Results and Discussion

The results presented in this report are extracted from the NRWQN database and the DYRESM_CAEDYM model report by Limnotrack Ltd (McBride et al. 2011). Refer to that report for specific details and the full statement of the results.

3.1 Hydrology, Temperature and Oxygen

Flow data supplied for the Makaroro River from Tonkin & Taylor and from the NRWQN monitoring data indicates that the river is flashy with an average flow of around 6 $m^3 s^{-1}$ and peak flows of >180 $m^3 s^{-1}$ (Figure 3-1). The monthly spot flow data from the NRWQN database does not capture the full range of flows with many of the higher flows being missed due to the low frequency sampling strategy used.

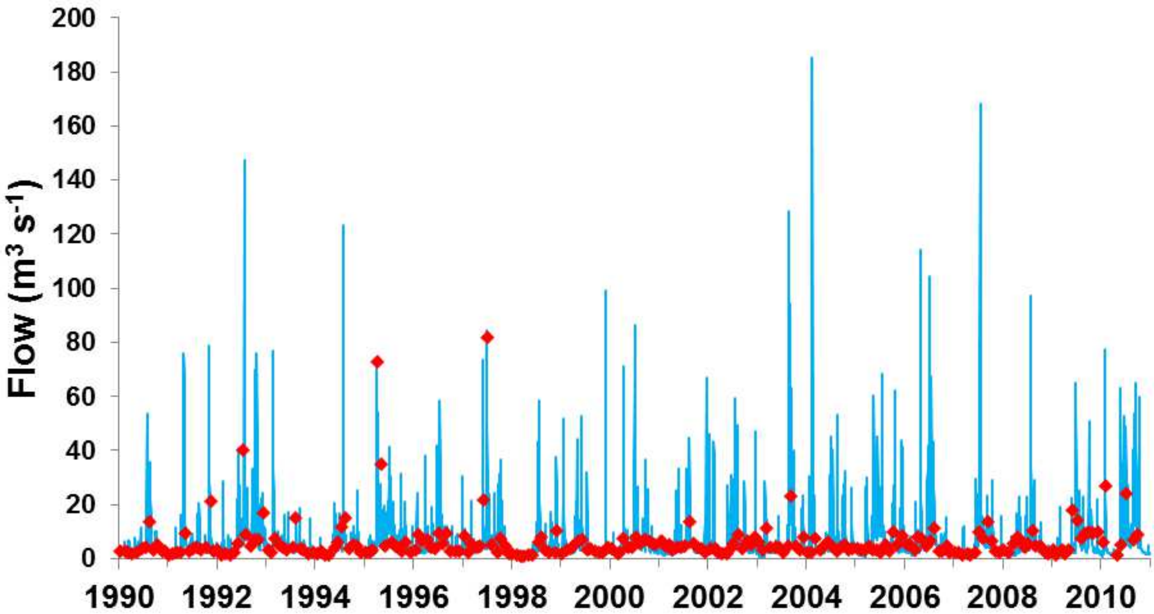


Figure 3-1: Flow in the Makaroro River at Burnt Bridge. Blue line is daily data from Tonkin & Taylor and red dots are monthly data from the NRWQN monitoring site HV1 database.

Notwithstanding this, the temperature (Figure 3-2) and oxygen concentrations (Figure 3-3) in the Makaroro River were modelled and there was good agreement with the monthly measurements in the NRWQN data. This calibration of the model provides a degree of confidence in the reliability of the predictions from the model.

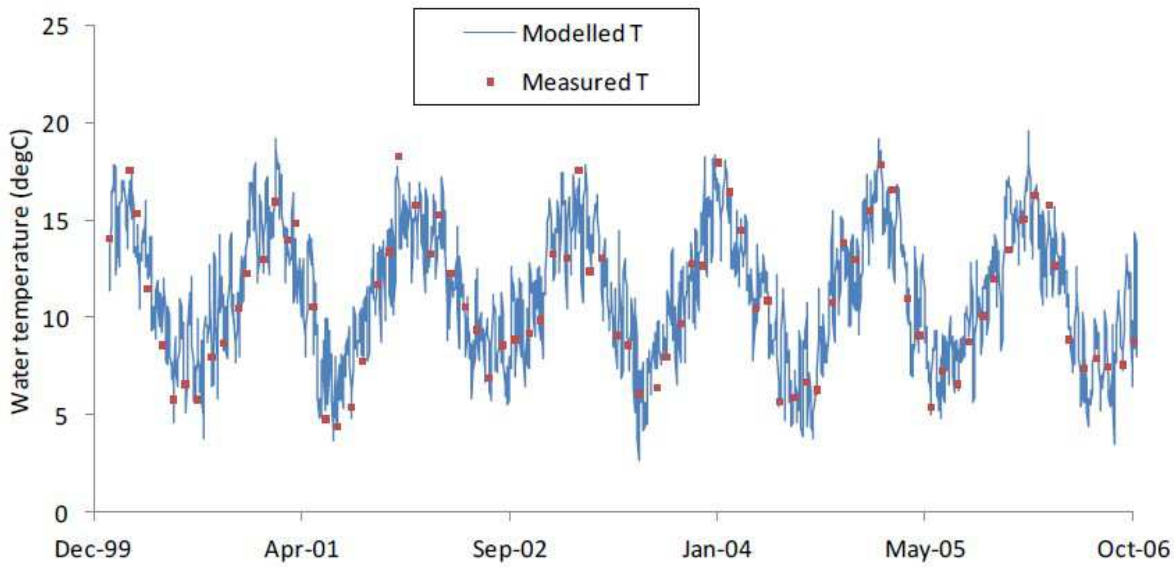


Figure 3-2: Estimated (daily) and measured (monthly) surface water temperature of the Makaroro River inflow. (Figure 4 from McBride et al. 2011).

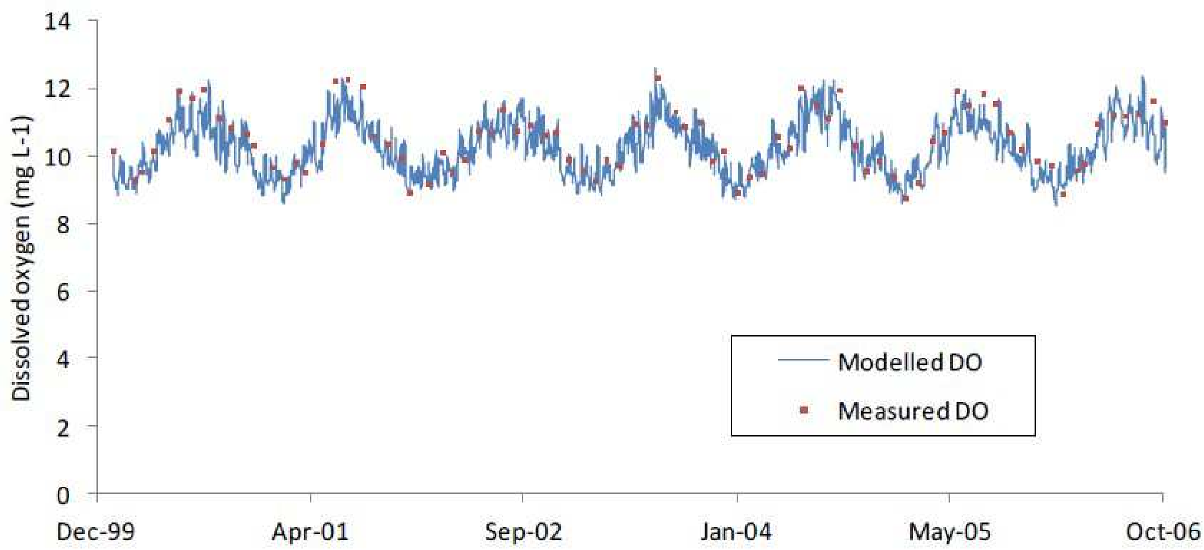


Figure 3-3: Estimated (daily) and measured (monthly) surface dissolved oxygen concentration of the Makaroro River inflow. (Figure 5 from McBride et al. 2011).

3.1.1 Filling time:

Two simulations were run both assuming only the minimum outtake from the toe of the dam for compensation water in the river downstream of the dam. Minimum compensation water as defined in the engineering report supplied by Tonkin & Taylor should equal 90% of the 7-day mean annual low flow. From the flow data supplied for the period 1972 to 2011, the 7-day MALF used in the model was 106,099.2 m^3 d^{-1} (about 1.23 m^3 s^{-1}). Flushing flows of 10.5 m^3 s^{-1} for 9 to 12 hours (nominally 10 hours), with 4 events per year are also required. Model simulation was based on 2000 data and the results were:

- If filling began on 30 June (wet period) it would take 95 days to reach capacity.
- If filling began on 11 January (dry period) it would take 185 days to reach capacity.

Modelling using data from different years may affect these predictions slightly. Notwithstanding, these data indicate that the filling time will be variable depending on the time of year filling begins and the local climate. Filling time will also be affected if water is drawn from the Makaroro reservoir for irrigation or power generation during the filling period.

When full, the reservoir had a depth of 75.5 m and the surface elevation simulated by DYRESM closely matched the surface elevations provided by Tonkin & Taylor (Figure 3-4).

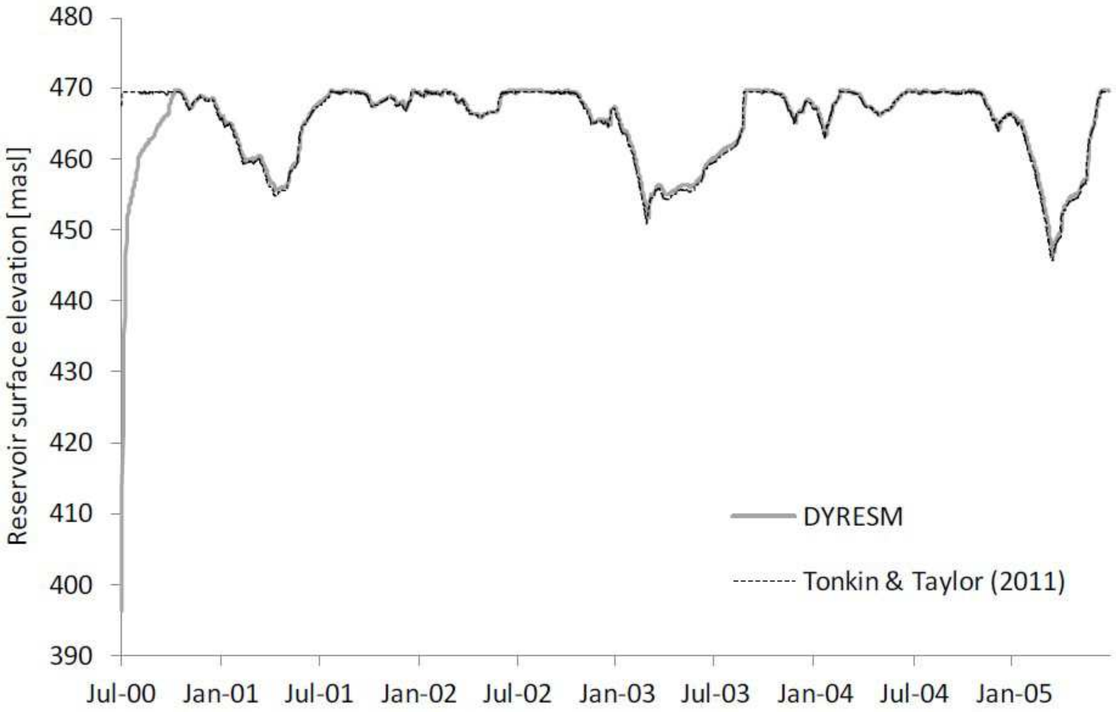


Figure 3-4: Comparison of projected reservoir water levels. Solid line is DYRESM output compared with the Tonkin & Taylor levels. (Figure 8 from McBride et al. 2011).

3.1.2 Residence time

Based on the full volume of 90 × 10^6 m^3 and a proposed mean annual discharge of 6.342 m^3 s^{-1} (Tonkin & Taylor data), the theoretical mean residence time in the Makaroro reservoir would be about 164 days.

3.1.3 Thermal stratification

The DYRESM model output indicates that the Makaroro reservoir will form a stable thermal stratification once each year during the summer months (Figure 3-5). This characterises the reservoir as being monomictic. It is estimated that stratification was likely to begin in October and continue through to mixing in April each year. The exact period will be influenced by local climate variability. On average over the 5-year period of the model, surface waters were >3°C warmer than the bottom waters for 196 days of the year.

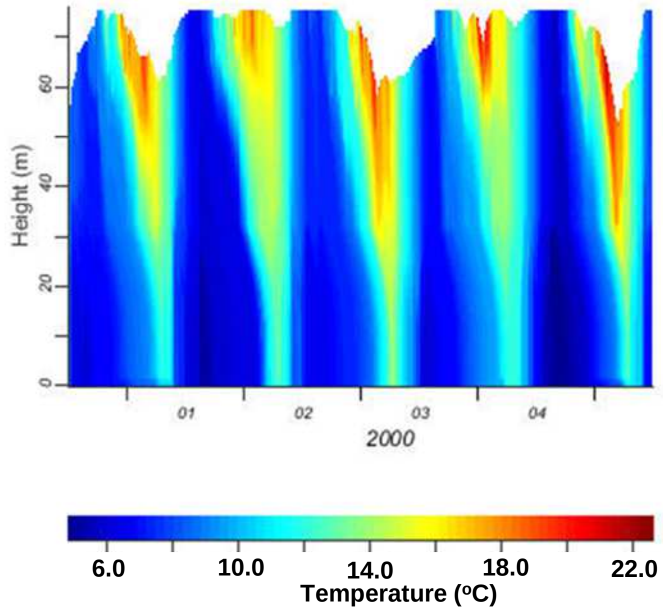


Figure 3-5: Simulated water temperatures. Temperatures (ºC) for the period 30/06/2000 to 30/6/2005. (Figure 9 from McBride et al. 2011).

The model indicated that surface temperatures of the reservoir would range from 5.4ºC to 22.7ºC and that the depth of stratification would be deeper than in natural deep lakes due to the effect of selective draw from the lower levels of the reservoir. Initially the thermocline would develop at a depth of about 15 m depth below maximum surface water level but would move down to around 60 m depth before mixing in April (Figure 3-5). Warming of the bottom waters confirm deep mixing (Figure 3-6).

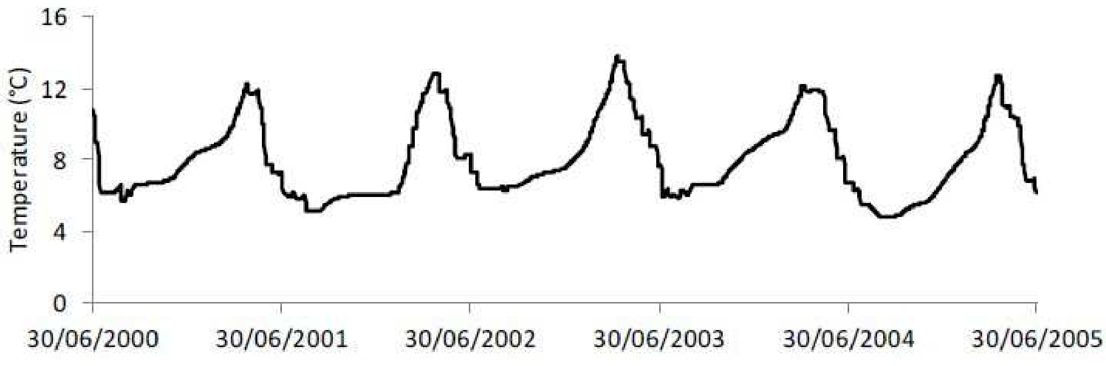


Figure 3-6: Simulated bottom water temperatures. Temperatures (ºC) at the bottom of the reservoir for the period 30/06/2000 to 30/06/2005 (extracted from Figure 16, McBride et al. 2011).

3.1.4 Dissolved oxygen dynamics

The DYRESM-CAEDYM simulation indicated that the upper water column would be well oxygenated (>70% saturated) at all times but the bottom waters would become depleted during the seasonal stratification (Figure 3-7).

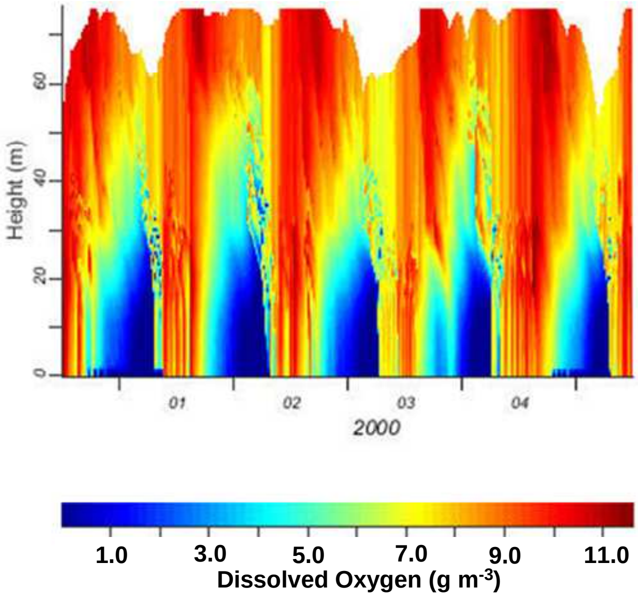


Figure 3-7: Simulated dissolved oxygen. Dissolved oxygen concentrations (mg L^{-1}) for the period 30/06/2000 to 30/06/2005. (Figure 10 from McBride et al. 2011).

The extent of bottom water oxygen depletion varied from year to year but in each year, the bottom waters became anoxic by the end of the stratified period (Figure 3-8).

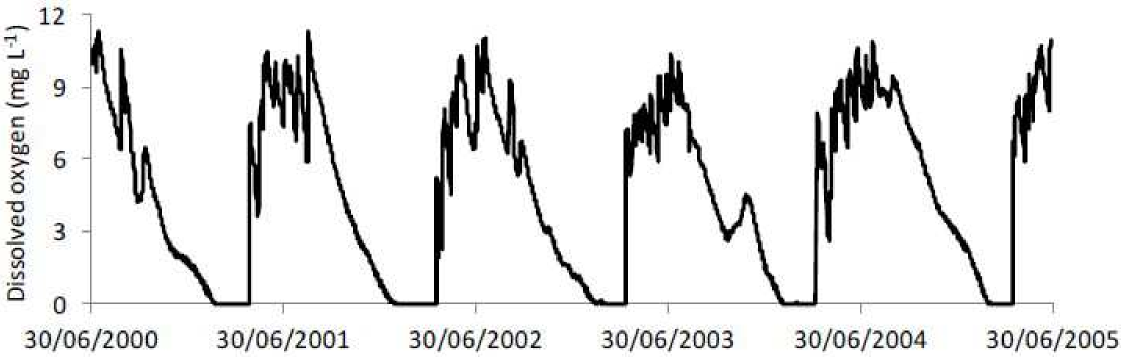


Figure 3-8: Simulated bottom water dissolved oxygen. Bottom water oxygen depleted is predicted to include periods of anoxia by the end of the stratified period. (Extracted from Figure 16, McBride et al. 2011).

The driver for oxygen depletion in the reservoir is sediment oxygen demand (SOD) from the decomposition of organic matter on and in the reservoir bed. The SOD value includes the organic matter associated with vegetation and soil left in the reservoir during the filling. As a best estimate for SOD a relationship was derived for the TC content of the reservoir soils and SOD values prescribed in previously published applications of CAEDYM — the baseline SOD value obtained was 2.5 g m^{-2} d^{-1}. This baseline SOD, which represents top soil and minimal vegetation, was modified to include a 10% and 20% increase in SOD to simulate different levels of vegetation left in the reservoir e.g., 10% might represent the leaving of river bed willows and scrub only, while 20% might represent leaving all vegetation. A scenario was also run with 20% less SOD to simulate the removal of all vegetation and top soil in the dam site before filling. This would be an unlikely scenario, but it was included in the modelling as part of the sensitivity testing.

Under the baseline value for SOD, the number of hypoxic days (i.e., days where the DO concentration was <2 mg L^{-1}) at the 395 mRL ranged from 141 to 85 decreasing over time as the TC in the sediment is consumed. In contrast, at 426 mRL the number of hypoxic days were <10 each year (Table 3-1). Leaving the vegetation in the reservoir would extend the period of bottom water hypoxia each year by about 30 to 40 days whereas removing the vegetation could halve the number of hypoxic days.

Table 3-1: Annual count of hypoxic days (DO <2 mg L^{-1}) at two levels. Baseline simulation (SOD = 2.5 g m^{-2} d^{-1}) and three alternative values of SOD based on percentage departures from the baseline SOD. (Table 4 from McBride et al. 2011).

	Baseline		SOD +10%		SOD +20%		SOD -20%	
Period	395 mRL	426 mRL	395 mRL	426 mRL	395 mRL	426 mRL	395 mRL	426 mRL
2000-2001	141	1	160	4	170	6	74	1
2001-2002	139	8	157	8	171	9	83	4
2002-2003	134	0	142	1	160	2	67	0
2003-2004	106	0	122	5	168	0	69	0
2004-2005	85	0	106	0	129	0	48	0

The water draw at 395 mRL was for compensation flow is set at 1.23 m^3 s^{-1}. The importance of this flow is apparent when the simulation is run without it (Figure 3-9). In this scenario, the reservoir becomes strongly stratified at the main draw depth of 426 mRL and the bottom waters become anoxic. In the 5 year simulation period the reservoir did not mix in winter for two consecutive years (Figure 3-9).

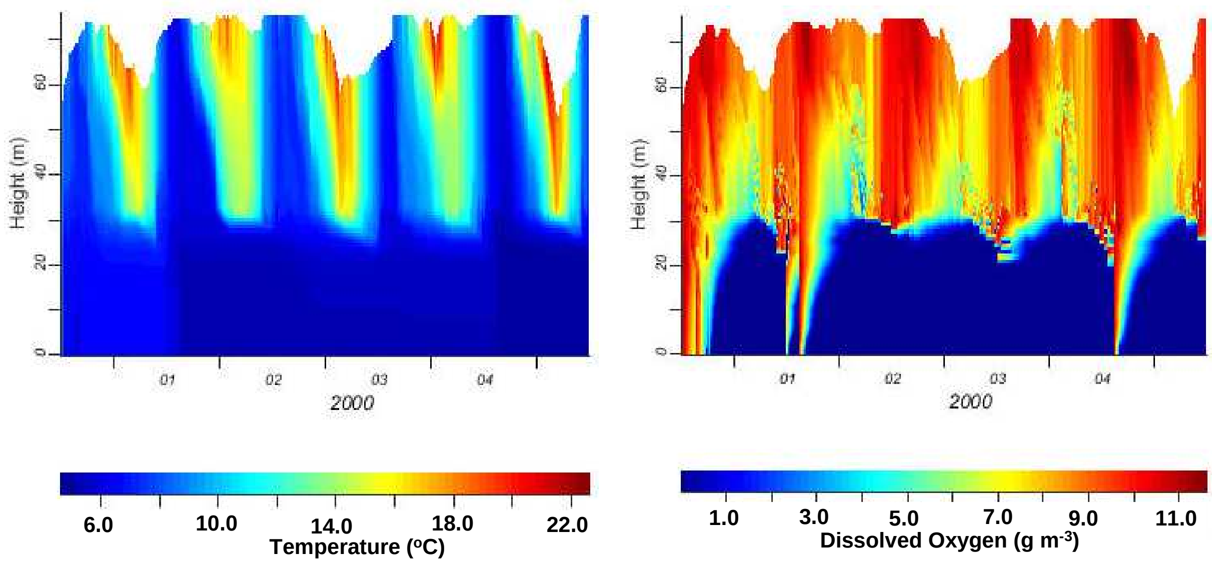


Figure 3-9: Simulated water temperatures (ºC) and dissolved oxygen (mg L^{-1}) . No compensation water outtake from the toe of the dam. (Figure 21 from McBride et al. 2011).

These results demonstrate the critical nature of selective draw and the depth of draw in a deep reservoir (Figure 3-10). If the outtake valves were positioned at the depths assumed in the initial modelling scenario, the reservoir would develop a dead volume of hypoxic water about 30 m deep in the bottom of the reservoir each year. Such a dead volume would dominate the biogeochemistry at the sediment-water interface and, because of the relatively large sediment area below 426 mRL (63 ha), it has the potential to cause the release of substantial amounts of nutrients and minerals from the sediments into the water column.

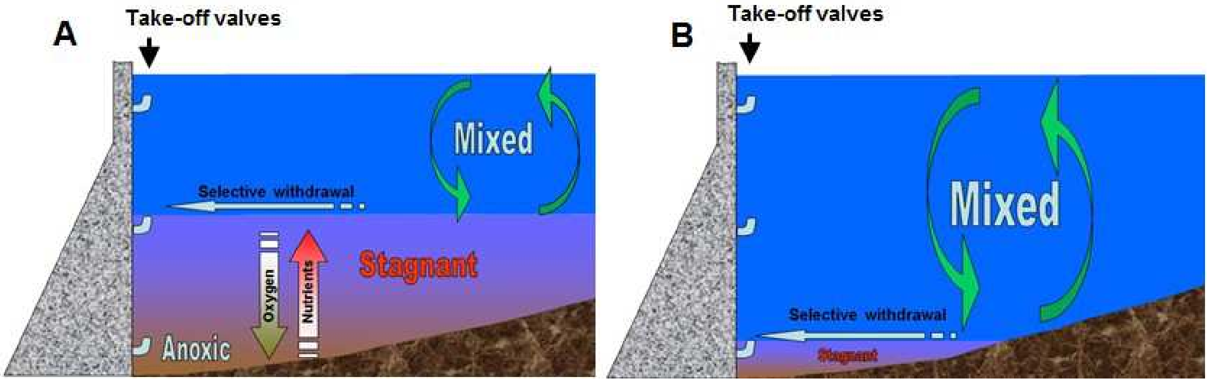


Figure 3-10: Schematic of how selective draw works. Selective draw from a mid-depth (A) causes stagnation or dead volume in the water below that depth because there is no mechanism for mixing oxygen below the draw depth. In practice it is better to draw from the lowest depth (B) so that the dead volume is minimal.

The observation that just drawing 1.23 $m^3 s^{-1}$ from the toe of the dam at 395 mRL can prevent stagnation supports the concept of drawing the main water supply from as deep as possible in the reservoir (Spigel & Ogilvie 1985; Casamitjana et al. 2003). In this instance, a deep draw depth at 400 mRL is likely to dramatically reduce the number of days of bottom water hypoxia and, because of the much smaller area of the bed beneath the dead volume (<0.5% of the reservoir area at 400 mRL versus 13% at 426 mRL), nutrient and mineral releases from the sediment would be expected to be substantially reduced, improving the overall water quality of the reservoir.

It is recommended that a model simulation is run setting the lower draw depth at 400 mRL or as deep as practical if 400 mRL is not possible, to test the effect on DO concentrations.

[This recommendation was adopted during the report review process and the results of that additional modelling are included in a separate section of this report.]

From the storage volume data for the proposed reservoir (Tonkin & Taylor data), the area of reservoir bed below 426 mRL is 13% of the total area of the reservoir and has a dead water volume of about 5.5% of the total volume of the reservoir. At a draw depth of 400 mRL, the reservoir bed area and volume below that level is <0.5% of the total reservoir area and volume. With the draw depth set at 426 mRL, aeration would be needed to prevent hypoxic conditions developing for the periods predicted in Table 3-1. However, if the lower draw depth is sufficient to maintain dissolved oxygen levels above 2 mg L^{-1}, there may be no need for aeration.

Under the scenario modelled, if aeration is not available, water blending is a practical method to ensure that the outtake water from the reservoir for irrigation and power generation is suitable for aquatic organisms when it enters the river. With one deep outtake the only water accessible for discharge is from that outtake and the water quality is fixed to the water quality at that depth. With two outtakes at different depths, the water from the two depths can be blended to meet the requirements of the downstream environment.

To maintain the deep currents that prevent stagnation, the majority of the water is drawn from the deepest outtake. A smaller proportion of well oxygenated water from closer to the surface can then be added to that deeper water through the upper valve to achieve the required water quality.

The compensation water cannot be blended and may discharge anoxic water downstream from the toe of the dam. However, as this is a small volume (1.23 m^3 s^{-1}), it can be aerated as it is discharged by ejecting it through a spray nozzle (e.g., Figure 3-11).

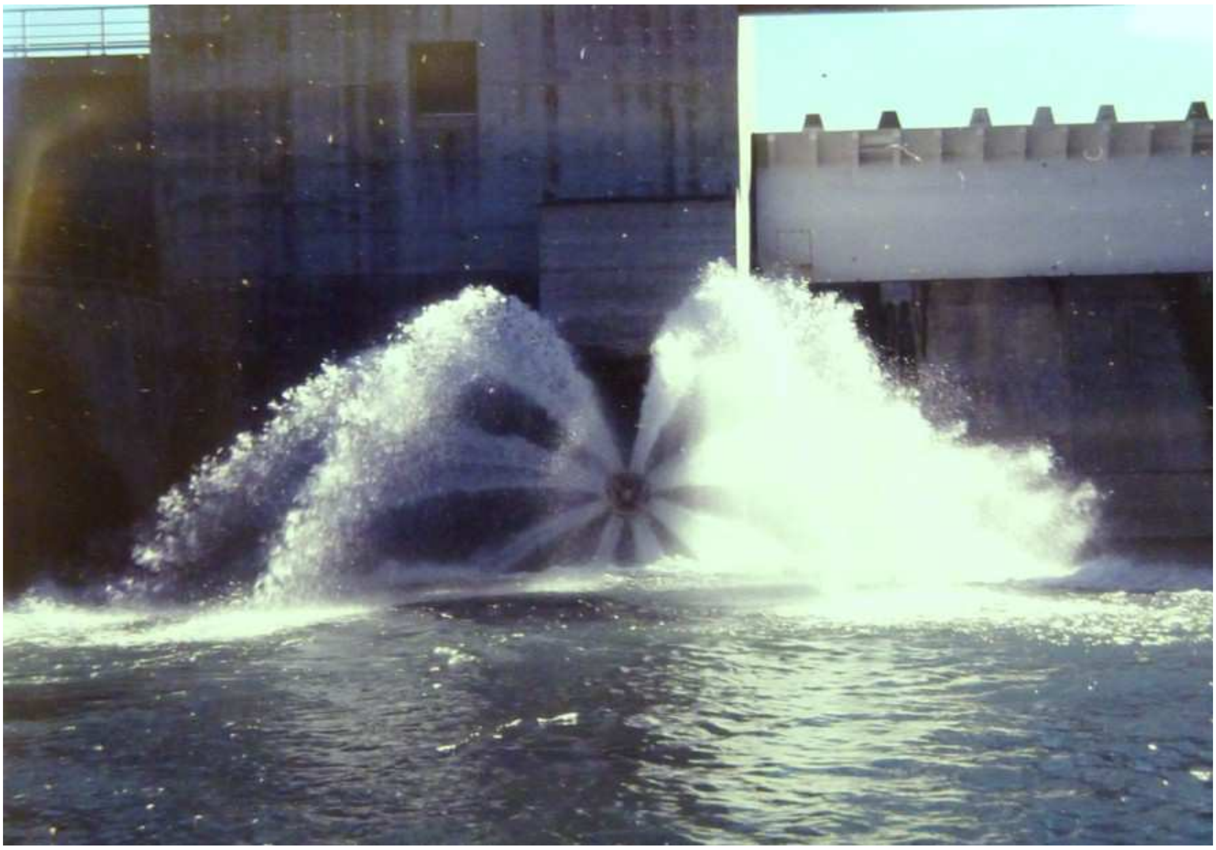


Figure 3-11: Example of a compensation water aeration nozzle. This nozzle sprays into a pool feeding the Poutu River below the dam across the outlet on Lake Rotoaira, Turangi. [Photo: Max Gibbs]

3.2 Nutrients and water quality

3.2.1 NRWQN data

Water quality parameters measured in the NRWQN database have low concentrations under low flow conditions. These concentrations change with increasing flow (Table 2-2):

- Turbidity increases almost lineally with flow but is not consistent. Some high flow events produce NTU values about 6-fold greater than the flow while medium-size flow events may have little effect on turbidity. This suggests that turbid events may be associated with land slide generating events eroding the recent sedimentary rock.

- Visual water clarity decreases with flow, falling to near 0 m when flows are above 10 $m^3 s^{-1}$.
- pH values in the river are mostly above 7.8 under low flow conditions peaking at >8.5. As flow increases the pH falls to <7.6. This suggests in-stream growths of periphyton flourish in the high light low flow environment. There has been a small but significant (P <0.001) decrease in mean pH over the last 20 years.
- DO % saturation is highly variable at low flow ranging from 90% to >120% but stabilising at about 98% above 20 $m^3 s^{-1}$. Overall there has been a small but significant (P <0.001) decrease in mean DO% saturation over the last 20 years.
- Conductivity is typically between 100 µS cm^{-1} and 140 µS cm^{-1} at low flows but rapidly falls to around 70 µS cm^{-1} at high flows.
- Ammoniacal nitrogen (NH_4–N) concentrations can range from 0 to 33 mg m^{-3} at low flows but were around 5 mg m^{-3} at high flows.
- Nitrate nitrogen (NO_3-N) concentrations can be variable up to 315 mg m^{-3} at low flows but are around 200 mg m^{-3} at high flows.
- Total nitrogen (TN) concentrations slowly increase with increasing flow and range from 200 to 600 mg m^{-3} at flows above 10 $m^3 s^{-1}$.
- Dissolved reactive phosphorus (DRP) concentrations are highly variable (0 to 18 mg m^{-3}) at low flows and tend to be around 10 mg m^{-3} at high flows.
- Total phosphorus (TP) concentrations are typically low (~10 mg m^{-3}) at low flows and increase with increasing flow and with increasing variability at flows above about 5 $m^{-3} s^{-1}$, reaching concentrations in excess of 900 mg m^{-3} at high flows.

Correlations between parameters measured were as expected with clarity decreasing as turbidity increased. Reducing pH and conductivity with increasing flow can be attributed to dilution effects, whereas the steadier NH_4-N and NO_3-N concentrations at high flows suggest a groundwater source. Groundwater nutrient concentrations are slow to change because of the large reservoir of similar water stored in the aquifers. Consequently, an increased input of that groundwater will not change the concentration of the NH_4-N or NO_3-N in the stream while adding rainfall, with low concentrations, will reduce the concentrations in the stream. Whether the form of the nitrogen is NH_4-N or NO_3-N depends on whether the groundwater in the aquifer is anoxic or aerobic, respectively.

While there was a significant (P <0.001) relationship between TN and turbidity, it only explained 47% of the variability. In contrast, there was a highly significant (P <0.0001) relationship between TP and turbidity (Figure 3-12) which explains 91.5% of that variability. The TP – turbidity relationship coupled with the relatively high calcium concentration (Table 2-2), is consistent with the erodible soils in the catchment being marine sediments raised by tectonic activity on the east coast of New Zealand.

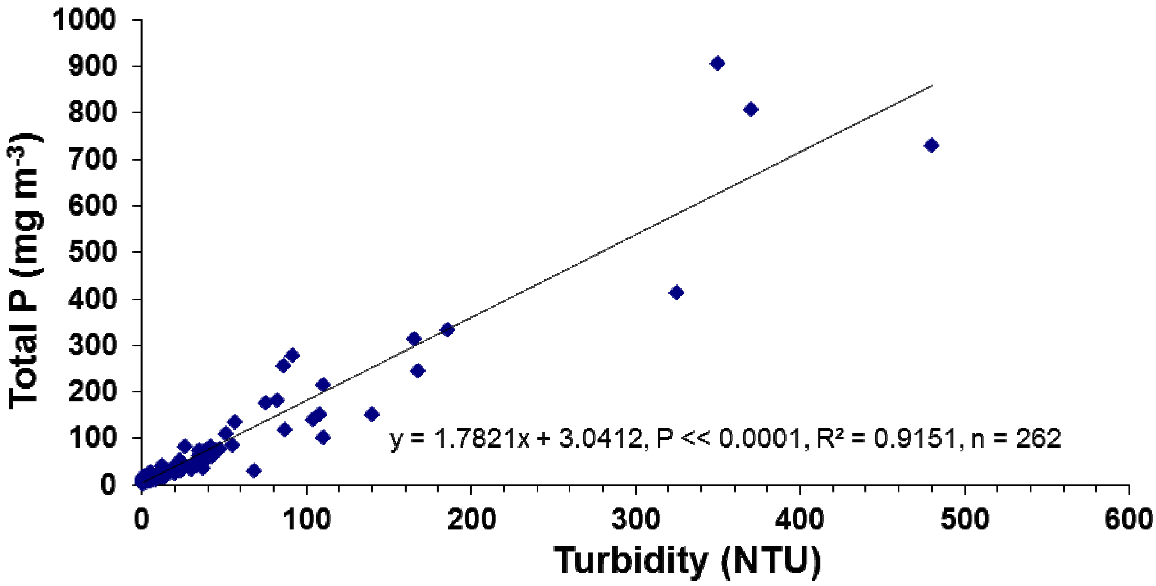


Figure 3-12: Relationship between total phosphorus and turbidity. Total P concentrations (mg m^{-3}) increased at 1.78 ± 0.07 times the turbidity (NTU).

3.2.2 DYRESM-CAEDYM modelling

The model simulations (Figure 3-13) indicate that the nutrient concentrations in the proposed reservoir are likely to be low, which is consistent with the average nutrient concentrations in the Makaroro River inflow (NRWQN data). However, because of the potential for oxygen depletion below depth elevation 426 mRL, nutrient release from the sediment can produce higher nutrient concentrations in the bottom 30 m of the reservoir water column. The highest concentrations are predicted in the small volume below the draw depth for the compensation water in the toe of the dam.

Dissolved reactive phosphorus concentrations are expected to be <15 mg m^{-3} throughout the water column , being lower nearer the surface but being as high as 80 mg m^{-3} below the compensation water outlet. Total P concentrations are also expected to be low (<50 mg m^{-3}) throughout the water column but were found to be up to 240 mg m^{-3} in the upper water column during the high rainfall event in spring 2003 (Figure 3-1). That is consistent with the turbid water entering the reservoir as a buoyant surface plume and with the high turbidity water having very high TP concentrations (Figure 3-12).

Simulated NH_4-N concentrations were low throughout the water column except in the bottom water below the depth of the compensation water outtake where concentrations could reach up to 700 mg m^{-3}. Nitrate was more evenly distributed through the water column as it was a major component of the water chemistry in the Makaroro River inflow and thus dominated the reservoir water chemistry, especially during filling. The effect of selective draw at elevation 426 mRL (30 m above the reservoir bed) is apparent with NO_3-N concentrations being augmented below that depth by nitrification of NH_4-N released from the sediments. The high rainfall event in spring 2003 was also apparent in the NO_3-N and TN data (Figure 3-13).

The NRWQN monitoring data for the Makaroro River did not include dissolved organic or particulate organic components of the main nutrients. Inflow concentrations of these parameters were derived from the NRWQN data as outlined in modelling report (McBride et al. 2011; p 19). Daily data for the DYRESM-CAEDYM modelling was derived from linear interpolation from monthly values using generalised parameter values assigned based on previously published values for oligotrophic to mesotrophic lakes (Schladow & Hamilton 1997; Gal et al. 2009; Trolle et al. 2011). The parameters derived were considered to be labile (i.e., biologically available) and included dissolved organic phosphorus, nitrogen and carbon (DOP, DON, DOC) and particulate organic phosphorus, nitrogen and carbon (POP, PON, POC) (Figure 3-14).

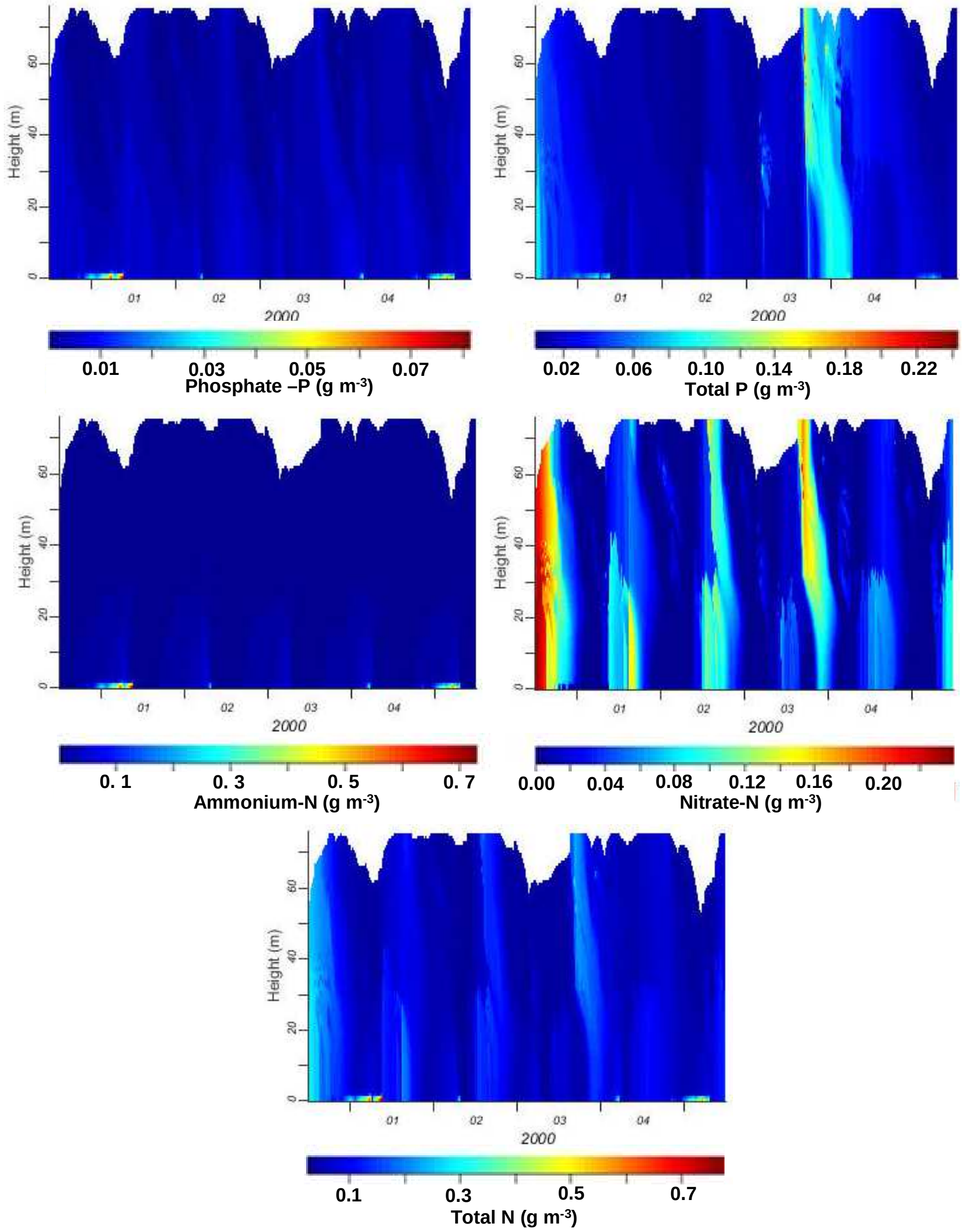


Figure 3-13: Simulated nutrient concentrations. Model run period 30/06/2000 to 30/06/2005, for phosphate, total phosphorus, ammonium, nitrate and total nitrogen. Note that the colour scales are different for each plot. (Figure 11 from McBride et al. 2011).

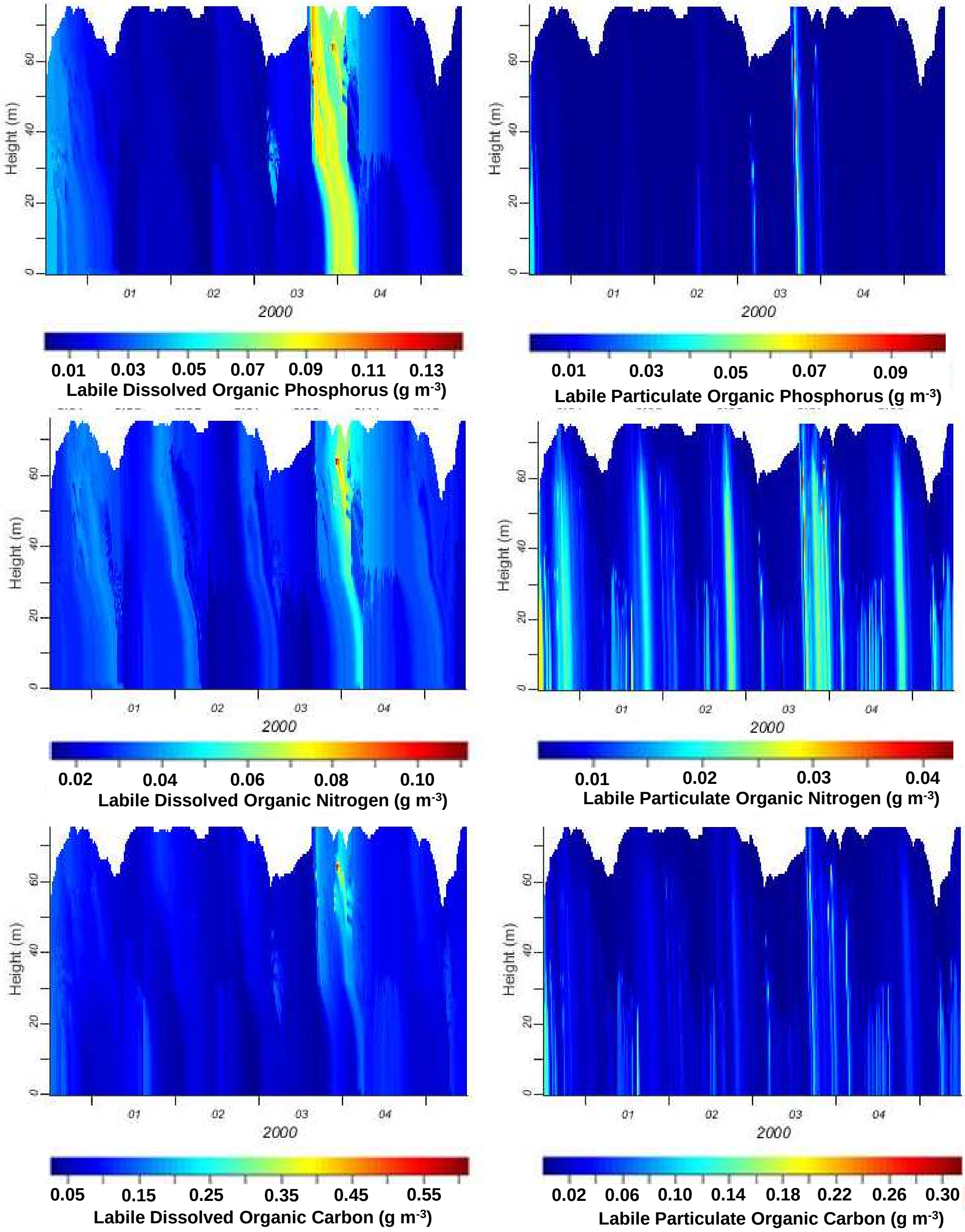


Figure 3-14: Simulated organic nutrient concentrations. Parameters modelled for the period 30/06/2000 to 30/06/2005 are labile DOP, POP, DON, PON, DOC and POC. Note that the colour scales are different for each plot. (Figure 12 from McBride et al. 2011).

3.2.3 Periphyton and phytoplankton

The NRWQN data for the Makaroro River had no algal data, and observations suggested that there was low periphyton biomass in the river. However, the increases in the % saturation of DO with increases in pH (Figure 3-15) suggest that there must be some periphyton growth in the river. The increase in pH with increasing DO %saturation is consistent with periphyton growth consuming CO_2 from the water during photosynthesis.

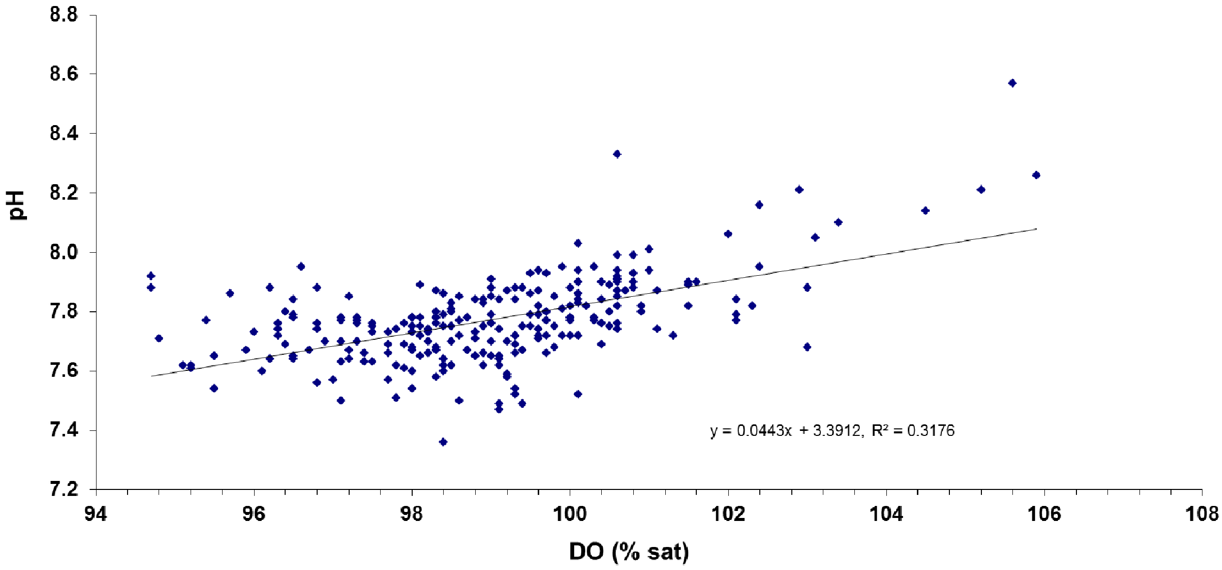


Figure 3-15: Relationship between pH and DO %saturation in the Makaroro River. Data from the NRWQN monitoring database from 1990 to 2010.

Growth of phytoplankton biomass in the Makaroro reservoir was simulated by 'seeding' low concentrations (0.1 mg m^{-3}) of chlorophyll *a* into the Makaroro River inflow for each of three phytoplankton groups – cyanobacteria, chlorophytes and diatoms. The simulated daily maximum surface total chlorophyll *a* concentrations ranged from 0.3 to 9.5 mg m^{-3} over the 5 year period of the model. Diatoms were the dominant group (maximum 7.3 mg m^{-3} chlorophyll *a*) followed by chlorophytes (maximum 1.2 mg m^{-3}) and relatively low cyanobacteria (maximum 1.2 mg m^{-3}). Chlorophyll *a* concentrations were typically highest during spring (Figure 3-16).

These results are entirely consistent with deep oligotrophic to mesotrophic lakes.

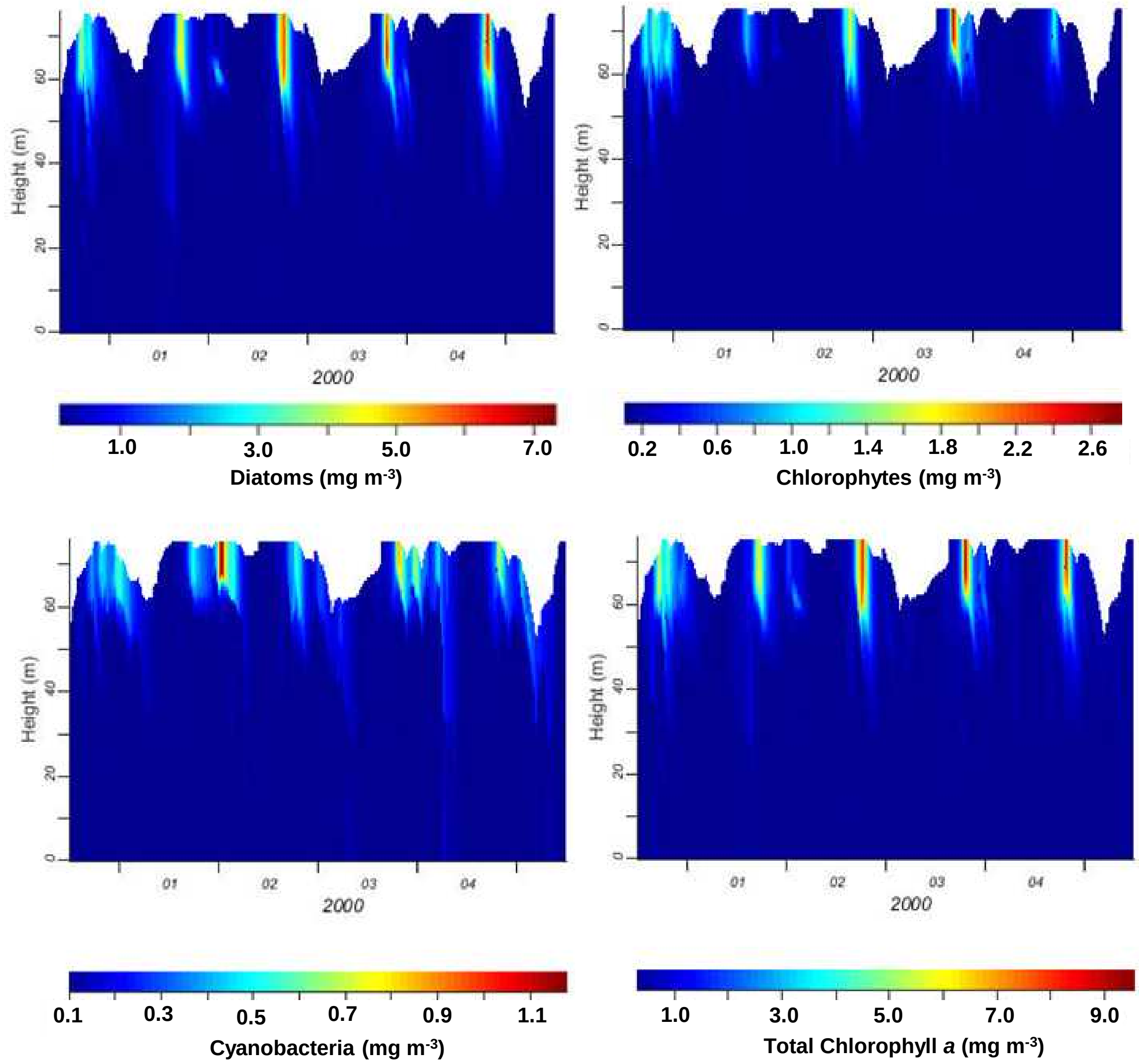


Figure 3-16: Simulated total chlorophyll *a* concentrations for the period 30/06/2000 to 30/6/2005. Individual simulation graphs are for diatoms, chlorophytes, cyanobacteria and total chlorophyll *a*. Note that the colour scales are different for each plot. (Figure 14 from McBride et al. 2011).

Note that the depth of mixing is important to the growth of phytoplankton in the reservoir. With draw-induced stratification at elevation 426 mRL, the mixed depth for the reservoir when full would be 43.7 m. If the water clarity, as indicated by Secchi depth, was in the order of 10 m, light, sufficient for phytoplankton growth, would penetrate to a depth of about 30 m (euphotic depth). The remainder of the mixed depth would be in darkness not supporting growth as the phytoplankton are mixed through the epilimnion. The balance between exposure to light and dark during mixing determines the phytoplankton growth rate, assuming sufficient nutrients. The critical depth is where phytoplankton growth is precisely matched by losses of phytoplankton biomass within the mixed layer (Sverdrup 1953). If the draw depth was raised to 455 mRL (upper outtake), draw-induced stratification would form at that depth and the mixed depth would be 12.7 m. The phytoplankton would be held in the light and would have the potential to grow faster (Figure 3-17).

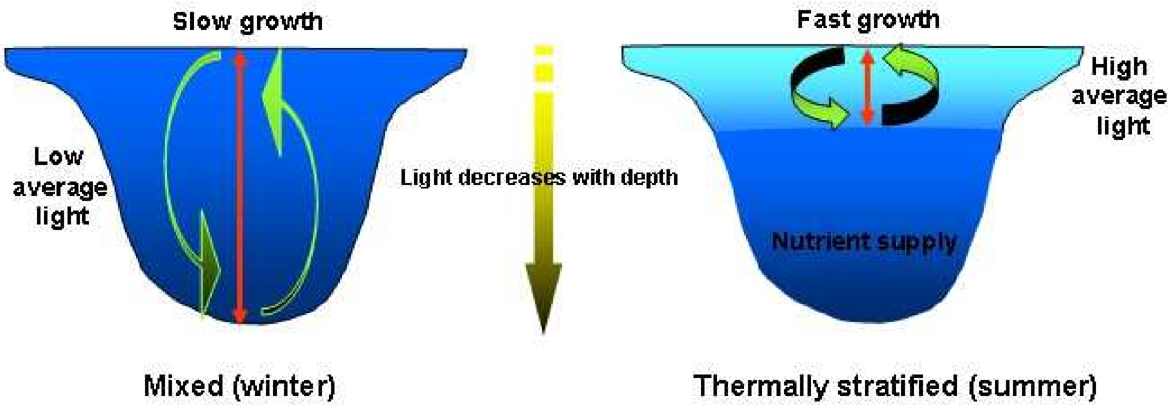


Figure 3-17: Schematic diagrams illustrating the effect of stratification on the growth of phytoplankton in a mixed and stratified water body.

3.2.4 pH

The pH of most natural waters is a function of the amount of mineral salts and carbon dioxide (CO_2) in the water. When CO_2 dissolved in water, the CO_2 molecules react with water molecules to produce a weak acid, carbonic acid (H_2CO_3), which tends to lower the pH. The H_2CO_3 and mineral salt concentrations in the water contribute to an equilibrium that produces the observed pH for that water.

Phytoplankton can affect that equilibrium by using some of the CO_2 for growth. When phytoplankton biomass is low, the pH is a function of the natural equilibrium. When phytoplankton biomass increases, some of the CO_2 is removed during photosynthesis to produce chlorophyll *a*. The loss of CO_2 from the water shifts the equilibrium towards alkaline conditions and the pH rises and, during phytoplankton blooms, may exceed 10. Such high pH would be unlikely to occur through the full depth of the water column in the Makaroro reservoir.

Decomposition of organic matter can also affect pH by adding extra CO_2 to the water. During mixed conditions this CO_2 is degassed into the atmosphere as the concentrations equilibrate to around 100% saturated. However, during stratified conditions, degassing doesn't occur in the bottom waters and CO_2 concentrations can become supersaturated. The extra H_2CO_3 in the water drives the pH down towards 5.5.

Consequently, during summer stratification in a lake with medium to high primary productivity, the surface waters are likely to have an elevated pH probably >8.5 while the bottom waters are likely to have a lowered pH of <6.

Aeration causes mixing by disrupting the stratification. It will also tend to degas the CO_2 from the water causing a slight rise in the pH in the water column to above 7. However, when the circulation currents are established, the prolonged contact with air during the mixing flow path will allow CO_2 concentrations to remain at near saturation levels and thus maintain a pH of around 7.

3.2.5 Trophic status

The simulated total nitrogen and chlorophyll *a* concentrations in the reservoir are those typically associated with oligotrophic or microtrophic (low productivity, high quality) lakes and reservoirs, according to trophic level index (TLI) values defined by Burns et al. (1999). The oligotrophic trophic level has the following ranges: chlorophyll *a* 0.82–2.0 mg m^{-3}, TP 4.1–9.0 mg m^{-3} and TN 73–157 mg m^{-3}. However, total phosphorus concentrations were more variable and, in 2003-2004, were high enough (55 mg m^{-3}) to be considered supertrophic (Table 3-2). Water clarity measured as Secchi depth for oligotrophic is in the range 7.8 – 15 m.

The use of the TLI assessment of water quality provides a means of comparing the water quality of one lake with another, assuming the parameters measured are associated with the productivity of the lake. The variability of the TP concentrations in 2003–2004 were not associated with primary production, rather they were linked to the suspended sediments (Figure 3-12) in the inflowing water during a flood event (Figure 3-1). Excluding the effects of the sediment P, the Makaroro reservoir is likely to have a trophic level classification of oligotrophic to mesotrophic.

Table 3-2: Surface (0 m) total nutrient concentrations and associated TLI3 trophic levels. (Burns et al. 1999; Verburg et al. 2010). (Table 3 from McBride et al. 2011).

Period	Average Chl *a*		Average TP		Average TN	
	(mg m^{-3})	Trophic level	(g m^{-3})	Trophic level	(g m^{-3})	Trophic level
2000-2001	1.4	Oligotrophic	0.025	Eutrophic	0.095	Oligotrophic
2001-2002	1.3	Oligotrophic	0.008	Oligotrophic	0.053	Microtrophic
2002-2003	1.3	Oligotrophic	0.013	Mesotrophic	0.059	Microtrophic
2003-2004	1.4	Oligotrophic	0.055	Supertrophic	0.082	Oligotrophic
2004-2005	1.2	Oligotrophic	0.014	Mesotrophic	0.052	Microtrophic

Notwithstanding this, once those suspended solids have settled to the bottom of the reservoir the phosphorus bound to the soil particles may be released under anoxic conditions in summer to stimulate primary production and in particular, the proliferation of cyanobacteria.

The high mean annual concentration of TP in the reservoir has an effect on the character of the reservoir water. Based on the Redfield (1958) relationship for phytoplankton growth, chlorophyll *a* molecules have an atomic ratio of 106 C : 16 N : 1 P. This is equivalent to an N:P mass ratio of 7.2. If the TN:TP ratio in the reservoir water column is much greater than 7.2:1, there is a high probability that phytoplankton growth will limited by the availability of P i.e., the reservoir would be classed as P-limited. Conversely, if the TN:TP ratio is much less than 7.2, there is a high probability that phytoplankton growth would be limited by the availability of N i.e., the reservoir would be classed as N-limited. There is a zone of co-limitation around 7.2.

The TN:TP ratios in the simulated reservoir water quality varied considerably over the modelling period (Figure 3-18) ranging from 1 to >9. For much of the time the TN:TP ratio was <5, especially after the 2003 event. This implies that the Makaroro reservoir would be mostly N-limited and would be sensitive to any nitrogen from farm runoff or soluble forms of N in the groundwater inflows.

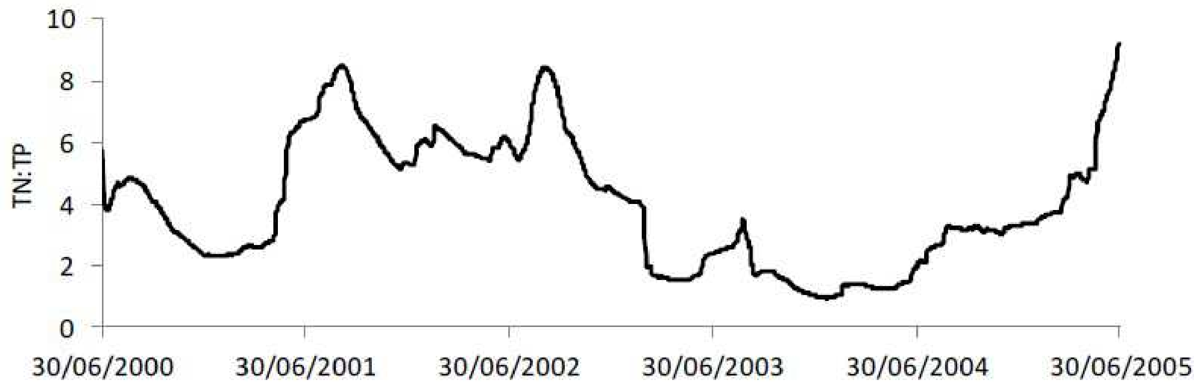


Figure 3-18: Basin average ratio of total nitrogen to total phosphorus (TN:TP) over the simulation period. (Figure 13 from McBride et al. 2011).

3.3 Outtake water

Based on the supplied daily reservoir outtake volumes (Tonkin & Taylor data), modelling showed that incoming water occasionally exceeded the capacity of the reservoir. On these days, water spilled over the crest of the dam, and was recorded within DYRESM as overflow (Figure 3-19). At all other times during the modelling the water was drawn from the outtake at an elevation of 426 mRL plus the compensation water flow from the toe of the dam.

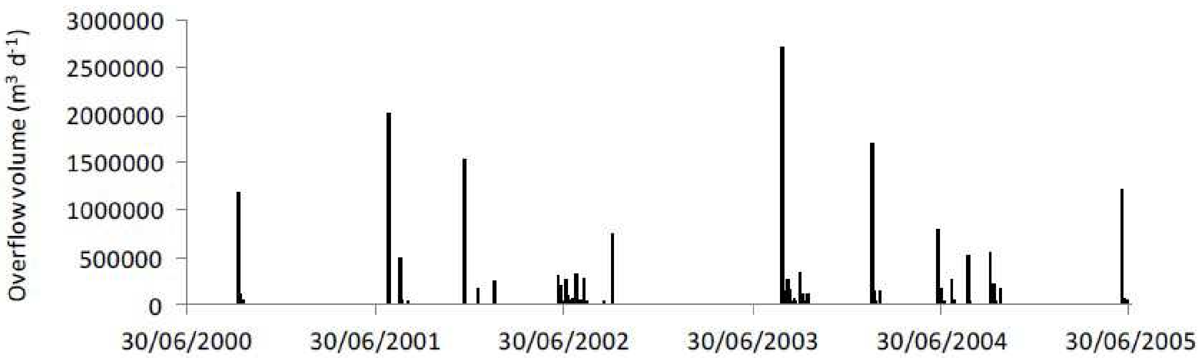


Figure 3-19: Overflow volumes (m^3 d^{-1}) spilled under high inflow conditions. Note the compensation water discharge at 1.228 m^3 s^{-1} = 106099 m^3 d^{-1}. (Figure 15 from McBride et al. 2011).

The quality of the overflow water will depend on the temperature difference between the Makaroro River inflow and the Makaroro reservoir water. This temperature difference will determine whether the flood water disperses as a buoyant surface plume or whether it plunges as a density current (e.g., Spigel et al. 2005) (Figure 3-20).

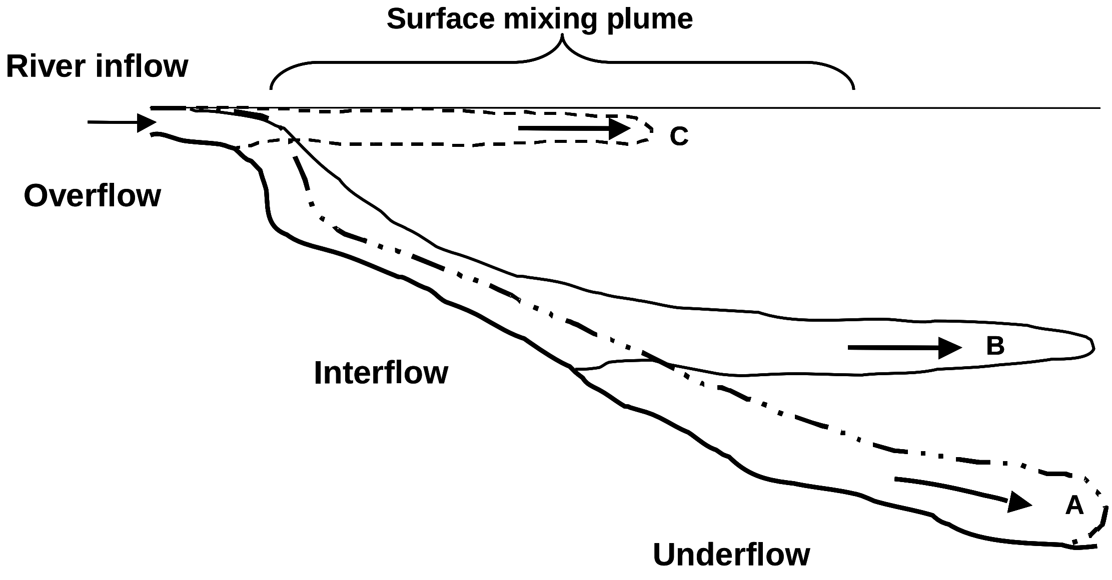


Figure 3-20: Density currents. **A**) Very cold water will become an underflowing density current moving along the bed of the reservoir, **B**) medium temperature water will plunge to a depth of equal density where it becomes and interflow, **C**) warmer water floats on the reservoir surface as an overflow which will form a visible plume on the surface.

If the rainfall event produces warmer water than the surface temperature of the reservoir, turbid inflow water will flow along the length of the reservoir and spill. If the inflow water is colder than the temperature of the reservoir, the turbid inflow water will travel down the bed of the reservoir as an underflowing density current to pool at the dam wall, displacing clean surface water from the spillway. An interflow condition is also possible where the inflowing turbid water finds a depth of equal density at a middle depth in the reservoir. Because of the deep draw regime, the insertion depth of the interflow could be the draw depth as that will have the strongest density gradient.

Depending on the entrance velocity as the Makaroro River discharges into the reservoir, oxygenated surface water will be entrained into the density current, partially re-oxygenating the anoxic water in the dead volume of the reservoir (Gibbs 1986). The amount of oxygenated water entrained into the density current will be affected by the shape of the river delta where the Makaroro River discharges into the reservoir. A gentle slope allows minimal entrainment from the upper surface of the density current. However, the formation of a gravel delta would allow the inflow water to jet out into the reservoir before it plunged, thus entraining surface water from all sides. Examples of density currents in New Zealand lakes include the Ohau Channel from Lake Rotorua into Lake Rotoiti before the diversion wall (Vincent et al. 1991) and the Tokaanu Tailrace and Tongariro River inflows to Lake Taupo (Spigel et al. 2005).

3.3.1 Suitability of water quality for aquatic life (initial modelling scenario)

Assessment of suitability of reservoir water quality for aquatic life, recreation and other uses is based on generally accepted criteria of temperature (<20^{o}C), dissolved oxygen content (>5 g m^{-3}), food supply and habitat availability.

The water quality in the Makaroro reservoir will be suitable for aquatic life, recreation (e.g., boating, swimming and fishing) and other uses such as native fauna refugia and aesthetic appreciation. Considerable habitat suitable for trout will still exist upstream of the reservoir while the reservoir will provide a new habitat and recreational facility. The upstream river and littoral zones (edge water areas to the limit of light penetration) of the reservoir would support existing and new habitat for eels and dwarf inanga (species that normally remain in shallower areas).

The bottom water (below the draw depth) in the reservoir is likely to become anoxic during summer stratification in the first few years after filling. Anoxic conditions would exclude those waters from use by most aquatic macro-organisms. Water quality effects associated with anoxia include death of organisms that require oxygen and cannot escape from anoxic regions, generation of methane and hydrogen sulphide gases, release of ammonium and dissolved phosphorus from sediments and decaying plant matter, and dissolution of iron and manganese from sediments. The duration of total anoxia each year depends on the amount of residual plant matter left in the reservoir at filling while the number of years of these anoxic events after filling depends on the rate of decomposition of that organic legacy. However, because the water quality above the draw depth will remain high throughout the year, the cost of removing that vegetation may outweigh the benefits of allowing the reservoir water quality to improve naturally as the oxygen demand decreases. The primary benefits will be the diverse habitats provided by the woody parts of the vegetation for aquatic organisms.

The predicted water levels in the reservoir will be more than 90% full in normal to wet years. In dry years the water level may fall on occasion by as much as 37 m (Figure 3-4) presenting the opportunity for erosion of the exposed reservoir bed by wind-waves. This will result in periods where the surface near-shore waters are turbid which may be beneficial as the low light and fluctuating water level will also prevent the growth of macrophyte weeds.

3.3.2 Suitability for recreation (initial modelling scenario)

Key indicators of importance for the recreational use of the reservoir are visual clarity, cyanobacteria and faecal indicators.

Visual clarity: Because the inflowing river water will almost always be colder than the open waters of the reservoir, turbid inflows are expected to be deep in the lake and therefore would be unlikely to affect visual clarity of the surface waters. However, when the water level in the reservoir is low, wave action on the exposed lake bed will most likely cause bed/bank erosion and thus a zone of highly turbid water is likely to develop around the edge of the lake where the substrate is clay. The extent of this turbid zone and thus its effect on suitability for recreation will depend on the wind strength, the relative water level and the time of year. The highest effect might occur in summer when people are most likely to use the reservoir for recreation.

Cyanobacteria: The expectation is for low phytoplankton biomass in the reservoir and that any growth of cyanobacteria would be minimal with the present input nutrient loads. The highest risk for cyanobacteria proliferation would be in mid-to-late-summer under calm conditions that would favour cyanobacteria to accumulate in the surface waters and drift inshore. This risk is expected to be low.

Faecal indicators: Assuming that the levels of *Escherichia coli* in the reservoir were similar to the levels reported for the Makaroro River in the NRWQN data (Table 2-2), the water in the reservoir should be suitable for recreation all year. *E. coli* standards for lakes in the One

Plan proposed by Horizons Regional Council[2] are for less than 260 MPN per 100 ml in summer (November to April inclusive) and less than 550 MPN per 100 ml in winter (May to October inclusive). The range of *E. coli* values reported in the NRWQN data are from 1 to 272.3 MPN per 100 ml with a mean value of 32.1 MPN per 100 ml.

[2] http://www.horizons.govt.nz/about-us/one-plan/

4 Discharge water quality (initial modelling scenario)

The quality of the water discharged from the reservoir will reflect the water quality in the reservoir. The reservoir water column is predicted to become thermally stratified for about 196 days and to become hypoxic below the draw depth of 426 mRL. Consequently, the draw depth is a critical factor affecting both the thermal structure and the degree of hypoxia in the bottom waters of the reservoir.

The “epilimnetic” water above the draw depth is predicted to be of relatively high quality and to have relatively high DO concentrations. This epilimnetic water may develop low levels of phytoplankton biomass during spring but that biomass is unlikely be drawn into the outtake 45 m below, and consequently it is unlikely to have more than a minor effect downstream.

The water column will warm up during the summer but temperatures from the 426 mRL outtake are unlikely to exceed the natural day water temperatures in the river channel (Figure 4-1). However, because the same temperature water will be drawn at night as during the day, it will suppress the day-night temperature cycle in the downstream river immediately below the dam until they are restored by contact with the stony river bed.

Oxygen depletion will occur within the reservoir below the draw depth but the discharge water from the 426 mRL outtake is predicted to have a long-term minimum DO concentration of >5 g m^{-3} in summer except in the first 2 to 3 years as the water quality stabilises (Figure 4-1). If the DO concentrations fall below 5 g m^{-3} in the outtake water, the deep water can be blended with water from the upper outtake valve at 455.5 mRL, which has higher DO concentrations, to raise the DO concentrations. Note that the higher outtake water will also have a higher temperature and both temperature and DO concentrations may need to be balanced.

Note also that fluctuating water levels in the reservoir may preclude the use of the upper outtake valve at 455.5 mRL in summer.

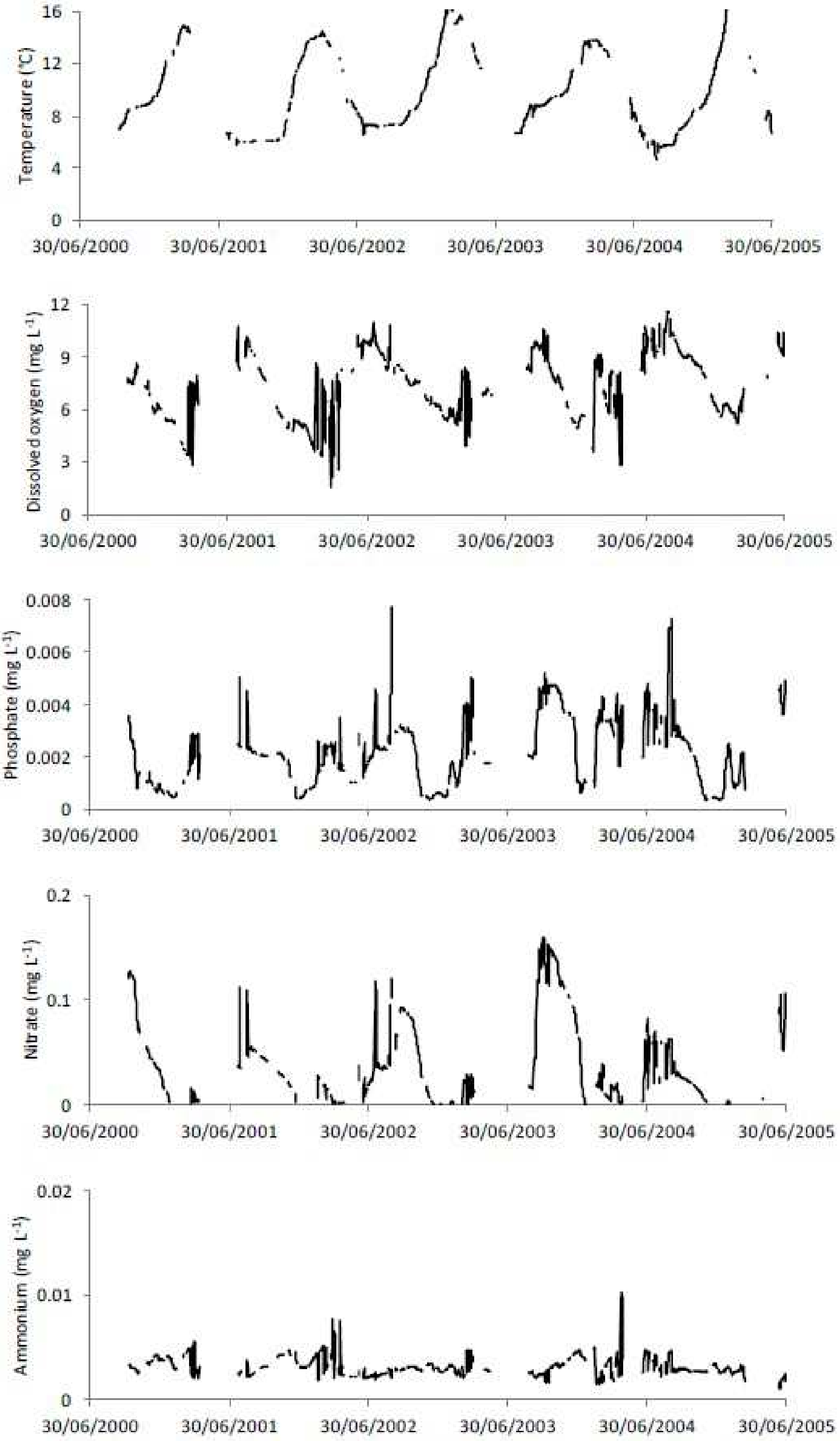


Figure 4-1: Simulated water quality in the main dam outlet (elevation 426 m). Gaps in the lines represent days when no water is withdrawn via the main dam outflow due to low water level. (Figure 17 from McBride et al. 2011).

During the mixed period, concentrations of NO_3-N and DRP will gradually increase (Figure 4-1) to inflow concentrations due to the relatively short residence time and the mixing from the hypolimnion at turnover. The NH_4-N concentrations are predicted to remain below 10 mg m^{-3} and would probably average around 5 mg m^{-3}.

While the outtake water will be discharged through the power station and via the irrigation network, the compensation water will be drawn from the hypolimnion at the toe of the dam. This water will be anoxic for the most of the stratified period and, consequently, it will have elevated concentrations of NO_3-N, NH_4-N and DRP. The predicted levels of these nutrients in this water would be sufficient to stimulate periphyton growth in the downstream river bed (Figure 4-2).

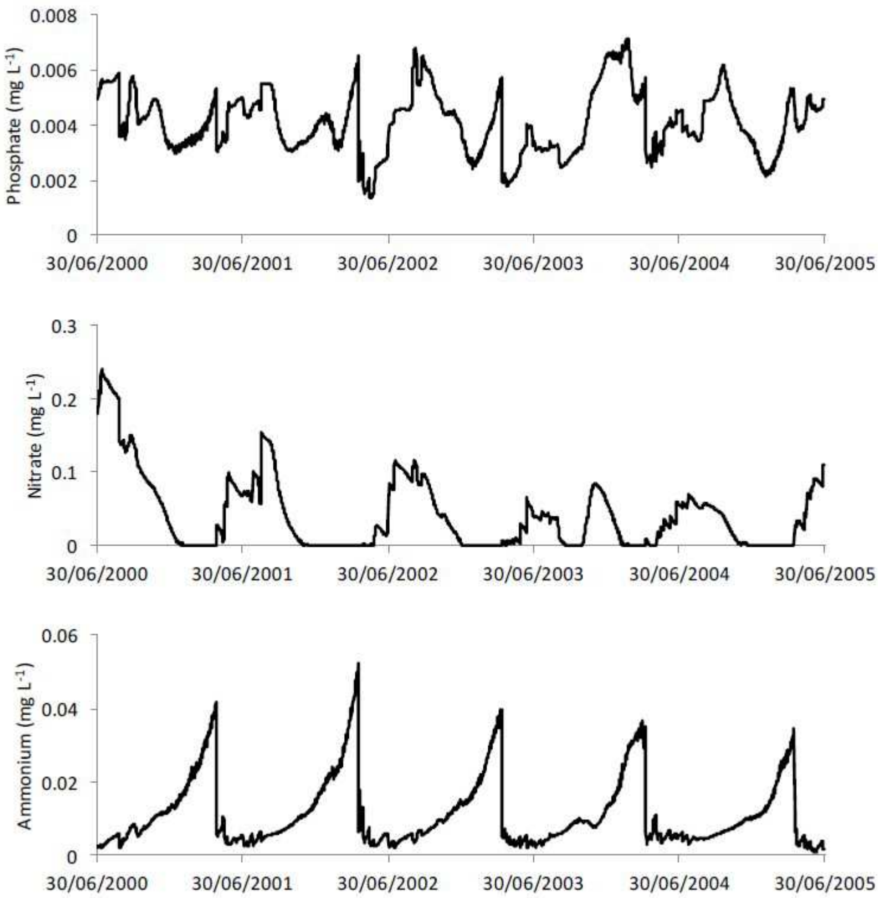


Figure 4-2: Simulated water quality of the dam toe outtake. (Extracted from Figure 16, McBride et al. 2011).

Concentrations of DRP and NH_4-N increase during the stratified period as these are released from the sediment and NH_4-N is not nitrified to NO_3-N in the anoxic water. During the well oxygenated mixed period, NO_3-N concentrations increase as the NH_4-N is nitrified at the sediment water interface (Figure 4-2).

It would be possible to draw the compensation water from above the main draw depth to provide high quality clean low nutrient water to the river below the dam. However, simulations eliminating the compensation water outtake from the toe of the dam indicate that this would not be a permanent solution as the reservoir would become anoxic below the draw depth and may remain stratified for several years without a winter mixed period (Figure 3-9).

Overall, because of the settling chamber effect of reservoirs, the outtake water will have higher clarity and lower suspended solids than the inflow water (Table 4-1). In-reservoir process that consume nutrients will tend to dampen the peaks and troughs of flow dominated nutrient dynamics in the inflow (Table 2-2) leading to an over-all improvement in the quality of the water discharged. The water quality of the reservoir (Table 4-1) will be the most likely quality of the water discharged from the reservoir.

Table 4-1: Basin average nutrient concentrations by year in the Makaroro River and the reservoir. (Data from Table 2, McBride et al. 2011 and the monthly NRWQN database).

Period	Inflow	Reservoir	Inflow	Reservoir	Inflow	Reservoir	Inflow	Reservoir	Inflow	Reservoir
	DRP	DRP	NO_3-N	NO_3-N	NH_4-N	NH_4-N	TP	TP	TN	TN
	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}	mg m^{-3}
2000 - 2001	5	2	84	59	2	2	31	26	129	97
2001 - 2002	4.5	1	69	16	3	2	11	8	115	50
2002 - 2003	4.5	2	60	23	1	2	12	13	92	53
2003 - 2004	4.5	2	69	33	1	2	68	53	122	79
2004 - 2005	5.6	2	57	15	3	2	11	14	98	49

4.1 Further investigations

The initial modelling scenarios have identified that water quality of the Makaroro reservoir and the discharge water from the reservoir are dependent on the depth water is drawn from the reservoir. With a main draw depth at 426 mRL, the bottom 30 m water depth of the reservoir will become anoxic each year for several months. A recommendation, from the initial draft of this report, that the DYRESM-CAEDYM model be used to determine the effect on bottom water hypoxia of lowering the main draw depth to 405 mRL, was adopted and the results of that modelling have been included as a separate section (section 5) in this report.

5 Supplementary Modelling

Three DYRESM-CAEDYM model runs with the main draw depth set at 405 mRL (scenario M1) and 443 mRL (scenario M2) to assess the effects of selective draw on density stratification and bottom water DO depletion (McBride 2012). An additional scenario (M3) was tested with minimum base flow (1.228 $m^3\ s^{-1}$) drawn from 405 mRL and the remainder, about 5.1 $m^3\ s^{-1}$, being drawn from the 443 mRL outtake.

5.1 Outtake design

The design of the outtake structure (Figure 5-1) includes two valve towers at different depths: the lower valve tower is built at around 400 mRL with valve openings adjustable from 402 mRL to 417 mRL. This valve tower is located in a 10m wide 40 m deep slot that branches off the right bank of the river channel about 100 m upstream of the dam wall. It opens into a 4 m diameter duct which releases water into the Makaroro River just below the dam wall via a power station. The second valve tower is built at an elevation of 440 mRL with a height sufficient to reach the surface. The valve at 443 mRL opens into a vertical 2.1 m diameter steel-lined shaft which connects into the 4 m diameter duct from the lower outtake valve structure.

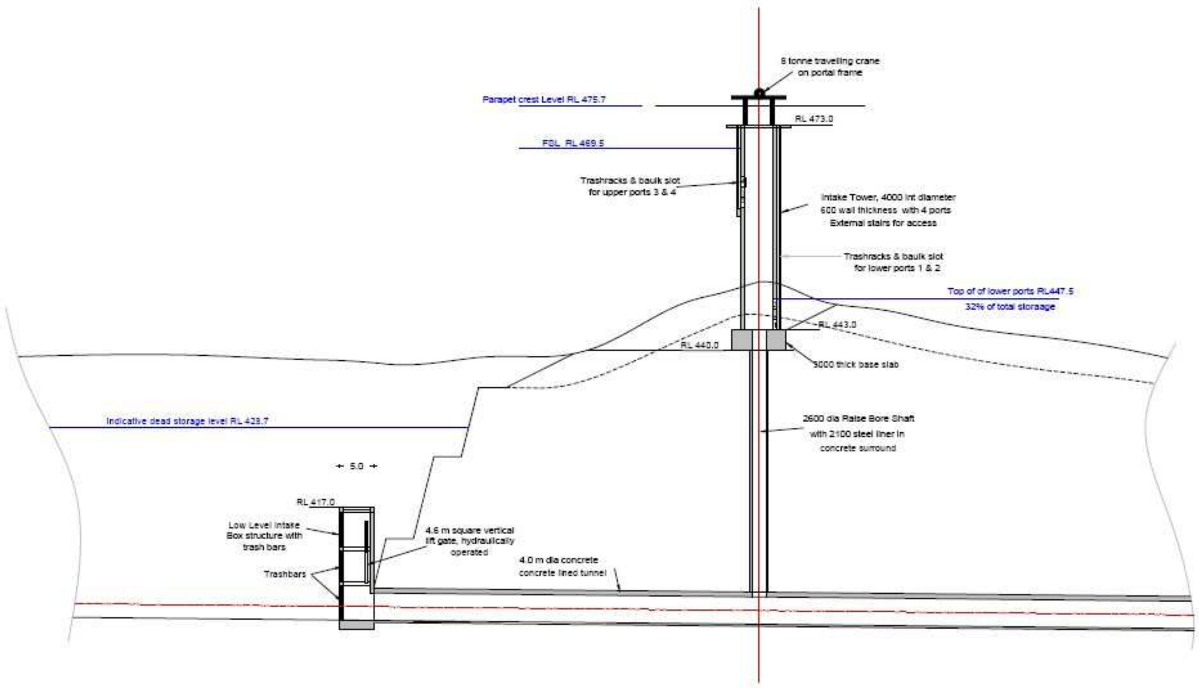


Figure 5-1: Valve tower design tested in the supplementary modelling. Information and design as provided by Tonkin & Taylor, 16 December 2011.

This design, coupled with the mean annual flow regime of inflow balancing outflow of around 6.3 $m^3\ s^{-1}$ and a minimum base flow of 1.228 $m^3\ s^{-1}$, will maintain flowing water in the Makaroro River at all times. The quality of that water, however, will be dependent on the depth of draw used during operation.

5.2 Model results

5.2.1 Temperature and DO

The depth of draw and the combination of draw depths had profound effects on both the temperature and the DO concentrations in the reservoir (Figure 5-2).

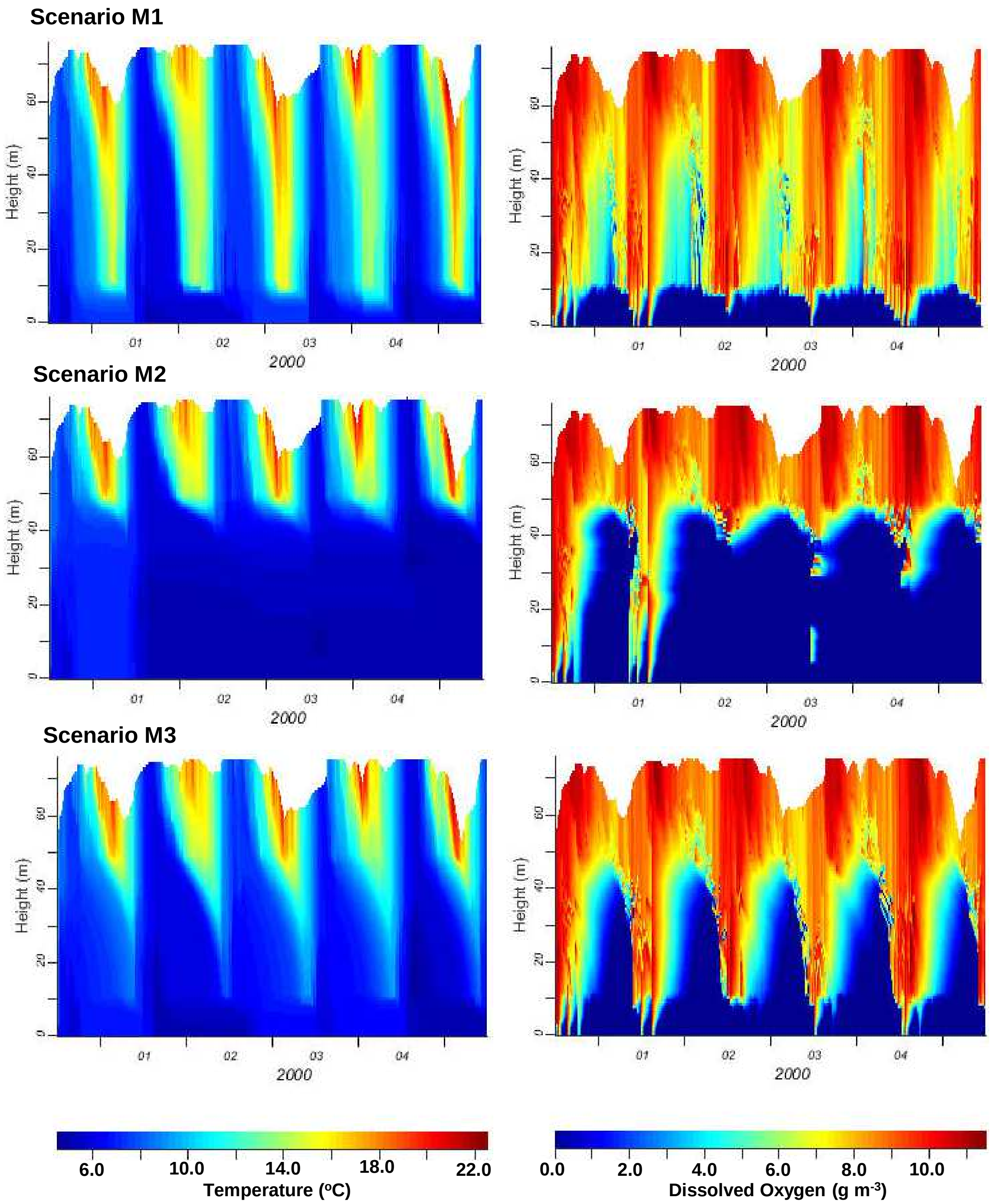


Figure 5-2: Simulated temperature (left) and dissolved oxygen (right) for the period 30-06-2000 to 30-06-2005. Simulations are for modelling scenarios M1 (top), M2 (middle) and M3 (bottom). (Figure 1 from McBride 2012).

Scenario M1

With all water being drawn from the 405 mRL outtake valve, the water column in the reservoir would be strongly stratified at the draw depth and may not completely mix each winter. While the water below the draw depth (dead zone) would become anoxic, the water being drawn into the 405 mRL outtake valve would have DO concentrations >5 g m^{-3} almost all year (Figure 5-3). However, because the water in the dead zone was anoxic, DO concentrations would briefly fall below 5 g m^{-3} during winter mixing. While the model simulates this condition, showing patches of low DO water high in the water column (Figure 5-2), the extent of the DO depletion, the minimum DO concentration and the duration of the apparent hypoxia are all functions of the reservoir hydrodynamics.

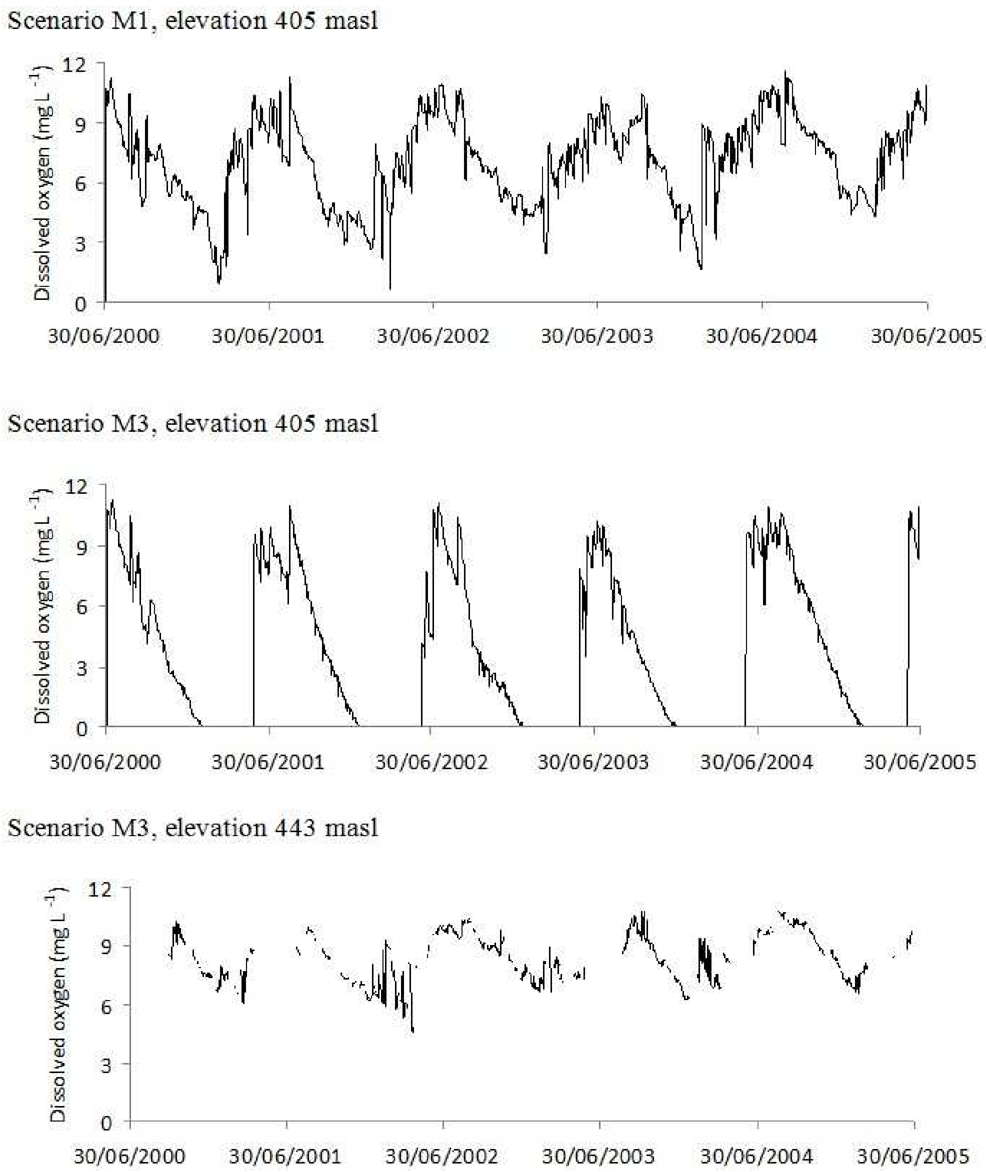


Figure 5-3: Simulated dissolved oxygen (DO) concentrations in the water discharged from the reservoir for scenarios M1 and M3. Both the lower (405 mRL) and upper (443 mRL) DO concentrations are shown. Gaps in the 443 mRL data represent periods when the outtake volume was equal to the prescribed compensation flow. (Figure 4 from McBride 2012).

At the draw elevation of 405 mRL, the hypolimnion is very small, being approximately 0.25% of the total volume of the reservoir when full. The 400-fold dilution of the anoxic water at winter mixing would result in a very small change in the DO concentration throughout the whole water column and this would disperse rapidly.

Scenario M2

With all water being drawn from the high level outtake valve at 443 mRL, the water column in the reservoir would be strongly stratified at that depth and would not mix in some years (Figure 5-2). The water below the draw depth would become anoxic giving the reservoir a dead zone of approximately 21% of the total volume of the reservoir. Before this water could be released it would need to be aerated with aeration starting during the winter mixed period to avoid the production of phytoplankton blooms as would most likely occur if aeration was started after stratification had become established and oxygen depletion was occurring (e.g., Figure 7-1 B).

Note that there would be periods of low flow when the outflow would be equal to the prescribed compensation water flow as indicated in the M3 – 443 mRL outflow graph (Figure 5-3) and the earlier simulations (Figure 4-1). Under these low flow conditions, the outflow may be greater than the inflow from the Makaroro River and the lake level would fall. However, because of the fixed outtake elevation, the water discharged would be skimmed from the surface of the reservoir. Because surface skimming no longer has a selective draw effect on stratification, the reservoir would be likely to develop thermal stratification at a depth of around 10 to 15 m below the surface. This would allow surface temperatures to increase while the nutrients in that layer would stimulate phytoplankton growth. These conditions would continue until the water level rose sufficiently to create draw-induced stratification. At winter mixing the release of elevated dissolved nutrient concentrations that had accumulated in the hypolimnion would stimulate substantial phytoplankton production in the reservoir. Nutrients not used in the reservoir would degrade the water quality of the outflow water stimulating periphyton growth in the river below the reservoir.

Although well oxygenated, the water discharged from the reservoir under scenario M2 would be the warmest in the reservoir, it would have the highest phytoplankton biomass (especially of cyanobacteria if these became dominant), it would have periods of high dissolved nutrients at mixing in autumn and it would have the highest “trash” content with leaves, sticks and logs.

To overcome the problems associated with oxygen depletion during summer, aeration would need to be initiated each year from early spring to ensure the discharge water from the reservoir was suitable for aquatic life.

Scenario M3

With a base flow of 1.228 $m^3 s^{-1}$ being drawn from the lower outtake valve and the remainder (5.1 $m^3 s^{-1}$) being drawn from the upper outtake valve at 443 mRL, the water column in the reservoir would be strongly stratified over the summer period but with the thermocline moving down through the water column from a 443 mRL start point to the lower depth of 405 mRL. This effect is due to the reduced outtake at 443 mRL when the reservoir water level is low in summer. The water column above the 405 mRL outtake valve would initially be well oxygenated but would experience oxygen depletion below the 443 mRL outtake valve by the end of summer each year after periods of low flow. The water drawn from the 405 mRL outtake valve would be anoxic for about 4 months each year (Figure 5-3; M3 elevation 404 mRL) but, when blended with the water from the 443 mRL outtake valve(Figure 5-3; M3 elevation 443 mRL), the water discharged from the reservoir, would be well oxygenated with DO concentrations >5 g m^{-3}. However, when it was not possible to draw water from the 443 mRL outtake valve due to low water levels, the water discharge from the reservoir would become anoxic.

Management strategies to avoid anoxic water discharge from the reservoir include allowing uncontrolled surface skimming as in scenario M2 during those periods, or a blending of those waters with a higher proportion of water from the 443 mRL outtake than from the 405 mRL outtake, or aeration.

Because these conditions are known to be going to occur each summer, aeration would need to be initiated early in spring to provide an outtake water quality suitable for aquatic life.

5.2.2 Nutrients

Nutrient concentrations in the reservoir were simulated for scenarios M1 (Figure 5-4) and M3 (Figure 5-6).

Scenario M1

In scenario M1, phosphate, total P, ammonium and total N concentrations would become enriched in the dead zone below the draw depth at 405 mRL during the stratified period due to sediment release under anoxic conditions. In contrast, the concentrations of those nutrients would be low in the water column above the draw depth. Nitrate-N concentrations were elevated in the water column above the draw depth during winter and spring consistent with the nitrate concentrations on the inflow water from the Makaroro River. Below the draw depth, nitrate concentrations reduced to zero associated with denitrification in the anoxic dead zone.

At winter mixing, the accumulated nutrients in the dead zone will be rapidly diluted 400-fold by the volume of water in the reservoir, implying that any effects are likely to be minimal and of short duration.

Results for this scenario (M1) also suggest that phytoplankton biomass, as indicated by chlorophyll *a* concentrations, is likely to rise in the upper water column during spring with near surface chlorophyll *a* concentrations reaching >7 mg m^{-3} but falling to <2 mg m^{-3} by summer. With the outtake valve drawing water from 405 mRL, this phytoplankton biomass is unlikely to be drawn into the discharged from the reservoir.

During the flood event in the 2003–2004 period, high nitrate and total P concentrations were indicated through the full water column depth. Both of these nutrients are associated with the inflow and thus indicate that there is still a degree of inflow-outflow coupling through the reservoir under high flows. Nitrate concentrations decreased more rapidly than the total P which is consistent with the total P being associated with fine sediment (Figure 3-12). The reduction in nitrate concentrations is partially attributed to denitrification.

Scenario M1

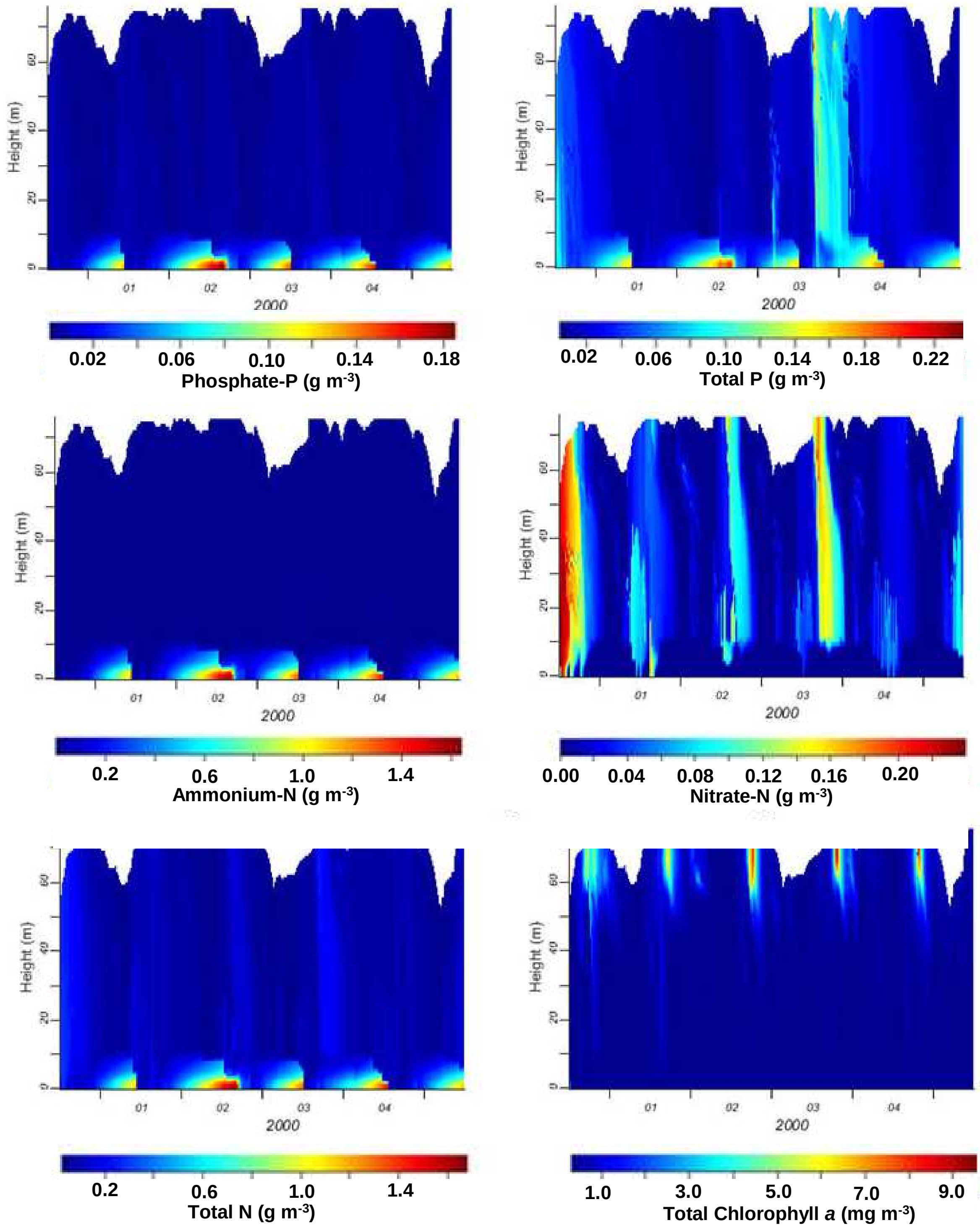


Figure 5-4: Simulated nutrient concentrations for scenario M1. Concentrations for phosphate-P, total phosphorus, ammonium-N, nitrate-N, total nitrogen and total chlorophyll *a* for the period 30/06/2000 to 30/06/2005. Note that the colour scales are different for each plot. (Figure 2 from McBride 2012).

A comparison of temperature structure in the reservoir water column with DO, chlorophyll *a*, nitrate-N, ammonium-N and phosphate concentration profiles in summer (Figure 5-5) illustrate the concept of selective draw-induced stratification and how it affects each parameter at different depths in the water column. Elevated concentrations of ammonium-N and phosphate in the bottom waters are consistent with anoxic conditions below the draw depth. The lack of nitrate-N below the draw depth is consistent with denitrification occurring in the anoxic dead zone. The September 2003 flood event had a substantial and prolonged effect on nitrate dispersion in the water column to be seen at these concentrations in January 2004. Such events will affect the downstream water quality in the Makaroro River.

Although the nutrient concentrations below the draw depth are high, they will experience a 400-fold dilution during winter mixing, as noted for the dissolved oxygen concentrations, and thus are likely to have minimal effect on the water quality in the reservoir or discharged from it.

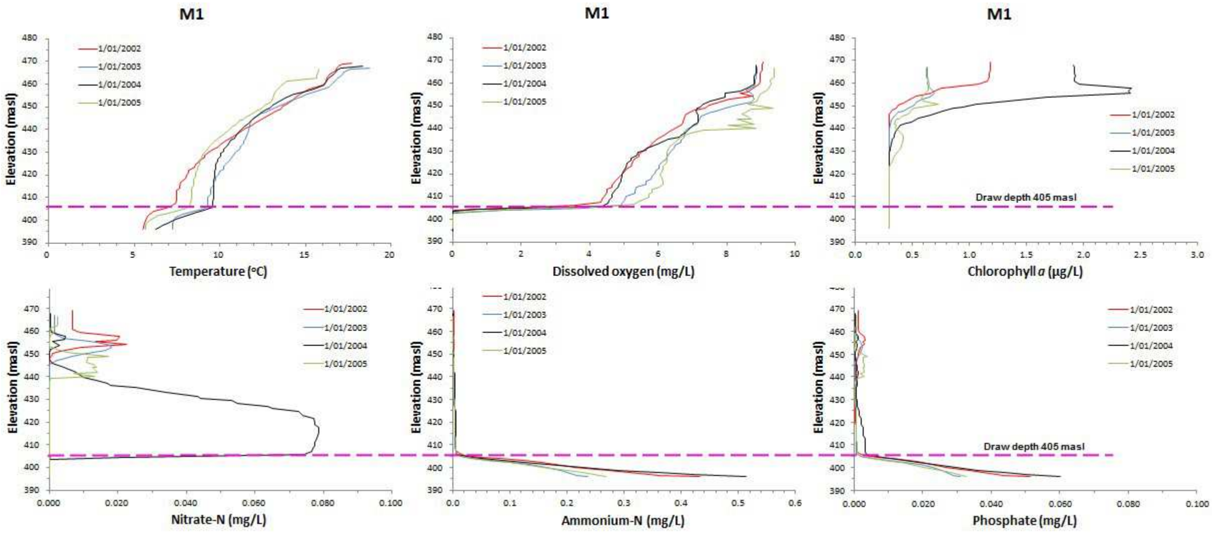


Figure 5-5: Simulated water column profiles on 1st January each year from 2001 to 2005 for scenario M1. Chlorophyll *a* and nitrate-N concentrations are highest above the draw depth (405 mRL) while ammonium-N and phosphate concentrations are highest below the draw depth where the water is anoxic. (Limnotrack model output data).

The water column profiles (Figure 5-5) also indicate that density currents can intrude as interflows carrying inflow water nutrients into the upper water column where they can be used for phytoplankton growth. The depth of the intrusion layer at between 440 mRL and 460 mRL coincides with the upper outtake valves at 443 mRL.

Scenario M2

The main difference between scenario M1 and M2 is that the draw-induced stratification depth is higher in the water column providing a larger dead zone volume. Whereas the dead zone volume for scenario M1 is around 0.25% of the total volume of the reservoir, the dead zone volume under scenario M2 will be around 21% of the total volume of the reservoir. With the larger volume of stagnant water to move, it is likely that the water column will not mix in some years. Consequently, nutrient release from the sediments will be cumulative and, when mixing does occur, there will be a substantial pulse of high nutrients through the reservoir. That will cause a reduction in the water quality in the reservoir and the water discharged from the reservoir. Unlike the short duration effect of the scenario M1 mixing with a 400-fold dilution effect, the maximum dilution effect for scenario M2 would be 5-fold. Such levels of nutrients are likely to stimulate phytoplankton growth in the reservoir and periphyton growth in the Makaroro River below the reservoir.

Aeration to maintain aerobic water in the reservoir at all times would prevent the release of nutrients from the sediments and provide discharge water suitable for aquatic life.

Scenario M3

In scenario M3, contour plots of water column nutrient and chlorophyll *a* concentrations (Figure 5-6) were similar to those from scenario M1 (Figure 5-4). With the bulk of the water being drawn from the high level (443 mRL) outtake valve there were lower dissolved oxygen concentrations in water column below that depth, allowing sediment release of nutrients and accumulation of those nutrients in the water column below the 443 mRL outtake level. Very high nutrient concentrations occurred in the dead zone below the lower 405 mRL outtake level. The effect of the two draw depths means that between 443 mRL and 405 mRL, the water quality was lower than in the scenario M1 simulation. Profiles of water quality parameters from the scenario M3 simulation (Figure 5-7) show that the water below 443 mRL had lower dissolved oxygen concentrations and higher nitrate, ammonium and phosphate concentrations than on the same profile dates from the scenario M1 simulation (Figure 5-5).

While the intrusion layers associated with the Makaroro River inflow were still present, changes in the profiles around the upper outtake valve (Figure 5-7) suggest that in the M3 scenario, the intrusion layer water was being drawn into the valve and thus dominated the outflow water quality from the reservoir. Being close to the surface, especially during low water level, the upper outtake valve was also drawing water containing elevated phytoplankton biomass. That was not observed in the scenario M1.

Because the dead zone below the lower outtake valve was strongly anoxic below it would have similar nutrient chemistry in both M1 and M3 scenarios. However, the dissolved oxygen data (Figure 5-3; scenario M3, elevation 405 mRL) showed that anoxic water was entering the lower outtake valve, the high nutrient concentrations in the dead zone water would also be drawn into that outtake raising the nutrient levels in the water discharged into the river below the dam. This has the potential to stimulate periphyton growth in the river bed downstream of the reservoir. Furthermore, at winter mixing, the accumulated nutrients in the dead zone and the water below the upper outtake valve would have a lower degree of dilution than in scenario M1 and possibly as little the 5-fold factor as suggested for scenario M2. Consequently, poorer water quality would be expected in the reservoir and in the water discharged from the reservoir from scenario M3 than scenario M1.

Notwithstanding this, the quality of the water in the reservoir and discharged from the reservoir is likely to be slightly better than in the inflow water from the Makaroro River.

Scenario M3

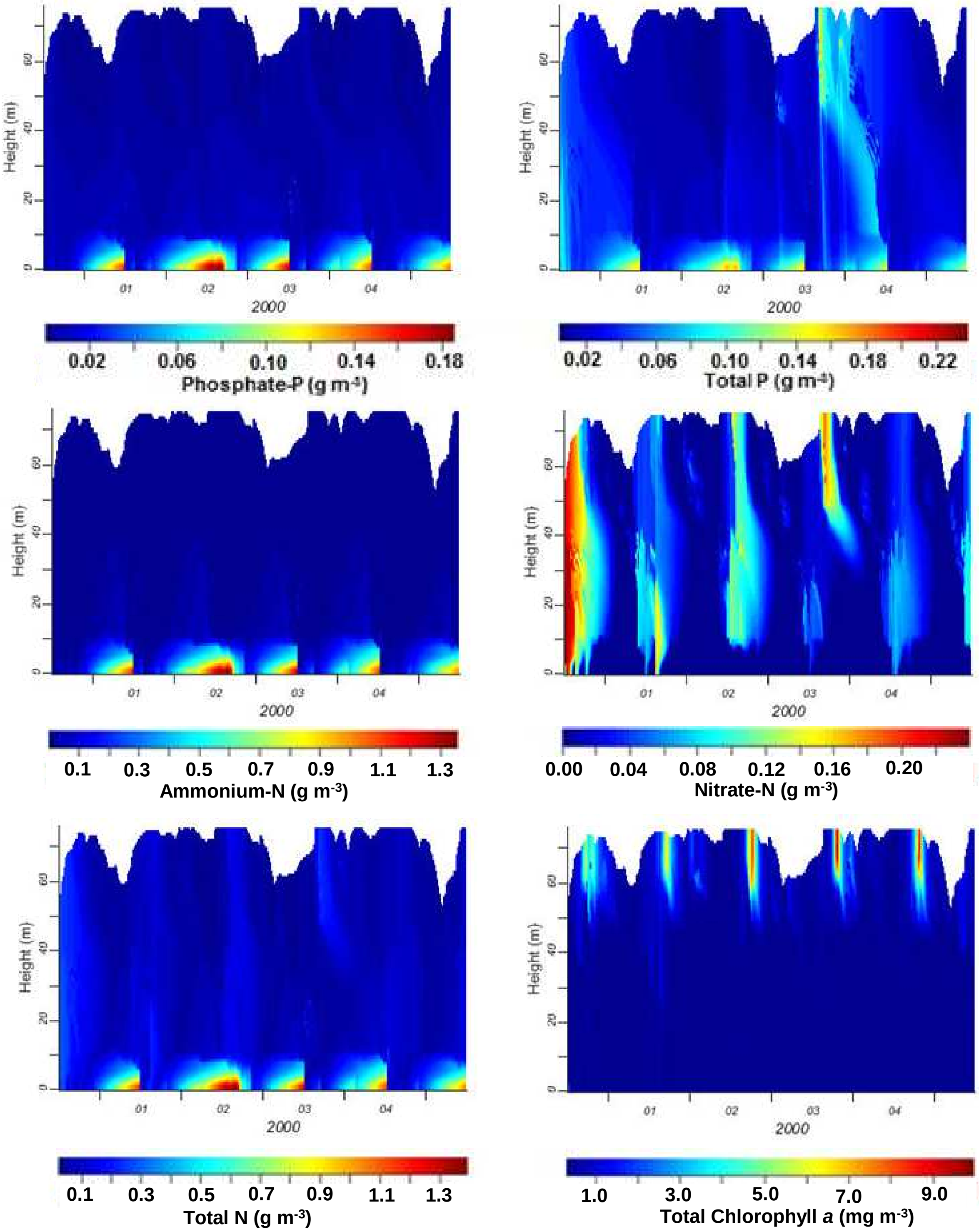


Figure 5-6: Simulated nutrient concentrations for scenario M3. Concentrations for phosphate-P, total phosphorus, ammonium-N, nitrate-N, total nitrogen and total chlorophyll *a* for the period 30/06/2000 to 30/06/2005. Note that the colour scales are different for each plot. (Figure 3 from McBride 2012).

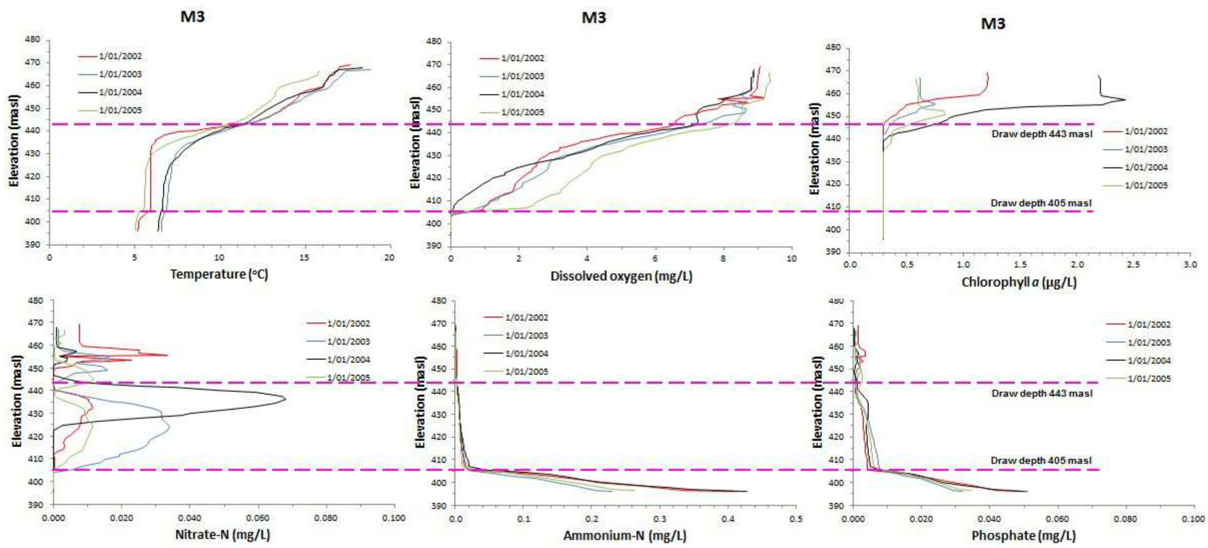


Figure 5-7: Simulated water column profiles on 1st January each year from 2001 to 2005 for scenario M3. Elevated concentrations of ammonium-N, nitrate-N and phosphate occur between the two draw depths and the upper draw depth appears to be drawing from the intrusion water layer from the Makaroro River inflow. (Limnotrack model output data).

5.3 Operating regime change effects on water quality

Subsequent to reporting the findings of the feasibility study modelling, changes have been made to the operating regime as defined in the Project Description report. The differences between the Feasibility Report Scenario and the Project Description Report Scenario have been set out by Tonkin and Taylor in Memo 27690, 7 March 2013, and are included here:

"Feasibility Report Scenario

Simulations carried out during the feasibility stage were oriented at determining the most practical storage to provide in the reservoir to supply environmental flows and to irrigate defined areas. Environmental flows comprised a minimum release from the reservoir (1.228 m^3/s). Releases of flushing flows were not simulated but an allowance of 1.5 million m^3 was made in storage for four flushing flows to be released each year during the irrigation season. Generation potential was also simulated and releases were made specifically for generation when the reservoir is close to full. No allowance was made for additional environmental releases or to supply additional irrigation when water is available.

Project Description Report Scenario

After completion of the Feasibility Report various scenarios were simulated to assess a variety of operating scenarios that would potentially increase water released for the environment and also provide secondary irrigation water when water is available. The selected scenario, **Scenario 3-28M** only allows primary irrigation from 1 September to 1 May and includes secondary irrigation up to 28 million m^3/annum, which is dependent on storage in the reservoir. These simulations did not include any releases specifically for hydropower generation.

The primary differences between the scenario used in the Feasibility Study and Scenario 3-28M used in the Project Description Report are summarised as follows:

	Feasibility Study Report	Project Description Report
Hydropower	Included in simulations	Excluded from simulations
Primary irrigation	Supplied as required all through the year. Capped at 95.8 million m^3/annum.	Supplied 1 September to 1 May only. Capped at 95.8 million m^3/annum.
Additional irrigation	Not allowed.	Included up to a maximum of 28 million m^3/annum. Releases dependent on storage in the reservoir. Supplied 1 September to 30 April.
Primary flushing flows	1.5 million m^3 allowed in storage for flushing flows. Releases are not included in simulation results i.e., storage could be lower than shown in simulation results during the latter part of the irrigation season.	Capped at 2 million m^3 with releases triggered according to a rule based on flows at Red Bridge. Higher priority than primary irrigation.
Secondary flushing flows	Not included.	Capped at 2 million m^3 released using the same rules as primary flushing flows but at a lower priority than primary irrigation supply.
Simulation period[1]	1 January 1972 to 31 December 2010	1 July 1972 to 30 June 2008

1 Simulated streamflow time series at the selected gauges are used to determine when flushing flows should be released. These time series were supplied from 1 July 1972 to 30 June 2008.

The proposed Makaroro Dam will have a Full Supply Level (FSL) of 469.300 m amsl and store 90 million m^3 of water at FSL. Allowing for 4 million m^3 of sediment to be trapped in the reservoir over twenty years and evaporation and other losses of 1 million m^3/year, working storage is estimated at least at 85 million m^3 over the financial feasibility analysis period of twenty years."

Potential effects of these changes

The main effect of implementing the Project Description Report operating regime (Scenario 3-28M) will be that there is a potential for more frequent occurrences of lower water levels to occur in summer-autumn. The significance of these lower water levels can be put into perspective by comparing the predicted water levels for Feasibility Study Report operating regime with those predicted for the Project Description Report operating regime (Figure 5-8). Under Scenario 3-28M the prediction was for two extra low water level events below 435 m amsl during the 30-year simulation period from July 1972 to July 2007. Conversely, the predictions also indicate that one of those low level events may not be so severe under the Scenario 3-28M operating regime as it might otherwise have been (Figure 5 8).

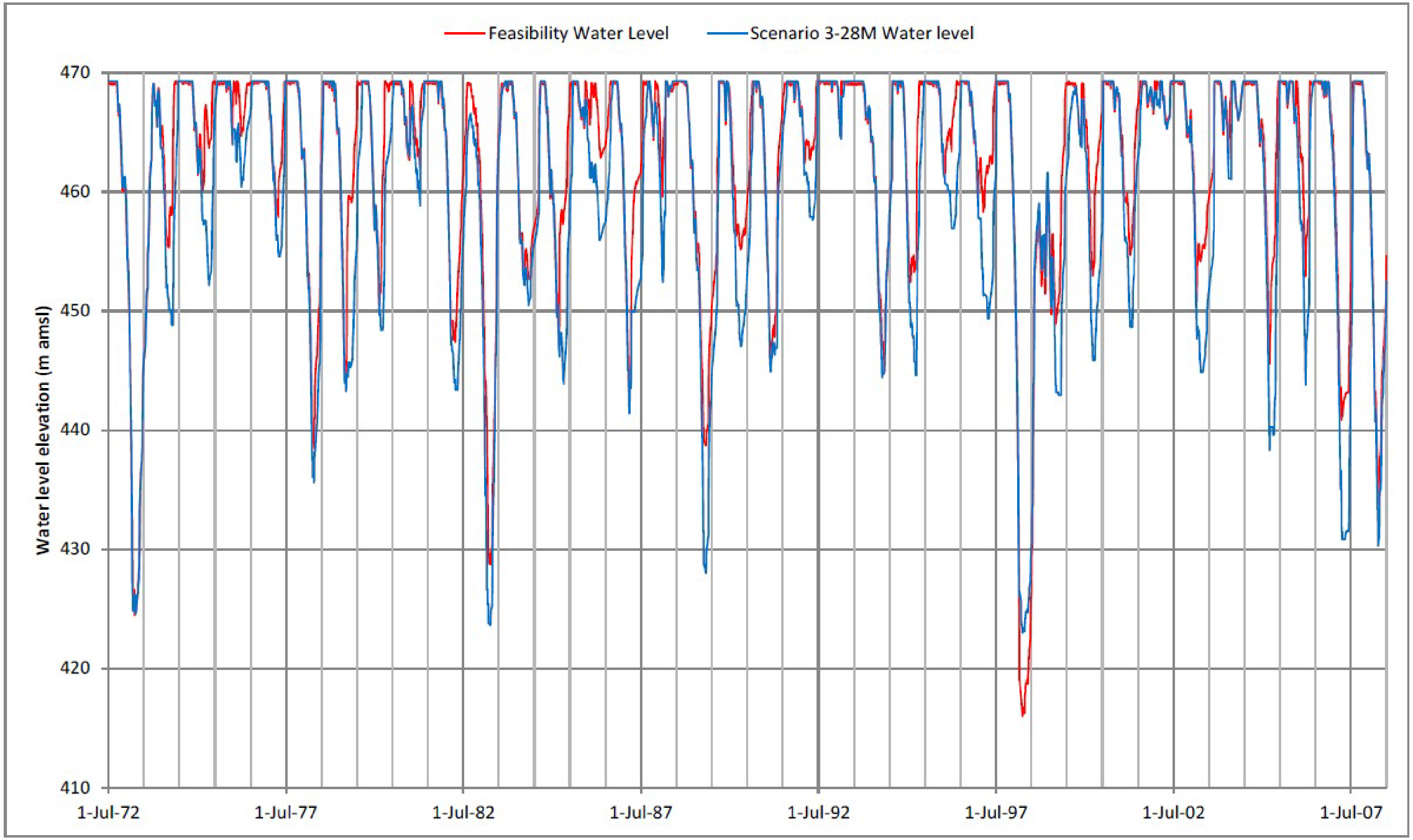


Figure 5-8: Predicted behaviour of water level with time in the Makaroro Reservoir. Comparison of the water levels associated with the Feasibility Study operating regime and the Project Description Report operating regime Scenario 3-28M. (Figure redrawn from Project Description Report Figure 3.6a as provided by Tonkin and Taylor in Memo 27690, 7 March 2013).

While the predictions using the Project Description operating regime show lower water levels in most years in the simulation period (Figure 5-8), the difference from the Feasibility Report operating regime is generally not severe and lies within the range of the DYRESM-CAEDYM modelling. Consequently, for most years, the expectation would be for little if any measurable difference in the water quality in the proposed Makaroro reservoir from that predicted in the Feasibility Study report.

In years when the water level is very low, the water quality predicted in the Feasibility Study report would still apply although the duration of any effects may be slightly longer. The most likely effects of low water levels are slightly warmer outflow temperatures and potentially lower clarity due to the increased opportunity for sediment resuspension by wind turbulence as well as disturbance by the currents from the inflow water. The potential effects on water clarity are addressed in detail in Section 6. These effects are likely to temporary and will be mitigated when the water levels rise again.

6 Suspended sediment and sedimentation

Reservoir sedimentation is described for the Makaroro A7 reservoir (proposed Makaroro reservoir) in section 4.7 of a report by Tonkin & Taylor (Tonkin & Taylor 2011). In that report assumptions have been made about relative sediment trapping efficiencies and the expected sediment accumulation in the reservoir over a 100 year period using an approach that provided a simplistic order-of-magnitude estimate of the average annual accumulation. It was assumed that the sediment bedload was similar to the suspended load (i.e., mountain streams), trapping efficiency was 100%, and a significant part of that material is expected to be discharged in floods. This gave an estimated 100 year sediment accumulation of 3 to 6 million m^3 and these values were rounded up to 8 million m^{-3} as an indication "that the catchment's bedload yield may appreciably greater than the simplistic estimate above."

Assuming all of this sediment accumulated in the deepest part of the reservoir, i.e., at the dam wall, the dam would fill to a depth of about 430 mRL, which would bury the outtake structure by 13 m. The Tonkin & Taylor estimate makes no distinction in this total catchment bedload yield between different grain size particles and where they would be likely to settle in reservoir.

Conceptually, heavy gravels and sands will deposit on entering the reservoir and form a delta on the river inflow with the finer sands settling to the reservoir bed as the current velocity slows with dispersion into the larger volume of the reservoir. As the Tonkin & Taylor sediment estimate assumes equal amounts of bedload and suspended material in the inflows, it is likely that about half of that 8 million m^{-3} sediment load will settle in the delta formation. That would leave about 4 million m^{-3} of finer sediment to settle further along the body of the reservoir. If all of that material settled at the base of the dam wall, the dam would fill to a depth of about 422 mRL, which is still 3 m above the lower outtake valve at 417 mRL. However, the finer sediment is not of uniform particle size and it is likely that the larger particles would settle out of the water column as they travelled along the length of the reservoir. That would reduce the amount of sediment settling at the dam wall, potentially reducing the fill depth to below 417 mRL and allowing the reservoir to continue to supply water at the design level over the whole 100 year period modelled.

The Tonkin & Taylor estimate assumed that the reservoir trapping efficiency was 100%, which presumably means all sediment was retained in the reservoir. With the change to a deep draw operating system with an outtake valve that can operate between 405 and 417 mRL, it is likely that some of the fine sediment entering the reservoir would be exported through the outtake valve, further reducing the amount of sediment that would accumulate at the dam wall.

Suspended sediment was not specifically modelled for the reservoir due to the lack of data available. However, total P has a relationship with turbidity (Figure 3-12) that can provide an indication of likely turbidity in the outtake water. Total P concentrations (mg m^{-3}) increased at 1.78 ± 0.07 times the turbidity (NTU) with an $r^2 = 0.91$, i.e., this relationship explains 91% of the variability in the data.

While it is not possible to assess the amount of suspended sediment from turbidity, the distribution of different size particles in a river generally follows a cumulative curve where about 90% of the suspended sediment has a grain size of <100 µm (0.1 mm) (Figure 6-1 A), which is classified as fine sand (grain size 125–250 µm). The Hjulström curve (Figure 6-1 B) which shows the relationship between sediment grain size and the water velocity required to erode (lift it), transport it, or deposit it (Hjulström 1939).

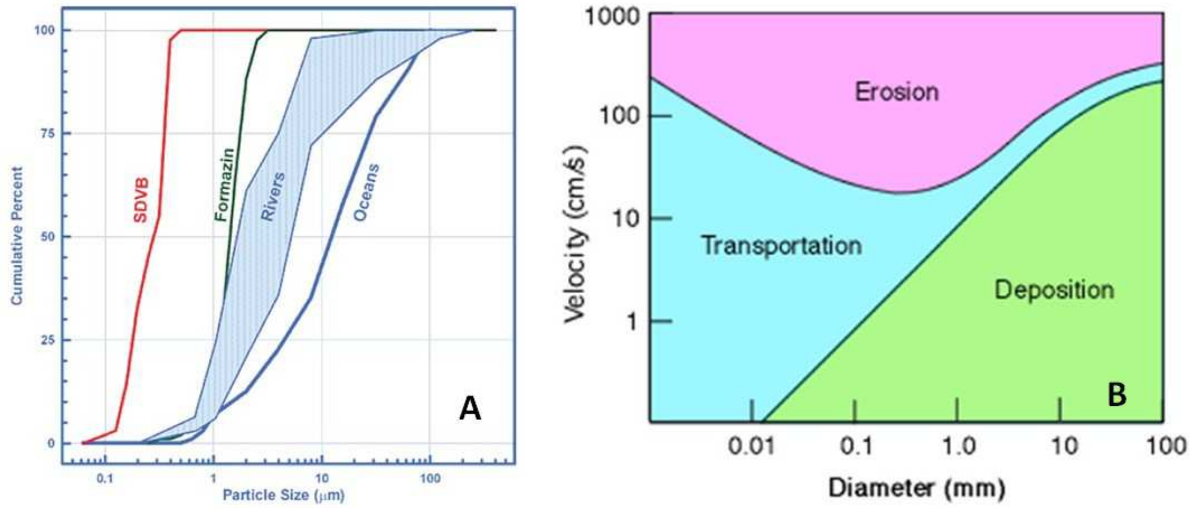


Figure 6-1: A) General variation in the size distribution of suspended sediments in rivers, B) the Hjulström curve showing the water velocity required to transport those particles. (Figure A from Downing 2008; Figure B redrawn from Hjulström, 1939).

These diagrams indicate that, once in suspension (e.g., from a flood event), about 90% of the particles in a river can be maintained in suspension at water velocities of <5 cm s^{-1}. The Hjulström curve also indicates that the <0.1 mm size fraction is unlikely to deposit out at velocities >1 cm s^{-1}. However, once the particles have settled, the Hjulström curve indicates that a much higher water velocity is required to resuspend those particles again.

Measurement of currents in the Rotorua lakes suggest that background level lake currents can have velocities of 1 to 2 cm s^{-1} and that wind action can produce current velocities >10 cm s^{-1} (Gibbs et al. 2011) which are accompanied by increased turbidity. While absolute proportions would need to be determined in the proposed reservoir, these theoretical values suggest that the fine sediment from the Makaroro River inflow will pass through the length of the reservoir to the outtake valve.

At the outtake valves, the current velocity will increase as the draw water passes into and through the 4 m diameter outlet pipe. At base flow (1.228 m s^{-1}) the flow velocity in the pipe would be around 10 cm s^{-1} and would be around 50 cm s^{-1}, at an operational discharge of 6.3 m^3 s^{-1}. Under the quarterly flushing discharges (10.5 m^3 s^{-1}), flow velocities in the pipe would exceed 83 cm s^{-1}. At these velocities, fine sediment will not deposit in the outlet pipe and some resuspension of deposited fine sediment is likely to occur near the entrance to the 405 mRL outtake valve.

At the outlet end of the discharge pipe, water velocities would exceed threshold velocities for bed scoring under operational and flushing flows. Such velocities may also occur if the water passes through a small power station and some form of bed protection would be required to prevent bed scouring. A simple solution is to pass the water through an energy dissipation device such as those used in the Tongariro Power Development scheme (Figure 6-2). The offset block arrangements used in the Wairehu Canal devices have the added advantage of boosting the DO concentrations in the water before it flows downstream.

Figure 6-2: Energy dissipation device on the Wairehu Canal to Lake Rotoaira in the Tongariro Power Development scheme. This structure causes sufficient turbulence to fully oxygenate the water passing over it.

Although there is a level of uncertainty around the sediment accumulation in the proposed Makaroro reservoir, the risk would be low to moderate that sediment accumulation would prevent the operation of the reservoir over the next 100 years, based on the available data, climate conditions and our present level of understanding of long narrow reservoir operation.

6.1 Operating regime change effects on water clarity

Subsequent to reporting the findings of the feasibility study modelling, changes have been made to the operating regime as defined in the Project Description report. The differences between the Feasibility Report Scenario and the Project Description Report Scenario are set out in section 5.3.

The main effect of the changed operating regime will be to produce lower water levels in most years (Figure 5-8). The most likely effects of low water levels are slightly warmer outflow temperatures and potentially lower clarity due to the increased opportunity for sediment resuspension by wind turbulence as well as disturbance by the currents from the inflow water.

In general the Makaroro reservoir will trap the larger sediment material (rocks, gravel and sand) near the inflow end and allow the finer material to settle along the main axis of the reservoir as it travels to the outlet end of the reservoir. The very fine material may remain in suspension for some time before settling and could be more easily disturbed and resuspended during periods of low water level.

Given that the lower intake is intended to be at 405 m amsl, the water level modelling (Figure 5-8) shows that there would still be at least 15 to 20 m of water above the sediments to reduce these disturbance effects. However, it is not just the bottom of the reservoir where sediment can be resuspended. During periods of low lake level, the exposed shoreline becomes a source of fine sediment as wave action causes erosion of the exposed lake bed. Observations from the 10 water supply reservoirs around Auckland City would suggest that this effect is likely to be confined to the near-shore waters and may be minor in open waters of the reservoir in comparison with the amount of fine sediment carried during a flood event.

These conclusions are consistent with comments made by Dr Murray Hicks in his peer review (5 March 2013) of Tonkin & Taylor's final Sedimentation Report (March 2013, Issue 3), where he says:

"Effects from sedimentation

Page 52: An additional downstream effect is that during floods the reservoir will delay the discharge of very fine suspended sediment into the river downstream – even if a lot of the coarser suspended load is deposited in the reservoir. Since it is the finer sediment that dominates the optical signature of turbid water, this can delay water clearing on event recessions. The consequent environmental effects of this might be something Cawthron could comment on."

The point to remember is that without the Makaroro reservoir, the downstream environment would receive the full impact of the fine sediment carried during a flood event. With the Makaroro reservoir, larger particles would be eliminated and the finer particles would be attenuated so that the effect of the fine sediment on the optical properties would be less severe.

Consequently, the potential effects on water clarity of implementing the Project Description Report operating regime (Scenario 3-28M) compared with the Feasibility Study Report operating regime are likely to be minimal. Further hydrological modelling was undertaken following the release of the Final Draft (March 2013) suite of documents, which superseded scenario 3-28M described above. The outcomes of this modelling with regards to lake level behaviour are presented in Figure 3.6a of the Final PD report (Tonkin & Taylor, May 2013). Visual examination of this plot indicates very minor differences with the 3-28M scenario described above, and the conclusions drawn above in relation to the 3-28M scenario are also valid for this latest scenario described in May 2013 Project description report.

7 Other considerations

Other considerations/recommendations regarding future dam site management before, during and after dam establishment include management of in-reservoir water quality through aeration, future proofing the reservoir from catchment activities that would adversely affect the water quality at some future date, health and safety, and monitoring.

7.1 Aeration

The modelling predicts that the water below the main draw depth will become hypoxic and potentially anoxic during summer. Oxygen concentrations in the reservoir can be managed for full DO saturation by placing an aeration bubbler (aerator) as a long strip bubbler at the outlet end of the reservoir.

7.1.1 Theory

When compressed air is pumped into the aerator, it produces a curtain of bubbles that rise to the surface. The bubbles in the water reduce the density of that water so that it is more buoyant than the surrounding (ambient) water, causing it rise (upwell) with the bubbles. The upwelling plume of water draws bottom water to the aerator to replace the rising water. The bottom water is entrained into the upwelling water and a current develops across the reservoir bed. As the plume rises, ambient water may also be entrained, increasing the volume of upwelling water. The upwelling water is initially less dense than the ambient water due to the presence of air bubbles. However, as more ambient water is entrained, density difference decreases and the upwelling water disperses laterally at a depth of equal density. As the amount of air used to drive the bubble field increases, the depth at which the upwelling water disperses rises until it reaches the lake surface and a current develops moving away from the aeration bubble plume.

Aeration is not a function of the amount of air passing through the aerator, it is achieved by mixing the bottom water into the surface where it can dissolve oxygen from the air. The bottom water brought above the thermocline warms as it mixes with the surface water and the resultant excess water above the thermocline forces the thermocline down until it reaches the reservoir bed. At that moment the bottom current towards the aerator can connect with the surface current moving away from the aerator to form a circulation current which keeps the whole reservoir mixed (Figure 7-1A).

While the aerator is in operation, the circulation current will be sustained at a maximum rate. When the aerator is turned off, the hydraulic inertial maintains a residual circulation current for several days until resistance of the ambient water to the circulation current and friction against the reservoir bed causes it to slow and eventually stop. Restarting the aerator while the circulation current is still moving, accelerates that current back to full speed. Consequently, it is possible to use the aerator initially on full time to set up the circulation current and then change the operation strategy to pulsed mode with the aerator on for several days then off for several days, thereby reducing the running costs.

7.1.2 Practice

The theory works well in practice and aerators are often used in water-supply reservoirs. For example, all 10 water-supply reservoirs operated by Watercare Services Ltd for Auckland city are fitted with aerators. The largest of these reservoirs is Mangatangi in the Hunua Ranges, which has a surface area of 169 ha and a depth at the dam wall of about 60 m. It is an elongated reservoir and is maintained as fully mixed throughout summer with a single aerator near the dam wall. The operation strategy is to induce the circulation current with continuous aeration and the switch to pulsed mode of two-days-on and two-days-off to keep the circulation current going and the water column fully mixed.

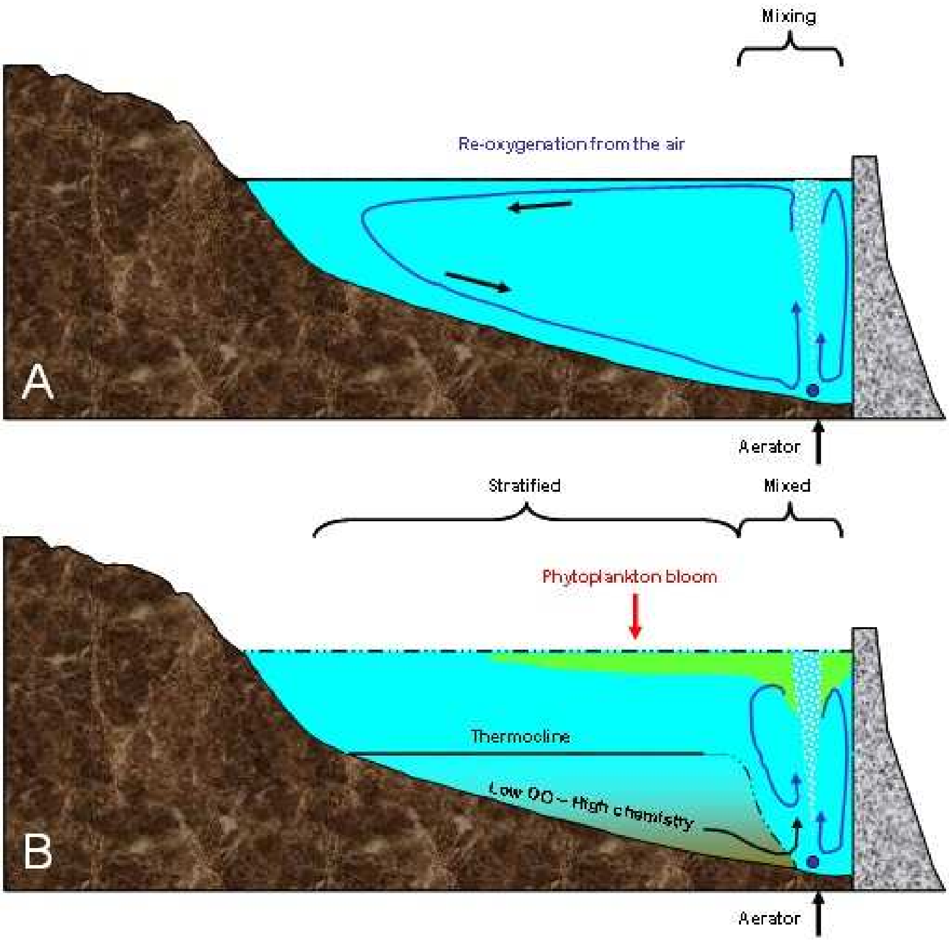


Figure 7-1: Aeration in reservoirs. **A**) Timed correctly, aeration generates a circulation current that allows the reservoir water to adsorb oxygen from the air before moving to the bottom of the reservoir. **B**) Starting after thermal stratification can mix nutrients from the hypolimnion into the epilimnion where they can stimulate phytoplankton growth.

The zone of influence of the aerator depends on the size, depth, bed topography and shape of the reservoir. Aerators are more effective in deep narrow reservoirs than in shallow round reservoirs. In deep reservoirs, the circulation current will be stronger because the greater depth imparts a greater mass moment of inertia to the upwelling water driving the circulation current. In long narrow reservoirs, the circulation current is constrained to a single direction thereby focusing more of the energy from the aerator into maintaining the circulation current.

Conservation of matter requires that, at the edge of the zone of influence, the surface water will move down (downwell) to complete the circulation current loop. In a narrow reservoir formed by damming a river, the bed of the reservoir is likely to slope down from the river inflow end to the dam wall. If the downwelling water can reach this sloping bed then the water will flow down the slope assisting the establishment of the circulation current. The circulation current will act like a conveyor belt drawing the aerobic surface water down to the bottom of the reservoir at the inflow end and entraining partially oxygen-depleted bottom water up to the surface at the dam end of the reservoir (Figure 7-1A).

Once established, the conveyor-belt circulation current zone of influence can extend over a considerable distance e.g., several km in the main body. Where a cold-water river inflow plunges as a density current as it enters the reservoir, the density current from the river inflow augments the bottom return flow of the circulation current, improving its efficiency and extending the zone of influence up stream.

The proposed reservoir on the Makaroro River will be a long narrow water body with a bed sloping from a cold river inflow to very deep water at the dam wall. These factors indicate that a single aerator installed near the dam wall is likely to be able to keep the whole reservoir mixed and maintain a high level of aeration throughout the reservoir water column.

7.1.3 Aeration activation threshold and monitoring

Start-up timing for aeration is important. If the hypolimnion has already gone anoxic, mixing it will send high concentrations of nutrients up into the surface water where it will stimulate phytoplankton production and potentially a bloom (Figure 7-1B). Consequently, monitoring the temperature and oxygen concentrations through the depth of the water column near the aerator is essential through spring as the reservoir begins to thermally stratify and oxygen concentrations in the lower water column begin to fall. Oxygen concentrations are used as the trigger for switching on the aerator and an appropriate strategy would be as follows:

1. Temperature low and profile uniform with DO near 100% saturation: **Aerator off**; **monitor monthly**. (*This represents the winter mixed condition*.)
2. Temperature higher in surface than bottom water with DO in bottom water below 100% saturation but above 8 g m^{-3}: **Aerator off**; **monitor fortnightly**. (*The reservoir is developing a weak thermal stratification*.)
3. Temperature higher in surface than bottom water with DO in bottom water below 8 g m^{-3} but above 7 g m^{-3}: **Aerator off**; **monitor weekly**. (*The reservoir is thermally stratified and developing bottom water oxygen depletion but DO is above the action aeration threshold*.)
4. Temperature higher in surface than bottom water with DO in bottom water below 7 g m^{-3}: **Aerator on continuously**; **monitor weekly**. (With DO above 6 g m^{-3} the aerator can rapidly mix the water column causing re-aeration to occur. 6 g m^{-3} is above the minimum level required for most fish species.)
5. Temperature high and profile uniform with DO concentrations uniform and above 7 g m^{-3}: **Aerator cycled at 2-days on and 2-days off**; **monitor weekly**. (*The reservoir is mixed and aeration is in maintenance mode. The most appropriate cycle can be determined experimentally – if 2-days off does not cause a measurable decrease in the DO concentration and the development of thermal stratification in the water column, the off period can be increased by a day – if it does, then the off period should be reduced by a day.* ***Minimum on period*** *is 2 days and this can be increased if required to maintain a mixed water column and DO concentrations above 7 g* m^{-3}.)

6. Temperature lower than previous measurement and profile uniform with DO concentrations uniform and above 7 g m^{-3}: **Aerator off**; **monitor weekly for a month then monthly**. (*This represents the autumn cooling phase of the annual cycle. The monitoring is continued at weekly intervals after switch off to ensure that the falling water temperature was not just a transient change in late summer.*)
7. Bottom line**: If DO concentrations fall below the threshold of 7 g m^{-3} at any time of year, the aerator should be turned on**.

Keeping a record all DO and temperature data and when aeration milestones occurred each year will build up an understanding of how the reservoir is responding to changes in the residual organic load in the sediment and whether there has been a change after storm events that bring new sediment into the reservoir or changes in the catchment landuse that have affected the trophic condition of the reservoir.

7.1.4 Aerator design and installation

There are many different designs of aerators, ranging from simple air bars across the bottom of the reservoir designed to mix or destratify the water column, to very complex arrangements designed to increase the DO concentration of the bottom water without mixing. There are also many point-aerator designs which are ideal for reservoirs and lakes where multiple aerators can be used. Consequently, recommendation for a specific design and operation parameters of an aerator system for the Makaroro reservoir are beyond the scope of this report.

Notwithstanding this, there are fundamental considerations which can be presented and a commonly used aerator is described.

The installation of an aeration system in the proposed reservoir should be completed during construction and before the reservoir is filled. The most common aerator design for water supply reservoirs is a long bar-type system with multiple bubble jets along the upper surface. If this system were to be used in the Makaroro reservoir, the aerator bar should be at a relative depth of 405 mRL across the main wall of the dam but not across the outtake tower. The aerator bar can be a heavy duty alkathene material and should be tethered by chain along its length to a number of anchor blocks of sufficient mass to overcome the buoyancy of the aerator bar when full of air. The anchor blocks should not be attached to the reservoir bed. This is to allow the aerator bar to be lifted and serviced should the need arise. With that in mind, the line of the aerator and location of the anchor blocks should be clear of obstructions that would prevent lifting or return to the reservoir bed while the reservoir was full – it would be prudent to select a level site during installation or level a site for the aerator near the dam wall.

Ideally, the bubble jets on the aerator bar should have “duck-bill” closures on their upper ends to prevent sediment entering the main aerator bar. The other design factors such as length, diameter and volume of the aerator bar, and the capacity of the air compressor required to supply air against a head of 70 m to achieve efficient aeration are engineering matters beyond the scope of this report.

7.1.5 Health and safety

A health and safety issue arises where aerators are used in publically accessible water bodies. The air bubbles in the plume occupy part of the water volume and thus that water has a much lower density that the surrounding water and will not support the weight of a boat or swimmer to the same extend as the surrounding water if completely inside the bubble plume. Boats within the bubble plume will have less freeboard. Swimmers are nearly neutrally buoyant and would potentially sink if they entered a bubble plume. Consequently, safety precaution notices for recreation activities on the reservoir are required.

7.2 Site clearance

Clearing all the vegetation within the footprint of the dam is likely to be impractical due to the topography of the site. The modelling indicates that the biomass associated with that vegetation will affect the oxygen budget in the reservoir in the first few years until the organic matter has decomposed. The modelling also indicated that the effect may be short-lived with the period of bottom water hypoxia decreasing substantially over the first 5 years.

It may, however, be expedient to remove tall trees around the edge of the reservoir that will be near or above the surface of the reservoir under normal operational conditions, as a safety precaution for recreational boating.

7.3 Catchment management

Because large areas of production pine forest occupy the northern catchment, consideration should be given to the effect of these on the reservoir when they are harvested.

- To future-proof the reservoir water quality, prior to filling it would be expedient to remove all production forest trees within a buffer zone at least 25 m from the predicted high water line of the reservoir and to plant the buffer zone with native plants that can reduce sediment runoff into the reservoir.
- Ideally, any roading infrastructure near the reservoir needed for the future harvesting of the remaining forest should be constructed at the same time.

These measures would mean all effects of soil disturbance would occur in the first five years allowing the water quality to improve without further setback.

The Makaroro River catchment is susceptible to landslides (184–260 ha of landslides and erodable land; 1.5–2.1% of catchment), which will introduce large amounts of sediment into the reservoir during storm events. With respect to extending the life of the reservoir, any action that exposes bare soil within the reservoir catchment is undesirable.

- It is recommended that the active removal of vegetation for land clearance on any steeply sloping land (>20 degrees) within the reservoir catchment be controlled by resource consent.
- It is also recommended that, prior to harvesting of production forest on steeply sloping land, sediment management plans be provided and approved by Regional Council.

Because the reservoir is likely to be N-limited for phytoplankton growth, catchment management strategies should be developed to prevent any increase in N loads to the upstream Makaroro River and the groundwater seeping into the reservoir.

7.4 Aquatic pest management

The newly formed reservoir will be devoid of aquatic pests such as exotic macrophytes, snails and pest fish. Exotic macrophytes such as Hornwort (*Ceratophyllum demersum*) would not only adversely impact on the recreational and ecological values of the reservoir, but would also affect the use of the water for power generation. Hornwort is a non-rooted plant that drifts around a water body at any depth and could be drawn into the outtake valve and pass into the turbines or potentially block the outtake valve by accumulating on the debris screens. Hornwort is typically transferred between water bodies on boat trailer (Figure 7-2) and in the engines of jet boats and jet skis that have been used on infested lakes. Special care is required to make sure this weed does not get into the reservoir as even the smallest node will grow.

Figure 7-2: Hornwort on a boat trailer. Launching a boat in Lake Rotoehu resulted in Hornwort attached to the boat trailer, often in difficult to reach areas around the inside of the wheel arches. The smallest node of this plant will grow. Consequently, it is important to ensure that boat trailers are clean before any boat is launched in the new reservoir.

Piscivorous pest fish such as perch would potentially devastate the native fish species in the reservoir while Koi carp would destabilise the near-shore bed of the reservoir enhancing turbidity during periods of low water level. These pest fish species and others such as, Rudd and Tench have been deliberately released by well-meaning people into some North Island lakes and reservoirs to provide sport fishing, to the detriment of the aquatic environment.

It is recommended that consideration is given to management of exotic macrophytes and pest fish through a campaign of prevention. For example, notices about cleaning boats and boat trailers before entering the lake, and warnings about the introduction of pest fish, exotic snails and plants from aquaria, could be posted at public access points and public amenity facilities.

7.5 Monitoring

The initial modelling scenarios have provided predictions of the likely water quality in the Makaroro reservoir. Once the reservoir is built and full, it will be important to monitor the actual water quality in the reservoir to follow the progress of the settling-in phase, while the residual organic matter is decomposed, and to understand the in-lake processes occurring in the reservoir that will characterise the water.

Whereas the parameters considered in this report included water temperature, DO, pH, colour, clarity, particulate organic matter, BOD, ammoniacal nitrogen, dissolved inorganic nitrogen, dissolved reactive phosphorus, total phosphorus and total nitrogen, not all of those parameters would need to be included in a routine monitoring programme for the reservoir.

The monitoring programme should be designed for a specific purpose rather than just simply collecting data. That purpose will define which parameters need to be measured. For the Makaroro reservoir, it is assumed that the monitoring programme is required to provide:

- information on DO levels in the water column in order to manage the aeration system and thereby keep the DO concentration above the minimum required for fish, and
- basic water quality information on the water in the reservoir in order to assess trophic condition and change over time.

The first part of the monitoring requirement is described in section 7.1, under Aeration.

As a general rule, basic water quality monitoring programmes should include depth-referenced temperature and dissolved oxygen concentrations plus visual clarity determined by Secchi depth. With the availability of relatively inexpensive sondes which measure a range of parameters including temperature, DO, pH, conductivity, turbidity, chlorophyll fluorescence and phycocyanin (as an indicator of cyanobacteria concentrations), a monitoring programme could be designed around the functionality of the multi-parameter sonde. In addition to the sonde parameters and Secchi depth, water samples would be collected from specific depths with a van-Dorne-type messenger-closing water sampling bottle, or with an integrated-tube[3] sampler, to measure dissolved and total nutrients, i.e., DRP, TP, NO_3-N, NH_4-N, TN, TC, total suspended solids (SS), and algal species abundance (cell counts and biovolume).

The data should be collected following strict protocols of **what**, **where**, **when**, and **how** to sample. For example, protocols for monitoring trophic levels in lakes and reservoirs are described in detail in a Ministry for the Environment report (Burns et al. 2000) and the techniques in that report should be adopted for the monitoring of the Makaroro reservoir.

The frequency of sampling should be sufficient to meet the purposes of the monitoring programme within the cost allocation for monitoring. As a guide, sampling monthly will provide good information on short- and long-term variability of individual parameters and provide a database that will allow the functions of the reservoir to be understood. Monthly sampling is also compatible with the aeration monitoring programme.

[3] An integrated tube sampler consists of a 20mm diameter tube of 20 - 30 m in length that, when lowered slowly vertically down through the water column, captures a water sample which represents the full depth of that tube. Analysis of that water provides an average or integrated value for that depth of water. In most situations a practical maximum tube length without a special bottom closure system is about 30 m.

8 Summary

The scenarios modelled for this supplementary desktop study indicate that a broad range of water qualities in the reservoir and discharged from the reservoir is possible. The highest water quality would be associated with scenario M1 which would have all water drawn from an elevation of 405 mRL. This scenario is likely to provide high quality water which would be, on average, better than the inflow water from the Makaroro River. The water in the reservoir would be well oxygenated and suitable for aquatic life except in a small (<0.25% of the total volume of the reservoir when full) dead zone below the outtake level although short periods of low dissolved oxygen concentration (<2 g m^{-3}) would be possible without aeration under base flow conditions at the end of the stratified period. An aeration system should be installed in the reservoir as described in section 6.1 to maintain bottom water DO levels above the minimum needed for fish and to accommodate the extreme events observed in other years, but not used in the simulations.

An aeration-style energy dissipation device (e.g., Figure 6-2) below the discharge point from the reservoir would prevent river bed scour and boost DO levels in the Makaroro River below the reservoir.

Scenarios that included base flow draw from the toe of the dam also provided water quality better than the inflow water quality but would require aeration during base flow only discharge period during summer stratification. The initial modelling scenario and scenario M3 demonstrated the use of a dual draw from 395 plus 426 mRL and 405 plus 443 mRL, respectively, where the outflow water was nearly always well oxygenated. However, if low water levels prevented discharge from the 426 or 443 mRL outtake valves, the discharge water from the low level outtake valve would become anoxic. In these scenarios (initial and M3) the upper water column would remain well oxygenated capable of supporting aquatic life. However, the available volume of habitable water would be small until natural thermal stratification isolated a surface mixed-zone layer. If the base flow from the reservoir was drawn from the 426 mRL or 443 mRL outtake valve as an outflow = inflow discharge, the downstream water would also be well oxygenated although warmer than the inflow and with elevated nutrients and phytoplankton biomass due to a surface skimming effect. If phytoplankton biomass was high, the pH would also rise. For the initial and M3 scenarios to operate efficiently, aeration would be needed during the summer stratified period.

The worst water quality came from scenarios where the outtake valves were high in the water column and there was no base flow discharge from the bottom of the dam. These scenarios, with all discharge water being taken from an elevation of either 426 or 443 mRL, produced semi-permanent stratification with the water below the draw depth becoming anoxic and enriched with ammonium-N and phosphate. With the potential for summer water levels to fall to near the draw depth in these scenarios, the reservoir water quality would not be suitable for aquatic life in summer without the use of aeration.

Although there are benefits to removing the vegetation in the reservoir extent before filling, the cost would be high and valuable aquatic habitat diversity would be lost.

Because the reservoir water will be sensitive to nitrogen, catchment management to reduce or maintain low levels of nitrogen will be important. Managing sediment inputs would have the dual effect of reducing phosphorus loads in the lake bed and infilling of the reservoir with silt. Future-proofing the reservoir by providing 25 m wide planted buffer zones between production forest land and the reservoir are recommended, as is the construction of the necessary infrastructure required for forest harvesting before the reservoir is filled. Because the catchment land is susceptible to erosion and particularly slipping, management strategies designed to minimise bare land exposure will also be important. Land clearance of steep land within the reservoir catchment should be a discretionary action in the regional plan requiring a resource consent, and sediment control plans should be provided and approved before harvesting production forest.

9 Acknowledgements

The NIWA field team Peter Arnold and Geoff Holland for collecting the soil samples, the NIWA laboratory team for the analytical data, and Dr Olivier Ausseil for providing the geophysical data when required.

10 References

Benson, M. (2010). Ruataniwha Plains water storage feasibility study: Demand for irrigation water. *Hawke's Bay Regional Council report*, November 2010.

Burns, N., Bryers, G., Bowman, E. (2000) Protocol for monitoring trophic levels of New Zealand lakes and reservoirs. *Lakes Consulting client report number* 99/2, prepared for Ministry for the Environment: 122.

http://www.mfe.govt.nz/publications/water/protocol-monitoring-trophic-levels-mar-2000/index.html

Casamitjana, X., Serra, T., Colomer, J., Baserba, C., P´erez-Losada, J. (2003) Effects of the water withdrawal in the stratification patterns of a reservoir. *Hydrobiologia,* 504: 21–28, also In: V. Straškrábová, R.H. Kennedy, O.T. Lind, J.G. Tundisi and J. Hejzlar (eds). *Reservoir Limnology and Water Quality*. Kluwer Academic Publishers, Netherlands.

Downing, J. (2008) Comparison of suspended solids concentration (SSC) and turbidity. *Application Note Code: 2Q-AA for Campbell Scientific, Inc*.

Fast, A.W. (1968) Artificial destratification of El Capitan Reservoir by aeration Part 1: Effects on chemical and physical parameters. *Fish Bulletin* 141. State of California, Department of Fish and Game: 98.

Gal, G., Hipsey, M.R., Parparov, A., Wagner, U., Makler, V., Zohary, T. (2009) Implementation of ecological modelling as an effective management and investigation tool: Lake Kinneret as a case study. *Ecological Modelling,* 220: 1697–1718.

Gibbs, M.M. (1986) The role of underflow in the transport of oxygen in Lake Rotoiti, North Island, New Zealand. DSIR. *Taupo Research Laboratory File Report* 91.

Gibbs, M., Budd, R., Hart, C., Stephens, S., Wright-Stow, A., Edhouse, S. (2011) Current measurements in Lakes Rotorua and Rotoehu 2010 and 2011. *NIWA Client Report* HAM2011-015 to Bay of Plenty Regional Council: 29.

Hjulström, F. (1939) Transportation of debris by moving water. In: Trask, P.D. (ed.) *Recent Marine Sediments; A Symposium:* Tulsa, Oklahoma, American Association of Petroleum Geologists: 5–31.

Kimmel, B.C., Groeger, A.W. (1984) Factors controlling primary production in lakes and reservoirs: A perspective. In: Lake and Reservoir Management. *Report* EPA-440/5-84-001. United States Environmental Protection Agency, Washington, D.C.: 277–281.

McBride, C., Özkundakci, D., Hamilton, D. (2011) DYRESM-CAEDYM modelling of proposed Ruataniwha reservoir water quality. *Limnotrack report to NIWA December 2011*: 48 plus CD-ROM of appendices and data used.

McBride, C. (2012) DYRESM_CAEDYM simulations of alternative offtake regimes for Ruataniwha Reservoir at dam wall. *Limnotrack memo to NIWA January 2012*.

Redfield, A.C. (1958) The biological control of chemical factors in the environment. *American Scientist,* 46: 205–221.

Schladow, S.G., Hamilton, D.P. (1997) Prediction of water quality in lakes and reservoirs: Part II: Model calibration, sensitivity analysis and application. *Ecological Modelling,* 96: 111–123.

Spigel, R.H., Ogilvie, D.J. (1985) Importance of selective withdrawal in reservoirs with short residence times: a case study. Proceedings of the 21st Congress of the International Association for Hydraulic Research, Melbourne, 19–23 August 1985, Volume 2: 275–279.*The Institution of Engineers, Australia, National Conference Publication* No. 85/13.

Spigel, R.H., Howard-Williams, C., Gibbs, M.M., Stephens, S., Waugh, B. (2005) Field calibration of a formula for entrance mixing of river inflows to lakes: Lake Taupo, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research,* 39: 785–802.

Sverdrup, H.U. (1953) On conditions for the vernal blooming of phytoplankton. *Journal du Conseil International pour l' Exploration de la Mer* 18: 287–295.

Tonkin & Taylor (2011) Ruataniwha Water Augmentation Scheme: Advanced prefeasibility Summary Report. *Tonkin & Taylor Consultant report number* 27195.000 to Hawkes Bay Regional Council, February: 120.

Tonkin & Taylor Ltd (May 2013a) Ruataniwha Water Storage Scheme Project Description. *Report prepared for Hawke's Bay Regional Investment Company. May 2013.*

Trolle, D., Hamilton, D.P., Pilditch, C.A., Duggan, I.C. (2011) Predicting the effects of climate change on trophic status of three morphologically varying lakes: Implications for lake restoration and management*. Environmental Modelling & Software,* 26: 354–370.

Verburg, P., Hamill, K., Unwin, M., Abell, J. (2010) Lake water quality in New Zealand 2010: Status and trends. *NIWA client report number* HAM2010-107 to Ministry for the Environment: 48.

Vincent, W.F., Gibbs, M.M., Spigel, R.H. (1991) Eutrophication processes regulated by a plunging river inflow. *Hydrobiologia,* 226(1): 51–63.

Appendix A Review questions and answers

During the review process, several important questions were asked. These are presented and addressed in this section. Where editing of the report has changed a section number, the revised section number has been inserted into the question. Note that “masl” has been changed to “mRL” throughout the report.

Question 1

The DYRESM model is a 1-D model and its application for reservoir modelling is good practise. However, the limitations with this model for a long narrow reservoir with several side arms and constrained bathymetry around the inlets should be recognised in the report.

The model is not (and is unable to be) calibrated. As such, it may be worth adding comments on the degree of uncertainty/risk to the client.

Answer

A more detailed explanation of the DYRESM model has been included in Section 2.2.2. The model provides a prediction of the likely water quality in a non-existent reservoir and, as stated, is unable to be calibrated. However, in line with best scientific practice, the model results have been compared with observations from lakes and reservoirs of similar morphometry and interpreted or accepted on the basis that they are a best estimate. The uncertainty/risk to the client is likely to be low to moderate.

Question 2

Tonkin & Taylor: The Executive Summary seems to say that the best water quality in reservoir and discharged will be achieved by drawing all water from the lower intake “M1: All water drawn from 405 mRL”.

This could provide an opportunity for cost saving if we no longer require the upper level intake tower and can just extract water from the lower intake. Sediment laden density currents may be entrained into the power station, but the currents are expected to comprise fine sediments that should not significantly increase wear and tear on power station equipment. Our current design of the low level intake comprises a structure approximately 17 m high. It will be critical that water can be drawn from multiple levels over this 17 m rise in order to avoid blockage from accumulating sediment in the long term. Furthermore, it may be prudent to increase the height of the lower level intake if the upper level tower is removed.

Answer

It is agreed that the reservoir could function effectively without the upper level intake tower. The need for that tower would only arise should a sediment laden density current over whelm the lower tower. The revised section on suspended sediment and sedimentation (section 6) examines that possibility in terms of possible burial over a 100 year period. It is considered that the risk would be low to moderate under present climatic conditions. If the upper level intake tower was not constructed, it would be prudent increase the height of the lower level intake tower. [Further discussion of outlet structures is covered in appendix B].

Question 3

Tonkin & Taylor: The report says that “the rate of sediment build up near the lake valve would be slow with much of the fine material being removed in the water discharged from the reservoir. [Executive Summary]”. The report assesses that most of the suspended sediment will stay in the water column [Section 6]. The Sedimentation Assessment estimates suspended sediment based on the WRENZ tool with SSYE model predict suspended sediment of 38,000–69,000 m3/year. The Brune method has been used to estimate that over 90% will be retained in the model. Do these findings regarding the retention of sediment in the reservoir change the Water Quality report findings?

Answer

The revision of Section 6 now considers the modelling done on the reservoir sedimentation (Tonkin & Taylor, 2011) and uses the values presented to assess the likely extent of sediment build up near the valve tower. While the Brune method may correctly estimate that >90% of that sediment will be retained in the model (i.e., the reservoir) it does not say where it will deposit. It is unreasonable to assume that sediment particles much larger than fine muds (i.e., <10 µm) will travel the >5 km distance through the reservoir without settling out. Consequently, where the sediment load deposits is very important. Observation of elongated lakes and reservoirs around the world indicate that in most cases, the heavier particles sediment near the river mouth forming a delta while the fine sand and silt travels further before settling to the bottom. The fine mud may travel the full length of the reservoir. However, instead of spreading as a turbid plume across the whole surface of the reservoir, those fine particles are likely to remain entrained within a temperature-induced density which will be directed to the outtake valve on the valve tower.

The retention of sediment in the reservoir was considered when interpreting the DYRESM-CAEDYM model results and describing the likely water quality of the reservoir. There is no need for any change.

Question 4

Tonkin & Taylor: We consider that taking water from a valve at the bottom of the reservoir will have only a very minor reduction in sediment accumulation rather than the report that states the lowest outlet will “go some way to reducing the accumulation of sediment in the bottom of the reservoir”.

Answer

This is a follow on question 3 and should be considered in that context. Unless there is a sediment laden density current produced from a large flood event, the expectation is for the sediment load to be water sorted as it is deposited along the length of the reservoir. The deep draw induces a flow along the bed of the reservoir augmenting any natural density current from the river inflow. Consequently, a proportion of the residual suspended sediments in the bottom water will be drawn out of the reservoir via the outtake valve rather than accumulating in the bottom of the reservoir.

Question 5

Tonkin & Taylor: Aeration by a compressed air aerator on the floor of the reservoir is recommended.

1) Do NIWA know of any reservoirs of a similar size to ours (90 million cu.m) where aeration has worked successfully? It may be worthwhile including these references, as well as a description of the associated aerator configurations.

2) A description of the recommended dimensions, configuration and layout would be helpful, including the positioning of the aeration line in relation to the dam face. The aeration device will need to be carefully positioned so that it does not get buried in sediment in the long term.

3) The capital and operational cost of providing aeration via the compressed air option need to be understood. Currently, the aeration option is presented as a backup to cover extreme events that are not modelled. If the cost is significant, then the extreme events need to be understood and modelled before committing to the aeration system.

4) Are the risks to public health from the aerator over stated? What is the density of the bubble plume at the surface after 70 m of mixing?

Answers

1) The El Capitan water supply reservoir on the San Diego River in California was built in 1934 with a capacity of 139 million m^3 and a water depth of 66.7 m when full. This reservoir is of similar shape, size and depth being formed by damming a high country river. Aeration was tested in the reservoir in 1965 producing a mixed water column with DO concentrations >5 g m^{-3} (Fast 1968). In New Zealand, the Mangatangi reservoir in the Hunua Ranges is about a third of the size with a capacity of 39 million m^{-3} and a water depth of around 60 m. It is also a drowned river valley with a long narrow main water body and several large side arms with stream inflows. This reservoir is run by Watercare Services as part of the water supply for Auckland City. Aeration is used to keep the reservoir mixed as described in section 7.1 of this report.

2) While a description of the general aerator configuration is provided in section 7.1.4, the recommendation for the design and operation parameters of an aerator system suitable for the Makaroro reservoir are beyond the scope of this report. The design for the El Capitan reservoir is included in that report (Fast 1968) and the design and operating conditions for the Mangatangi reservoir can be obtained from Watercare services Ltd, Auckland.

3) The operating parameters for an aeration system will depend on the aerator system(s) used and the(ir) design parameters. The revision of this report clarifies the need for an aeration system and the general description (section 7.1.4) defines where it needs to be relative to the dam wall and the outtake valve. Pumping air to a depth of 70 m will require a compressor capable of overcoming the hydrostatic head of 7 atmospheres pressure i.e., at least 105 psi (725 kpa).

4) The density of aerated water depends on the proportion of air in the unit volume of water and the water depth. As non-aerated water is entrained into the rising water, that ratio will change as the water gets closer to the surface. However, the reducing ratio of air to water will be offset by the increasing size of the bubbles (by 7 times) as the water pressure above the bubbles decreases with depth. The risk has been cleared stated in the revised report (section 7.1.5). It would require unusual circumstances for a boat to sink when entering a bubble plume, but it could happen if the reduced freeboard allowed a wave or wake to swamp the boat. Similarly, swimmers are unlikely to swim out to the aeration plume, but it is not uncommon for people to dive off boats in the middle of a lake for a swim on a hot day. Diving of a boat into the aeration plume could prove fatal as the swimmer would need to swim out of the plume before the human body's natural buoyancy would help them back to the surface.

Question 6

Tonkin & Taylor: The report highlights the opportunity to aerate discharged water by a dissipator structure (e.g., FCD valve or hydraulic jump dissipator). However, this may be difficult during typical operation when flow is passing through the power station, which will involve some oxygenation but not the same degree as a dissipator structure.

The power station arrangements have only been developed to a prefeasibility level. However, if a separate and additional dissipator structure were to be incorporated downstream of the power station, besides the cost of the structure, it is likely that such a device would result in less head to generate power.

Answer

Once the water from the reservoir is inside the outtake pipe, it doesn't matter whether or not it passes through a power station before it is discharged into the Makaroro River, the water will have sufficient energy to damage the river bed unless some form of energy dissipater is installed below where the water emerges and before it enters the river. Depending on the design chosen, additional aeration may be a bonus. It is difficult to envisage how this would reduce the head to generate power.

Question 7

Tonkin & Taylor: In Section 7.2, the report states that "Clearing all the vegetation within the footprint of the dam (presumably meaning reservoir too) is likely to be impractical due to the topography of the site". We expect clearance of most scrub and trees to be possible and have allowed for this in our cost estimates. On the other hand, removal of all top soil as associated with the 20% lower SOD simulation (end of page 25) would be unusual and extremely expensive. Perhaps some expansion on what is meant by "all the vegetation" would be helpful.

Answer

This has been clarified in the revision. There is no expectation that all plants and soil should be removed from within the reservoir footprint. That was a specific case included as part of the sensitivity testing (section 3.1.4).

Question 8

Tonkin & Taylor: The recommendation to remove all production forest and plant natives to form a buffer zone on edge of the reservoir and to require advance construction of roading infrastructure for harvesting the remaining forest needs to be substantiated.

1) Is this recommendation supported by modelling and a water quality assessment?

2) The discharges of water borne sediment, organics and chemicals from these areas would be expected to have a low load compared to the total load from the catchment e.g., the report estimates 185 ha of eroding areas supplying suspended sediment. (Note the Sedimentation Assessment estimates 260 ha of erodible area above the dam site). The recommended approach would add considerable cost to the Scheme and could have implications for construction programme.

3) It is standard practice for forestry harvesting to include measures to manage erosion and control sediment in sensitive areas adjacent to watercourse and lakes. These approaches, with additional controls if necessary, should be sufficient to manage the water quality in the lake from forestry harvesting.

Answers

The text has been revised from “recommend that” to “consideration should be given to”. While the reservoir is being constructed, there is an opportunity to implement measures that will protect the water quality of the reservoir in the future. These measures should be considered:

1) The suggestions made are not modelled but are based on observations of the effects of production forest harvesting on lakes, reservoirs and estuaries. The measures suggested would overcome many of the problems water bodies experience when production forest is harvested along the shores.

2) There is a difference in the characteristics of the sediment from erodible catchment land (low organic content geological material) and clear-felled production forest (high organic content biological material). Both will have a similar range in particle sizes. The erodible material from the catchment represents more-of-the-same material that is slowly entering the lake over time in a nearly continuous flux, and the in-lake functions have developed to cope with this material. In contrast, the erodible material from the pine forest is released into the lake in a single pulse of highly organic matter and the in-lake functions may not cope. The impact of that organic material is likely to be a sudden depletion in water column DO concentrations and the release of nutrients from the sediment.

3) The “standard practice” mentioned is usually effective, however, when the forest boundaries are determined by inundation of standing forest as the reservoir fills, these practices will be hard to implement effectively. It would be easier to implement the standard practice measures before the reservoir is filled.

Question 9

Roger Young, Cawthron Institute: “I don’t like the idea of intentionally releasing turbid bottom water from the reservoir during the flushing flows, despite some possible benefits. If sediment flushing from the reservoir is the aim I think this should be done during naturally high flow periods”.

Answer

With a deep draw valve tower, the shift from around 6.3 $m^3 s^{-1}$ to 10.5 $m^3 s^{-1}$ is unlikely to substantially alter the sediment load from the reservoir. In general, the water discharged from the reservoir will be less turbid that the Makaroro River inflow. Even during flood flow events, the water spilled from the reservoir is likely to be less turbid than the inflowing water.

Question 10

Olivier Ausseil, Aquanet Consulting Ltd: “In practice, will the mixing/current created by the aerator go a long way up the reservoir (and side arms), or would it be limited to the downstream end of the main body of the reservoir? More importantly, does the mixing need to go a long way up the reservoir?”

Answer

There is likely to be a continuum of different water quality along a long narrow riverine reservoir, such as the Makaroro, with a turbid, well oxygenated riverine zone at the inflow end progressing through a mid-reach transition zone to a more oligotrophic lacustrine (lake-like) basin closer to the dam wall (Figure A-1).

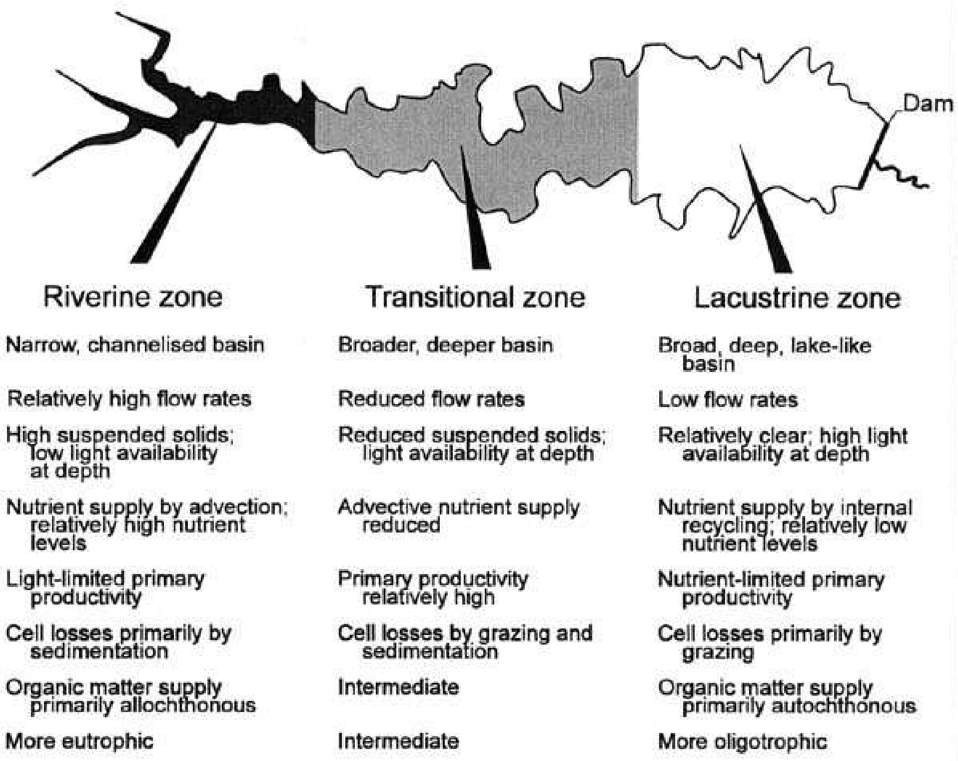


Figure A-1: Longitudinal zonation of water quality conditions in reservoirs with complex shapes formed by damming rivers (Modified from Kimmel and Groeger,1984).

If a point aerator is located in the middle of the lacustrine zone, the mixing current created by the aerator is likely to be confined to the lacustrine zone with some possible extension into the transitional zone. This is because the water entrained into and dispersing from the zone of aeration can move in all directions as a non-coherent flow. However, when the aerator is located close to the dam wall and is in the form of a long aeration bar across the width of the reservoir rather than a point aerator, all the water entrained into the bottom of the zone of aeration must come from upstream and the water leaving the aeration zone at the surface must move upstream creating a counter-current which will eventually become a conveyer belt type current. While the mixing current is being established it may not extend far upstream but once it is established it may extend well into the transitional zone.

Because of the orientation of the Makaroro reservoir in the landscape, southerly winds will help move the surface water upstream extending the zone of lateral mixing. Underflowing density currents, which are more likely to occur during the stratified period (cold nights cool the inflow below the temperature of the open water of the reservoir which has a much higher thermal inertia than the river), will entrain surface water along the bottom of the reservoir enhancing the volume/mass in the circulation / mixing current. The water depth and the amount of air used will also contribute to the distance upstream influenced by the aerator.

In practice, the selective draw depth will determine the overall quality of the water in the lacustrine zone and aeration will augment the DO concentrations by keeping the water column above the draw depth well mixed.

Aerator-driven mixing is effective in all 10 of the water supply reservoirs for Auckland City.

Appendix B Dam outlet structures – letter

5 July 2012

Dr Olivier Ausseil
Principal Scientist
Aquanet Consulting Ltd
51 Windsor Street
Palmerston North

Dear Dr Ausseil

Subject: Dam outlet structures

This letter is in confirmation of discussions and advice provided by myself to Olivier Ausseil, Mark Taylor and Roger Young via telephone conference call on 5 June 2012 in response to specific questions about aspects of the report on the proposed Ruataniwha reservoir water quality (Gibbs et al. 2012). The main points of the discussion have been correctly captured in an email from Olivier Ausseil on 5 June 2012 5:01 pm.

First, there was a misconception of how the modelling handled daily temperature changes in the water quality simulation when the inflow temperature record was monthly. The model uses daily data modelled from climate records and calibrated against the monthly measurements. In this way the model provides the best possible estimate of all parameters with time step of one day.

A key concern appears to be the uncertainty around the predicted water quality discharged from the reservoir if there is only a single outtake valve. Continuously drawing water from the lowest possible outlet will provide the best long-term water quality in the reservoir and downstream. This is represented by scenario M1 in the report and would be my preferred normal operating regime for the dam. There are three points to consider:

1. The water quality in the first 5 years is likely to be poorer than in subsequent years because of the decomposition of organic matter (soil and plant material) left within the inundation footprint of the reservoir. The actual water quality in the bottom waters will be a function of the amount of that organic matter and the rate of decay. The modelling indicates that stratification induced by selective draw may leave a small pool of low oxygen water below that depth all year. It is likely that that is an artefact of the modelling and winter turnover may mix the reservoir to the bottom. If that pool resisted winter mixing, it is unlikely that it would be possible to flush out that water. Consequently, the use of an aerator to assist winter mixing would ensure a better water quality in the reservoir and downstream.

2. In the longer term i.e., after the first 5 years, selective draw may maintain the predicted water quality without the need for aeration. However, there may be unforeseen circumstances that could require aeration. For example, during periods of drought i.e., low inflow, flow through the outtake may be insufficient to maintain the water quality in the water above the draw depth. Operation of the aerator would be triggered by in-reservoir

monitoring of the dissolved oxygen concentrations through the depth of the water column, as described in the report (Gibbs et al. 2012).

3. While scenario M1 is my preferred normal operating regime for the dam, scenario M3 demonstrates that using outtake valves at two different levels can result in a blending of the waters to some intermediate water quality. This is only possible if a design option including a high level outtake is used. The inclusion of more than one outtake valve would provide a safeguard by which higher water quality could be released downstream should the lowest outtake valve be predominantly poor water quality (low flow scenario above) or be overwhelmed by a turbidity-induced density current. On the basis of in-reservoir and downstream water quality management alone, there is no need for an upper level outtake structure. The water released from the dam will be slightly cooler than the natural stream without the dam in summer and slightly warmer in winter, and the sediment load downstream will be reduced during flood events. However, from an operational perspective, it would be prudent to have a second outtake valve available to allow dam operation to continue if the bottom outtake valve is temporarily not operational for maintenance or to avoid a high turbidity density current being drawn through the system.

Lake Opuha near Fairlie, South Canterbury, is a case study that demonstrates the unexpected problems that can occur with reservoirs. Lake Opuha was built with a single near-bottom outtake valve. The operational regime was to ensure the lake was full in spring before excess water could be used for power generation. There was a large amount of organic matter left in the lake and this decomposed during filling causing bottom water oxygen depletion. The small compensation flow was insufficient to allow the deep draw outtake to maintain a well aerated water column in the lake. Consequently, when power generation began, anoxic water was released complete with high nutrient, mineral and biogas (methane and hydrogen sulphide) concentrations.

An aerator would have managed the anoxia – an aerator has now been installed – or a second higher level outtake valve would have allowed better quality water to be discharged. The retrofitting of additional outtake valves is being considered.

Further to the teleconference discussion are the future effects of climate change. One purpose of the Ruataniwha reservoir is to provide irrigation water in times of drought. With climate change there is an increased risk of being unable to maintain sufficient continuous withdrawal flow to maintain the reservoir and downstream water quality. The installation of an aeration system and the inclusion of multiple outtake valves is a sensible and pragmatic contingency against such “critical events” becoming more frequent and having serious consequences for the downstream water quality.

As I concluded in the telephone conference, I would recommend that:

1. The M1 scenario should be adopted as the normal operating regime for the lake.
2. An aeration system should be installed near the dam wall.
3. At least one higher level outtake valve should be included in the design of the dam.

Best regards

Dr Max Gibbs

Limnologist and Environmental Chemist

Reference

Max Gibbs, Chris McBride, Deniz Özkundakci and David Hamilton (2012) Ruataniwha Plains water storage project: Characterisation of reservoir water quality. *NIWA Client Report* No. HAM2011-136 prepared for Hawkes Bay Regional Council. April 2012: 128.

Appendix C

Limnotrack Report (McBride et al. 2011)

Initial modelling report plus data CD.

Limnotrack Memo (McBride 2012)

Supplementary modelling report.

LIMNOTRACK

DYRESM-CAEDYM modelling of proposed Ruataniwha reservoir water quality

December 2011

Prepared for NIWA by Chris McBride, Deniz Özkundakci and David Hamilton

Executive summary

The proposed Ruataniwha Reservoir, located on the Makaroro River in Hawke's Bay, is intended to enhance the reliability of water supply for irrigation on the Ruataniwha Plains. Limnotrack was commissioned by the National Institute of Water and Atmospheric Research (NIWA) to apply the coupled hydrodynamic-ecological model DYRESM-CAEDYM model to simulate hydrological, hydrodynamic and water quality aspects of the proposed reservoir. The period from July 2000 to June 2005 was simulated in order to assess the thermal structure of the reservoir water column during and after reservoir filling, as well as the chemical and biological attributes of reservoir and outflow water. Flow regime and meteorological forcing data were obtained from Tonkin & Taylor and NIWA based on hydrological modelling and climate monitoring stations, respectively, and incoming water quality was defined using National River Water Quality Network monitoring data. In order to parameterise the model — and in the absence of reservoir water quality observations with which to calibrate it — our approach was to derive model parameter values from the literature, sensitivity analyses, and empirical relationships between environmental forcing data and parameters from previously published applications of DYRESM and/or CAEDYM.

Based on the Ruataniwha DYRESM-CAEDYM simulations, the reservoir would take about 95 days to reach capacity if a minimum offtake volume was extracted during the filling phase. However, this would ultimately depend on climate (rainfall) over the filling period and thus time of year may be an important consideration. Simulations based on a water extraction regime provided by Tonkin & Taylor showed a monomictic thermal water column structure, with stable temperature stratification during warmer months accompanied by significant oxygen depletion in bottom waters. Nutrient levels in the reservoir were typically low, despite moderate simulated releases of dissolved inorganic nutrients during oxygen depletion. Three generalised classes of reservoir phytoplanktons were simulated (diatoms, chlorophytes, and cyanobacteria without nitrogen fixation), of which diatoms were the dominant class. However,

simulations suggested that low population densities of cyanobacteria may be able to persist in the reservoir during warmer months. Simulated nutrient concentrations and phytoplankton biomass suggest that water quality in the reservoir is likely to be classed as oligotrophic to mesotrophic. The ratio of nitrogen to phosphorus concentrations of the water column indicate a moderate to strong potential for nitrogen limitation of phytoplankton growth for sustained periods of time.

A model sensitivity analysis of sediment oxygen demand suggested that carbon content of the reservoir basin (based on soil carbon and vegetation cover) will strongly influence oxygen depletion rates in the bottom waters of the reservoir. Furthermore, a simulation that moved the extraction of the stream baseflow from the toe of the dam to the main outlet, showed that the height of outflow extraction had a dramatic effect on the thermal structure of the water column, leading to infrequent water column turnover with significant implications for oxygen depletion in bottom waters and reservoir water quality.

The DYRESM-CAEDYM simulations highlight important issues regarding water quality on the proposed Ruataniwha Reservoir. While overall water quality is like to be good-to-fair, an often low TN:TP ratio indicates a potential for occurrences of nitrogen-fixing cyanobacteria, which could be problematic if phosphorus inputs to the reservoir are not well managed. Deviations from the flow regime provided may also have significant consequences for water quality. Careful attention should be paid to the effects of outflow regime on stratification dynamics, due to the cascading effects of extended stratification, oxygen depletion, and subsequent nutrient release driving algal growth. Furthermore, reservoir operation and management will strongly influence downstream water quality, and the height of outflow extraction will determine the oxygen and nutrient status of the Makaroro River downstream of the dam. Striking a balance between downstream water quality and maintaining regular turnover of the reservoir water column is important, and further modelling could aid in the optimisation of an appropriate outflow regime.

Table of contents

List of Figures

List of Tables

1. Introduction

Irrigation is thought to be essential in order to increase the security of pasture and crop production on the Ruataniwha Plains in Hawke's Bay (Tonkin & Taylor, 2009). In order to ensure irrigation demands are met in the future, a recent feasibility study from the Ruataniwha Water Storage Project (Tonkin & Taylor 2009) concluded that the best water management option would be a single dam site.

Limnotrack was commissioned by the National Institute of Water and Atmospheric Research (NIWA) to apply the coupled hydrodynamic-ecological model DYRESM-CAEDYM to the proposed Ruataniwha reservoir, in order to provide estimates of water quality during filling and subsequent operation of the dam for a total period of five years. DYRESM-CAEDYM resolves one-dimensional (vertical) variations in water temperature, as well as chemical and biological properties of water that are relevant to ecosystem productivity and trophic state.

The aim of the current model application was to assess the effects of environmental factors including incoming water quality from the Makororo River, atmospheric deposition of nutrients, climate, the physical structure of the reservoir water column (with and without thermal stratification), and retention of water within the reservoir.

This report presents the DYRESM-CAEDYM simulation results relevant to water quality in the proposed Ruataniwha Reservoir. A comprehensive description is provided for the derivation of input data for the model, as well as parameterisation of model components using existing empirical data in the catchment and previously published model applications. Outcomes are presented for simulations of reservoir hydrodynamics (i.e. thermal stratification patterns), dissolved oxygen, dissolved reactive and total phosphorus, dissolved inorganic nitrogen species and total nitrogen, suspended solids and three generalised algal groups intended to represent the phytoplankton population in the reservoir.

2. Methods

2.1. Study area

The proposed Ruataniwha Reservoir is situated in Central Hawke's Bay. The dam site will be located on the Makaroro River, approximately 10 km upstream of the 'Makaroro at Burnt Bridge' monitoring site for NIWA's National Rivers Water Quality Network (NRWQN). The reservoir will have a crest elevation of 469.6 masl, and when full will be 70.4 m deep with a surface area of approximately $3.6x10^6$ m^2 and a volume of approximately $90x10^6$ m^3 (Appendix 2.2). Land use in the approximately 12000 ha reservoir catchment is diverse, with a high proportion of indigenous vegetation, some high-producing pasture and a small proportion of harvested forestry (Table 1).

Table 1. Land use within the catchment of the proposed Ruataniwha reservoir, provided by Tonkin & Taylor from the New Zealand Land cover database (LCDB2).

Land-use Description	Area [ha]
Alpine Gravel and Rock	41.2
Broadleaved Indigenous Hardwoods	628.9
Deciduous Hardwoods	9.6
Forest Harvested	338.7
Gorse and Broom	3.3
Herbaceous Freshwater Vegetation	5.9
High Producing Exotic Grassland	1453.3
Indigenous Forest	7176.6
Lake and Pond	3.2
Landslide	184.6
Low Producing Grassland	10.4
Major Shelterbelts	0.6
Manuka and or Kanuka	1239.9
Other Exotic Forest	3.7
Pine Forest - Closed Canopy	106.8
Pine Forest - Open Canopy	275.5
River	1.9
River and Lakeshore Gravel and Rock	137.3
Sub Alpine Shrubland	244.5
Tall Tussock Grassland	235.9
Total catchment area	12101.8

Water quality in the Makaroro River is variable. According to the NRWQN record, dissolved nutrient concentrations are typically relatively low. However, turbidity is occasionally high, commonly associated with elevated total nutrient concentrations, particularly phosphorus.

2.2. Dynamic Reservoir Simulation Model (DYRESM) description

In this study, the one-dimensional (1D) hydrodynamic model DYRESM* was coupled with the aquatic ecological model CAEDYM*, to simulate hydrodynamics and water quality in the Ruataniwha reservoir. DYRESM resolves the vertical distribution of temperature, salinity, and density, and the vertical mixing processes in lakes and reservoirs. CAEDYM simulates time-varying fluxes that regulate biogeochemical variables (e.g., nutrient species, phytoplankton biomass). The model includes comprehensive process representations for carbon (C), nitrogen (N), phosphorus (P), and dissolved oxygen (DO) cycles. Inorganic suspended solids were not simulated due to a lack of input data. Several applications have been made of DYRESM-CAEDYM to different lakes (e.g., Bruce et al., 2006; Burger et al., 2007; Trolle et al., 2008; Gal et al., 2009; Özkundakci et al., 2011) and these publications have detailed descriptions of the model equations.

The biogeochemical variables in CAEDYM may be configured according to the goals of the model application and availability of data. In this study, three groups of phytoplankton were included in CAEDYM, representing generically cyanophytes (without N-fixation), diatoms, and a combined group termed chlorophytes. The interactions between phytoplankton growth and losses, and sediment mineralisation and decomposition of particulate organic matter, influence N and P cycling in the model as shown in the conceptual model in Figure 1. Sediment oxygen demand is assigned a constant maximum possible rate, which is regulated by oxygen concentration in the overlying water column. Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on temperature, nitrate and DO concentrations of the water layer immediately above the sediment surface, with calibration of parameters specific to each new application but with an extensive parameter library now available from the large number of studies undertaken with the model.

*Developed at the Centre for Water Research, The University of Western Australia.

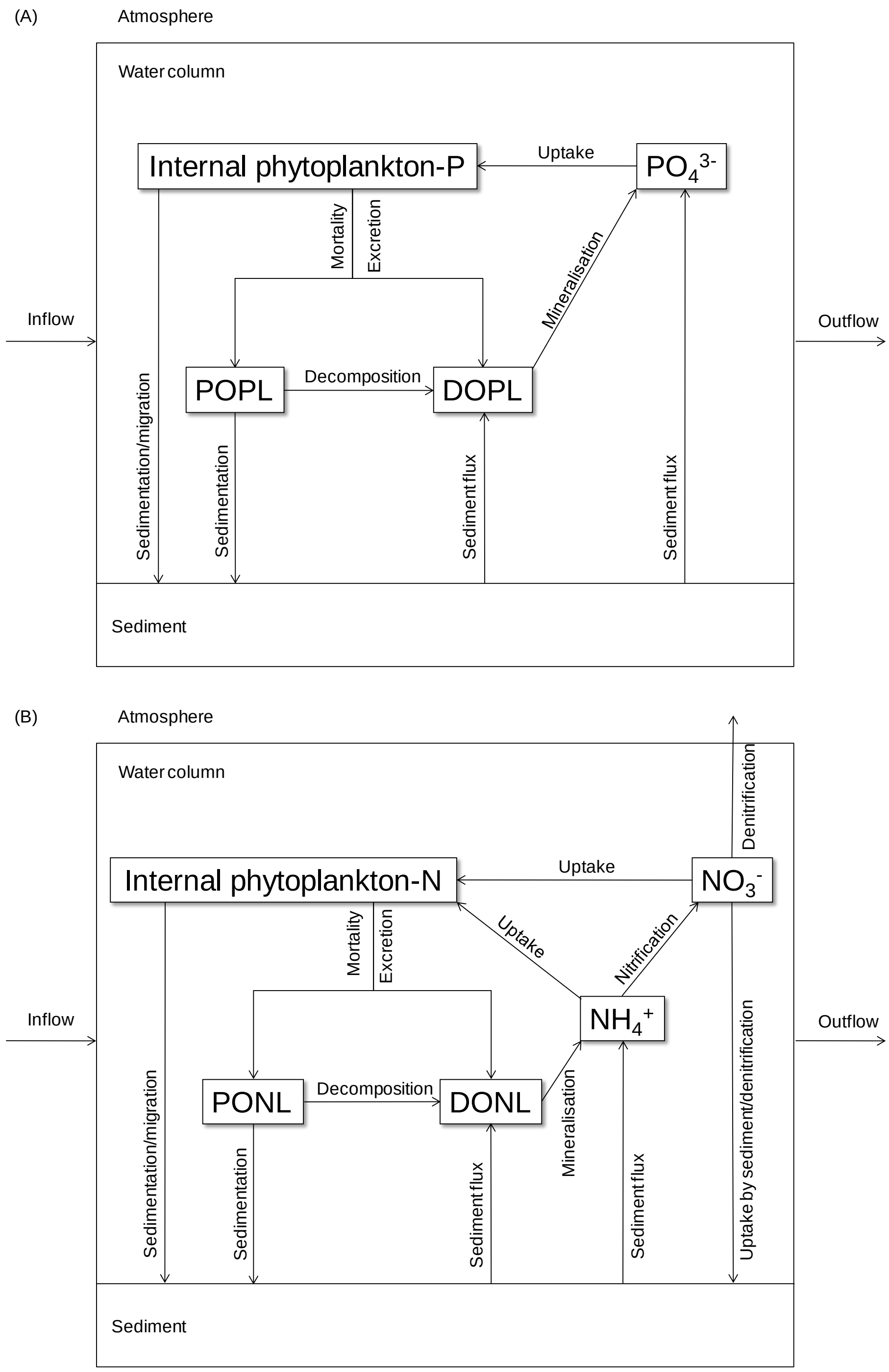


Figure 1. Conceptual model of CAEDYM nutrient dynamics within the current model application to the proposed Ruataniwha reservoir for (A) phosphorus and (B) nitrogen.

2.3. **Model period**

The chosen baseline simulation period was 30 June 2000 to 30 Jun 2005, due to the availability of forcing data (inflows, climate). This period also allows for the possibility of extending the model duration to ten years, if required at a later date.

2.4. **Meteorology**

Meteorological data required for the simulation period were obtained from five sites within the NIWA virtual climate data network that lie within the proposed reservoir catchment (Appendix 1.1). DYRESM requires daily input data for air temperature (°C), shortwave radiation (W m^{-2}), long wave radiation or cloud cover (fraction of whole sky), vapour pressure (hPa), wind speed (m s^{-1}), and rainfall (m).

2.4.1. ***Air temperature***

Available air temperature data from the virtual climate data network were daily minimum and maximum temperatures only. Therefore, measured daily average, minimum and maximum temperature data were obtained from the nearest available NIWA cliflo (http://cliflo.niwa.co.nz) site (Appendix 1.2, Dannevirke, ID#D06212) and the genetic algorithm model Eureqa (Schmidt & Lipson, 2009) was used to obtain a weighted average of daily minimum and maximum air temperature that best represented measured daily average air temperature:

$$T_{avg} = 0.412 * T_{max} + 0.565 * T_{min} \quad (1)$$

where:

T_{avg} is estimated mean daily temperature in degrees Celsius

Equation 1 was then applied to the virtual climate network daily minima/maxima data in order to estimate daily average air temperature within the proposed reservoir catchment (Figure 3).

2.4.2. ***Wind speed***

Daily wind speed values (m s^{-1}) were calculated from the mean of daily average wind speed for the five virtual catchment sites. Visual inspection of the wind data showed an offset of wind speed measurement post-2004, with yearly minima of ~1.2 m s^{-1} (Figure 2A). Comparison with a nearby NIWA cliflo (www.cliflo.co.nz) weather station, Takapau Plains (Appendix 1.3), network number, ID#06024) suggested this was unrealistic. Therefore virtual climate wind speed data after 31-12-2004 were adjusted (Figure 2B) using the equation:

$$U_{adj} = 1.1081 * U - 1.3297 \qquad (2)$$

where:

U_{adj} is post-2004-adjusted wind speed in m s^{-1}

U is mean daily wind speed from five virtual climate stations in m s^{-1}

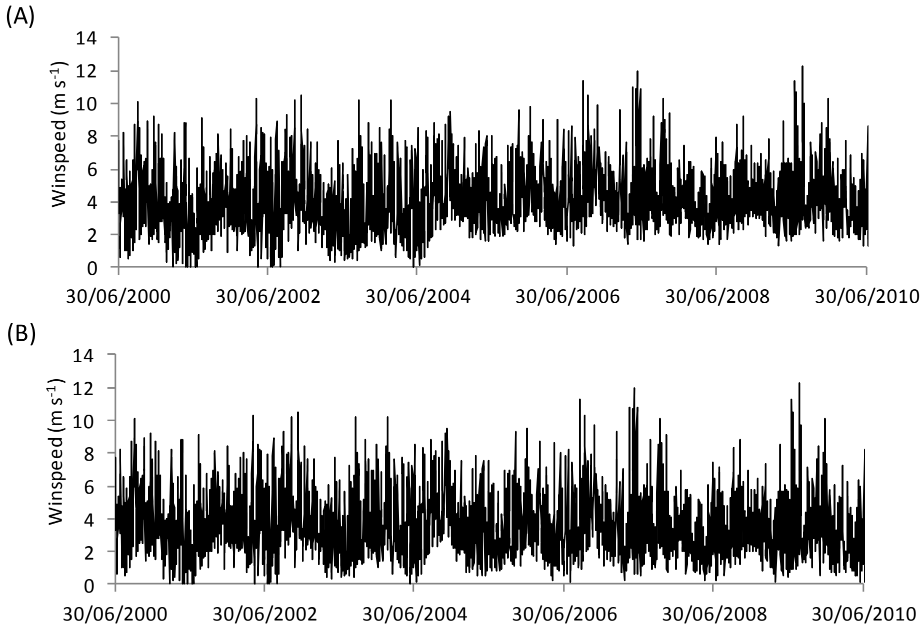


Figure 2. Average of daily wind speed from five virtual climate stations within the proposed Ruataniwha Reservoir catchment, (A) prior to post-2004 adjustment, and (B) after adjustment.

2.4.3. ***Short-wave radiation***

Average daily shortwave radiation (W m^{-2}) was calculated from the mean of daily radiation for the five virtual catchment sites (Figure 3).

2.4.4. *Cloud cover*

DYRESM requires either longwave radiation or cloud cover (0 to 1) as input. Because values for longwave radiation were not available, estimated cloud cover (Figure 3) was derived from shortwave radiation data, using the equation:

$$CC = (Val1 - SW)/(Val1-Val2) \quad (3a)$$

where:

SW is shortwave radiation in W m^{-2}

Val1 is estimated clear-sky shortwave radiation (Equation 3b)

$$Val1 = (245+145 * SIN(((yd * 2 *\Pi/366)+1.743)))) * 1.05 \quad (3b)$$

Val2 is estimated full cloud-cover shortwave radiation (Equation 3c)

$$Val2 = (30+25*(SIN(((yd *2*\Pi)/366)+(1.743))))*2 \quad (3c)$$

where:

yd is day of the year (0 to 365, or 366 in a leap year)

2.4.5. *Vapour pressure*

Average daily vapour pressure (Figure 3) was calculated from mean measurements of the five virtual catchment sites, using the *Magnus-Tetens* formula (TVA, 1972 Equation 4.2):

$$VP =(RH/100)*EXP(2.303*((7.5*T_{avg}/(T_{avg} +237.3))+0.7858)) \quad (4)$$

where:

VP is vapour pressure in hPa

T_{avg} mean daily temperature in degrees Celsius

2.4.6. *Rainfall*

Average daily total rainfall (m) was calculated from the mean of total daily rainfall at all five virtual catchment sites (Figure 3). For simulations of water quality, rainfall within the DYRESM meteorological input was set to zero and instead incorporated as a surface inflow, in order to account for atmospheric deposition of nitrogen and phosphorus onto the reservoir.

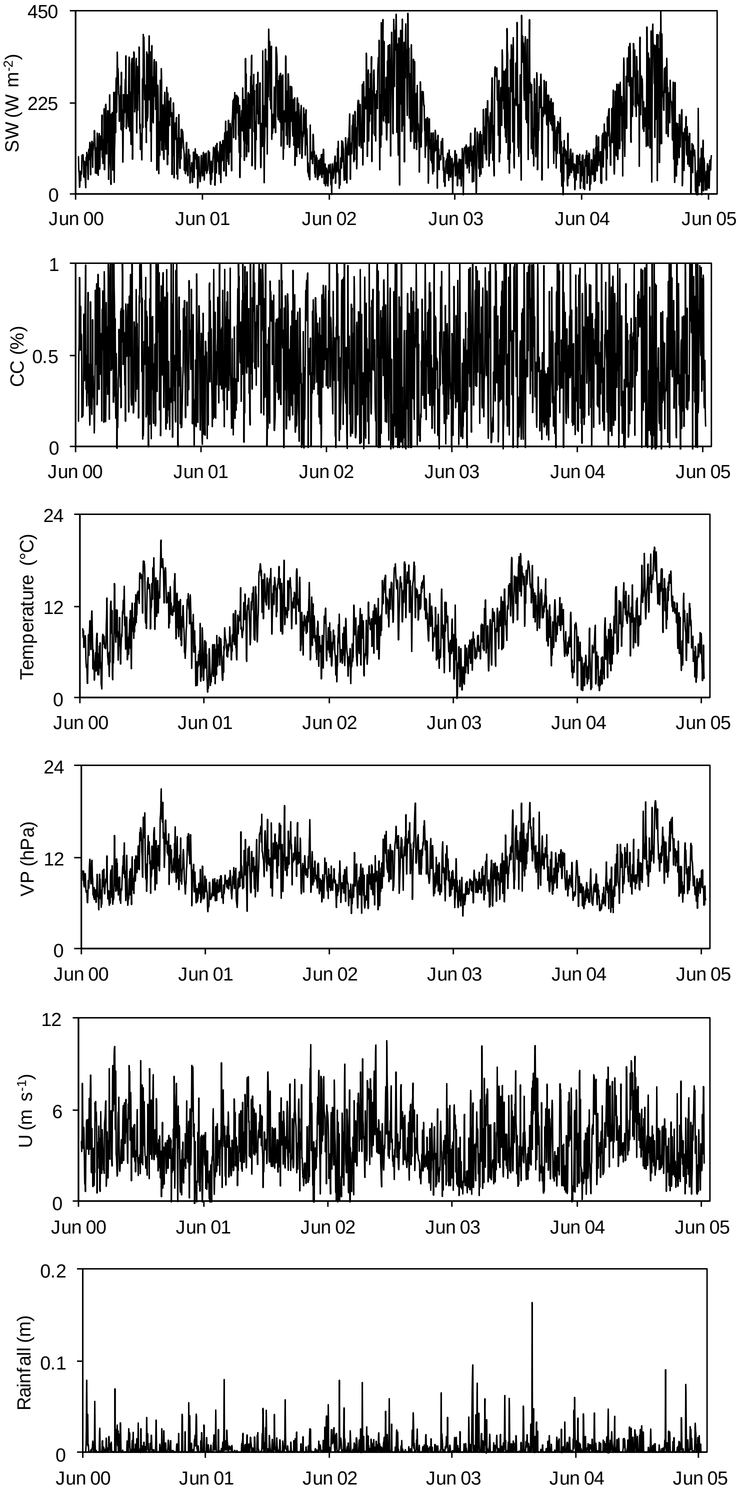


Figure 3. Meteorology input data to DYRESM.

2.5. Inflows

2.5.1. *Makaroro inflow*

Daily surface inflow discharges to the lake for all simulations were obtained from hydrological modelling of Makaroro River flow (1972 to 2010) at the Burnt Bridge monitoring site (Appendix 2.4). Monthly water quality data were available for the period January 2000 to September 2011 for Makaroro River at Burnt Bridge (Appendix 1.4) which is a monitoring site for NIWA's National Rivers Water Quality Monitoring Network (NRWQN).

2.5.1a. *Water temperature*

Surface inflow temperatures for the Makaroro were estimated using the method described in Mohseni et al. (1998):

$$T_s = \frac{\alpha}{1+e^{\gamma(\beta-T_a)}} \qquad (5)$$

where:

T_s is the estimated stream temperature

T_a is the measured air temperature

α is the coefficient for the estimated maximum stream temperature

γ is a measure of the steepest slope of the function

β represents the air temperature at the inflection point

Quality of fit was defined by the difference between modelled water temperature and available in situ measurements from the NRWQN Burnt Bridge record. Model parameters were adjusted in order to minimise the root-mean-square error (RMSE) and maximise the Pearson correlation co-efficient, using *Microsoft® Excel Solver*.

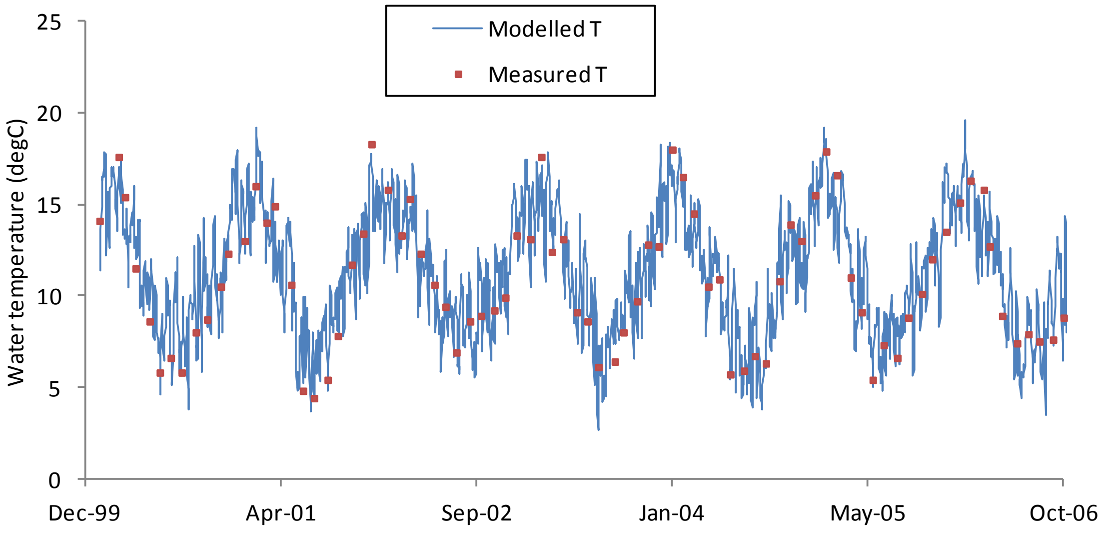


Figure 4. Estimated (daily) and measured (monthly) surface water temperature of the Makaroro River inflow.

Temperature of the rainfall inflow was set to be equal to the surface lake water temperature, so that rainfall was always inserted into the surface layer of the reservoir.

2.5.1b. *Dissolved oxygen*

Dissolved oxygen concentrations of all inflows were estimated as a function of water temperature (Mortimer 1981) based on data from Benson and Krause (1980):

$$DO = exp(7.71 - 1.31 ln(T + 45.93)) * M \quad (6)$$

where:

DO is dissolved oxygen in mg L^{-1}

T is water temperature in $^{\circ}C$

M is a saturation co-efficient

Quality of fit was again defined by the difference between modelled dissolved oxygen and NRWQN Burnt Bridge data. The co-efficient M was adjusted in order to minimise the root-mean-square error (RMSE) and maximise the Pearson correlation co-efficient, using *Microsoft® Excel Solver*.

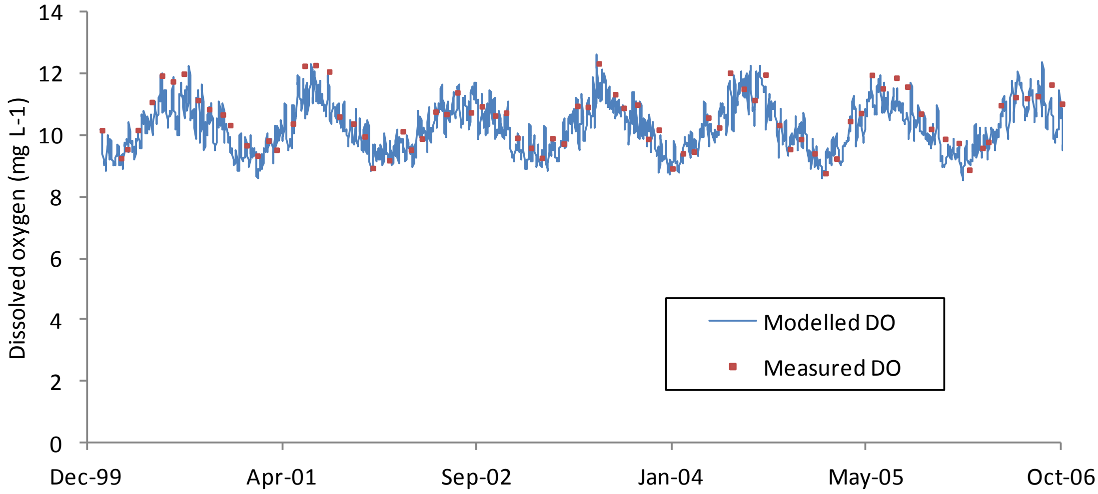


Figure 5. Estimated (daily) and measured (monthly) surface dissolved oxygen concentration of the Makaroro River inflow.

2.5.1c. *Nutrients*

Daily ammonium, nitrate and phosphate concentrations for all major inflows were derived from linear interpolation of monthly NRWQN nutrient measurements, as outlined for other model applications (Burger et al., 2007; Trolle et al., 2011; Özkundakci et al., 2011). Labile organic nitrogen and phosphorus concentrations (ONL and OPL, respectively) were evenly divided into dissolved (D) and particulate (P) fractions using the equations:

$$\text{DONL or PONL} = (\text{TN} - \text{NH}_4\text{-N} - \text{NO}_3\text{-N}) / 2 \qquad (7a)$$

$$\text{DOPL or POPL} = (\text{TP} - \text{PO}_4\text{-P}) / 2 \qquad (7b)$$

Labile dissolved and particulate organic carbon concentrations were calculated using inflow labile organic nitrogen concentrations and a 'Redfield' molar ratio of 106:16 for C:N (Redfield, 1958):

$$\text{DOC or POCL} = (\text{DONL or PONL}*106*M(\text{C})) / (16*M(\text{N})) \qquad (7c)$$

where:

M(C) is the molar mass of carbon

M(N) is the molar mass of nitrogen.

The Makaroro surface inflow was prescribed a 'seeding' concentration of 0.1 μg L^{-1} chlorophyll *a* for the assigned cyanophyte, chlorophyte, and diatom groups.

2.5.2. Rainfall inflow

For simulations of water quality, rainfall was removed from the meteorological input to the model and included as a surface inflow to the reservoir, as mentioned above, in order to account for atmospheric deposition of N and P which would not otherwise be represented in the present model version. To accomplish this, rainfall in the meteorological input file (Appendix 3.1, *.met) was set to zero, and the volume of the total rainfall input to the reservoir (Appendix 3.2, *.inf) was calculated by multiplying measured rainfall by the (level-dependent) reservoir surface area for each daily time-step. Rainfall nitrate (NO_3-N) and phosphorus (PO_4-P) were set to constant concentrations of 0.285 and 0.013 g m^{-3}, respectively, which are approximations of concentrations based on typical N and P areal loads and rainfall amounts for the Taupo Volcanic Zone (Hamilton 2005). No particulate or dissolved organic nitrogen, phosphorus or carbon fractions were prescribed to the rainfall inflow representing atmospheric deposition.

2.5.3. Outflows

Two water outtakes are specified in the proposed dam plans (Appendix 2.3), one at 455.5 masl and another at 426 masl. Daily total outflow volumes were provided by Tonkin & Taylor for the period 1972 – 2011 (Appendix 2.4). Furthermore, Tonkin & Taylor recommend (Appendix 2.5) a baseflow to be extracted from a third outtake at the toe of the dam wall, equal to 90% of the 7-day mean annual low flow (7-day MALF, = 106099.2 m^3 d^{-1}).

For the purpose of the model application, the 90% 7-day MALF was subtracted from the total outflow volume and withdrawn from the toe of the dam at one meter above the reservoir bottom (elevation 395 masl). The remaining flow was withdrawn from the lower outlet (elevation 426 masl) and the upper outlet was not utilised. This ensured that water extraction was always from below the water level even during low water levels.

2.6. Model parameterisation

The modelling of a theoretical reservoir presents a unique challenge, as there are no available field measurements of reservoir water quality with which to optimise sensitive parameters within the model. Therefore, the calibration approach consisted of standard model parameter values obtained from the literature, sensitivity analyses, and derivation of parameter values from empirical relationships between environmental forcing data and parameters from previously published applications of DYRESM and/or CAEDYM.

2.6.1. *Hydrodynamics*

DYRESM hydrodynamic parameters are generally considered to require little or no calibration in order to reproduce thermal dynamics. However, the 'effective surface area co-efficient' can affect the strength, duration and depth of thermal stratification. We therefore undertook a simple sensitivity analysis for this parameter (refer section 2.7.2). The water column height of stream flow insertion in DYRESM is controlled by parameters for stream-bed half angle, slope, and drag co-efficient, which were set to default values (70, 0.001 and 0.016 respectively; Appendix 3.1, *.stg).

2.6.2. *Oxygen dynamics*

Static sediment oxygen demand (CAEDYM parameter 'SOD') is typically calibrated in order to obtain best fit between model simulations and observed hypolimnetic dissolved oxygen depletion during periods of stratification. The calibrated parameter is not fixed but varies in the model according the overlying water concentrations of dissolved oxygen and temperature. In the absence of any measurements for calibration, we sought to derive a relationship between total carbon (TC) content of lake sediments and SOD values prescribed in previously published applications of CAEDYM. The resulting relationship (Figure 6, R^2 = 0.70) yielded a sediment oxygen demand of 2.52 g m^{-2} d^{-1} for the Ruataniwha reservoir.

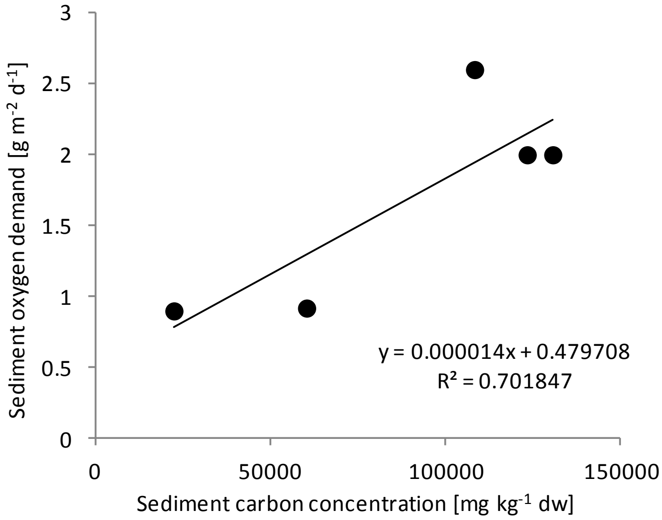


Figure 6. Relationship between sediment total carbon and CAEDYM parameter 'sediment oxygen demand' (SOD) for five previously published applications of DYRESM-CAEDYM.

2.6.3. ***Sediment nutrient release***

2.6.3a. *Phosphorus*

Sediment release rate for phosphate (CAEDYM parameter 'SmpPO4') was derived similarly to SOD, but using the relationship between sediment total phosphorus (TP) and phosphate release rate from five previous models (Figure 7, R^2 = 0.81), giving a phosphate release rate of 0.021 g m^{-2} d^{-1} for the Ruataniwha reservoir.

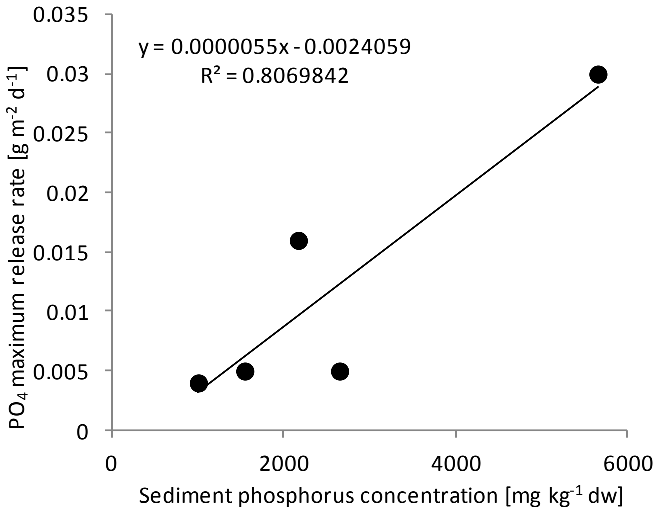


Figure 7. Relationship between sediment total phosphorus and CAEDYM parameter 'release rate of PO_4' (SmpPO4) for five previously published applications of DYRESM-CAEDYM.

2.6.3b. *Nitrogen*

The relationship between ammonium release rate and total nitrogen content of sediments for previously published models was not strong (R^2 = 0.12), possibly due to the varying effects of nitrification/denitrification and organic nitrogen remineralisation rates. Therefore, the mean TN:TP ratio from Ruataniwha soils was multiplied by the derived phosphate release rate, yielding a release rate for ammonium of 0.019 g m^{-2} d^{-1}.

2.6.4. *Water column nutrient chemistry*

For parameters relating to the decomposition and mineralisation of organic nutrient species (e.g., DONL, DOPL), generalised parameter values were assigned based on previously published values for oligotrophic to mesotrophic lakes (Schladow & Hamilton 1997; Gal et al. 2009; Trolle et al. 2011).

2.6.5. *Phytoplankton dynamics*

Dynamic internal stores of nitrogen and phosphorus were used for all three simulated classes of algae. Parameters for algal growth, mortality, nutrient metabolism and excretion, were again taken from the available literature (Schladow & Hamilton 1997; Trolle et al. 2011). Diatoms were parameterised to be negatively buoyant, whereas chlorophytes and cyanophytes were considered neutrally buoyant to reflect motility and buoyancy control, respectively.

2.6.6. *Water quality initialisation*

The newly-constructed reservoir was prescribed an initial water elevation (height) of 2 m, and initial water quality was set to match the most recent NRWQN monitoring data. Concentrations of all algal groups were set to 1 ug chl *a* L^{-1}, to reflect the low levels of phytoplankton in the Makaroro River (Max Gibbs, *pers. comm.*) and a small increment due to growth within the reservoir itself.

2.7. Sensitivity analyses

2.7.1. *Filling time*

In order to examine potential variation in reservoir filling time, a simulation was run with a start date of 11 January 2000 instead of a start date of 30 June 2000.

2.7.2. *Thermal stratification*

DYRESM parameterisation is generally consistent between model applications. However, the DYRESM parameter 'effective surface area coefficient' (ESAC) can affect the stratification dynamics within a lake or reservoir. This parameter is used to account for the effects of varying catchment topography on the transfer of wind energy to the water column. For the baseline simulations, the effective surface area coefficient was set to the surface area of the reservoir for water levels corresponding to full capacity (ESAC = 3.6×10^6 m^2). A further scenario was simulated, using the minimum simulated reservoir surface area during the 5-year baseline simulation period.

2.7.3. *Effects of removing versus retaining vegetation within the reservoir basin; sediment oxygen demand.*

Oxygen demand in the hypolimnion is largely dependent on carbon concentration that drives bacterial respiration in surficial sediments of the lake bottom. For the baseline model scenario, sediment oxygen demand was estimated (Figure 6) using values provided for soil carbon content (Appendix 2.7). The assumption for this scenario was that vegetation within the reservoir basin would be cleared and removed prior to filling.

The proposed reservoir basin currently contains significant vegetation cover. In order to estimate the potential impact of retaining vegetation during filling, and also to assess uncertainty in the method of parameterisation for sediment oxygen demand (SOD), three further scenarios were simulated, with SOD values of +10%, +20% and -20%.

2.7.4. *Removal of dam toe outflow*

In order to assess any impact of simplifying dam outtake by shutting the outlet at the toe of the dam after reservoir filling, a scenario was simulated which involved withdrawing the entire outflow from the outtake at 426 masl for the period subsequent to the 95-day filling time.

3. Results

Simulations of the coupled hydrodynamic-ecological model DYRESM-CAEDYM were run for the period 30 June 2000 to 30 June 2005. A start date at the beginning of winter was chosen because reservoir thermal and ecological characteristics are simpler when lakes are typically well-mixed due to colder weather.

3.1. Hydrodynamics

3.1.1. *Water level*

The filling phase lasted approximately 95 days, after which time the reservoir reached a depth of 75.5 m. Once full, surface elevation as simulated by DYRESM matched the surface elevations provided by Tonkin & Taylor extremely closely (Figure 8).

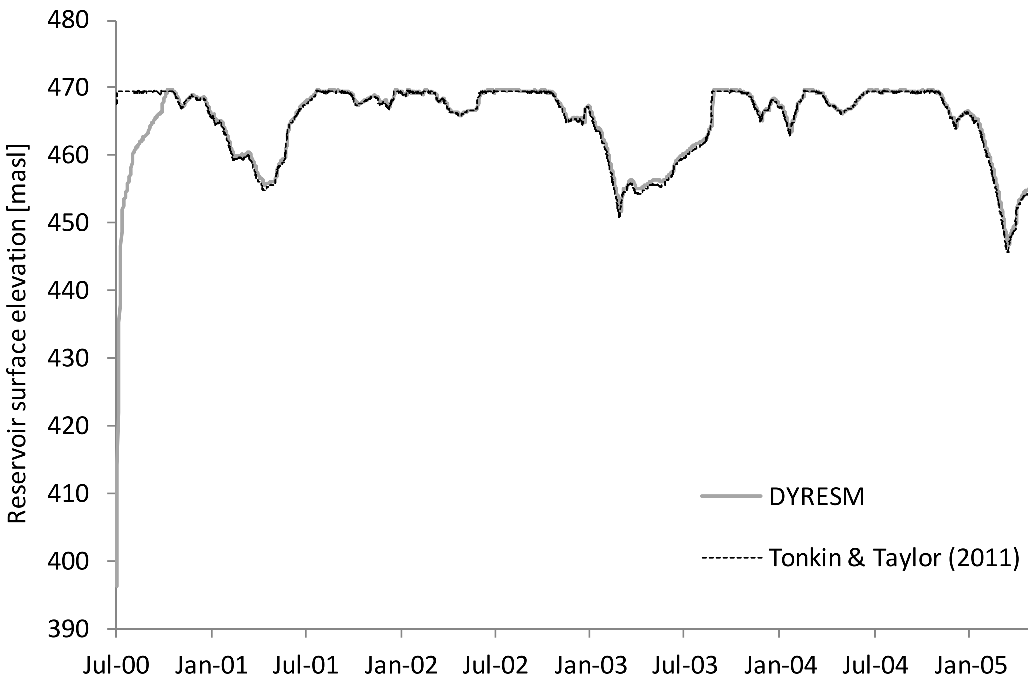


Figure 8. Comparison of projected reservoir water level from Tonkin & Taylor (Appendix 2.4), and the current application of DYRESM for the period 30/06/2000 to 30/06/2005.

3.1.2. *Water temperature*

The DYRESM simulation showed a thermal structure typical of a deep monomictic lake, with stable stratification during summer and a fully mixed water column during colder months. Surface water temperature ranged from 5.4 to 22.7°C. Compared with other deep lakes, the surface layer extended to considerable depth due to the effect of removal of water from lower levels of the reservoir. On average over the 5-year period, surface waters were > 3°C warmer than bottom waters for 196 days of the year. The thermocline in the water column deepened through the year, with mixing typically occurring in early to mid-April.

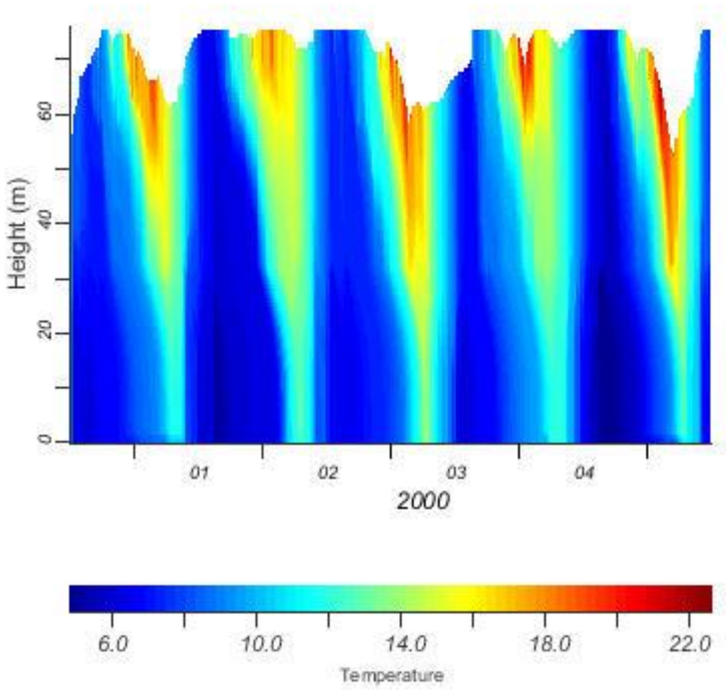


Figure 9. Simulated water temperature (°C) for the period 30/06/2000 to 30/06/2005.

3.2. Reservoir water quality

3.2.1. *Oxygen dynamics*

The DYRESM-CAEDYM simulation showed depletion of dissolved oxygen (DO) in the hypolimnion of the reservoir during seasonal stratification, with bottom waters approaching complete anoxia near the end of the stratified period (Figure 10). Upper layers of the reservoir remained well oxygenated (> 70% of saturation) at all times.

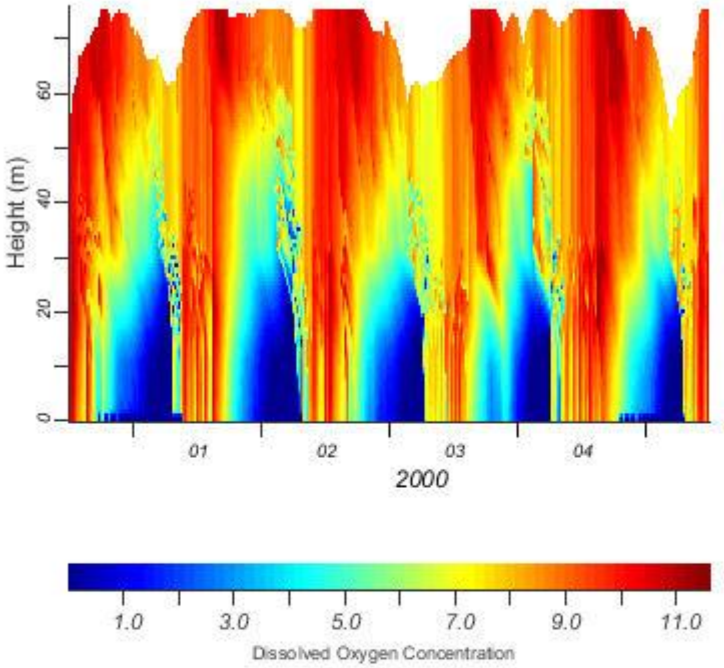


Figure 10. Simulated dissolved oxygen (mg L^{-1}) for the period 30/06/2000 to 30/06/2005.

3.2.2. *Nutrients*

Simulated phosphorus concentrations in the reservoir were generally low, with phosphate ranging from 0 – 0.08 mg L^{-1} and higher concentrations generally confined to a small volume of water below the dam toe outlet. Total phosphorus concentrations ranged from 0 to 0.24 mg L^{-1}, with elevated concentrations during summer 2003 – 2004 associated with high total nutrient concentrations observed in the Makaroro River (Figure 11).

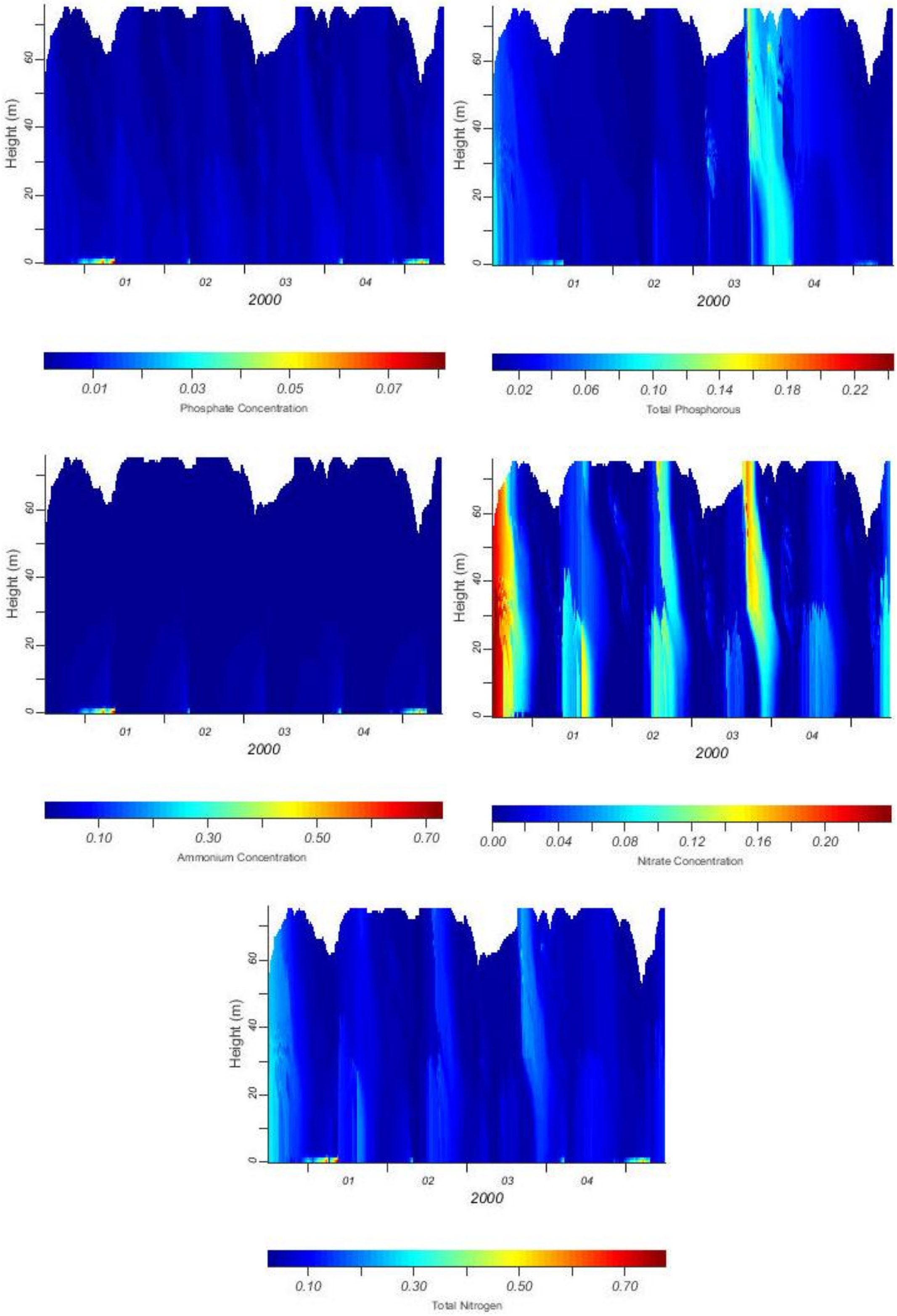


Figure 11. Simulated nutrient concentrations (mg L^{-1}) for the period 30/06/2000 to 30/06/2005, for phosphate, total phosphorus, ammonium, nitrate and total nitrogen. Note that the colour scales are different for each plot.

Simulated ammonium concentrations in the reservoir were generally low, ranging from 0 – 0.7 mg L^{-1}, with the higher concentrations confined to the small volume of water below the dam toe outlet, and associated with sediment nutrient release during hypoxia. Nitrate was more evenly distributed through the water column due to inflow via the Makaroro River. Total nitrogen concentrations ranged from 0 to 0.8 mg L^{-1} and were relatively stable over the simulation period (Figure 13). Organic nutrient concentrations were also relatively stable over the simulation period, although elevated concentrations were again observed in association with the inflow event over summer 2003 – 2004 (Figure 14).

Table 2. *Basin average* nutrient and chlorophyll concentrations by year.

Period	Average DO (mg L^{-1})	Average PO_4 (mg L^{-1})	Average NO_3 (mg L^{-1})	Average NH_4 (mg L^{-1})	Average TP (mg L^{-1})	Average TN (mg L^{-1})	Average TN:TP
2000-2001	8.506	0.002	0.059	0.002	0.026	0.097	3.622
2001-2002	8.344	0.001	0.016	0.002	0.008	0.050	6.338
2002-2003	8.328	0.002	0.023	0.002	0.013	0.053	4.377
2003-2004	8.438	0.002	0.033	0.002	0.053	0.079	1.625
2004-2005	8.677	0.002	0.015	0.002	0.014	0.049	3.931

Concentrations of chlorophyll *a* and total nitrogen were typically associated with oligotrophic or microtrophic (low productivity, high quality) lakes and reservoirs, according to values defined by Burns et al. (1999). However, total phosphorus concentrations were more variable, and in 2003 were high enough to be considered Supertrophic (Table 3).

Table 3. *Surface* (0 m) total nutrient concentrations, and associated TLI3 trophic levels (Burns et al. 1999).

Period	Average Chl *a*		Average TP		Average TN	
	(µg L^{-1})	Trophic level	(mg L^{-1})	Trophic level	(mg L^{-1})	Trophic level
2000-2001	1.4	Oligotrophic	0.025	Eutrophic	0.095	Oligotrophic
2001-2002	1.3	Oligotrophic	0.008	Oligotrophic	0.053	Microtrophic
2002-2003	1.3	Oligotrophic	0.013	Mesotrophic	0.059	Microtrophic
2003-2004	1.4	Oligotrophic	0.055	Supertrophic	0.082	Oligotrophic
2004-2005	1.2	Oligotrophic	0.014	Mesotrophic	0.052	Microtrophic

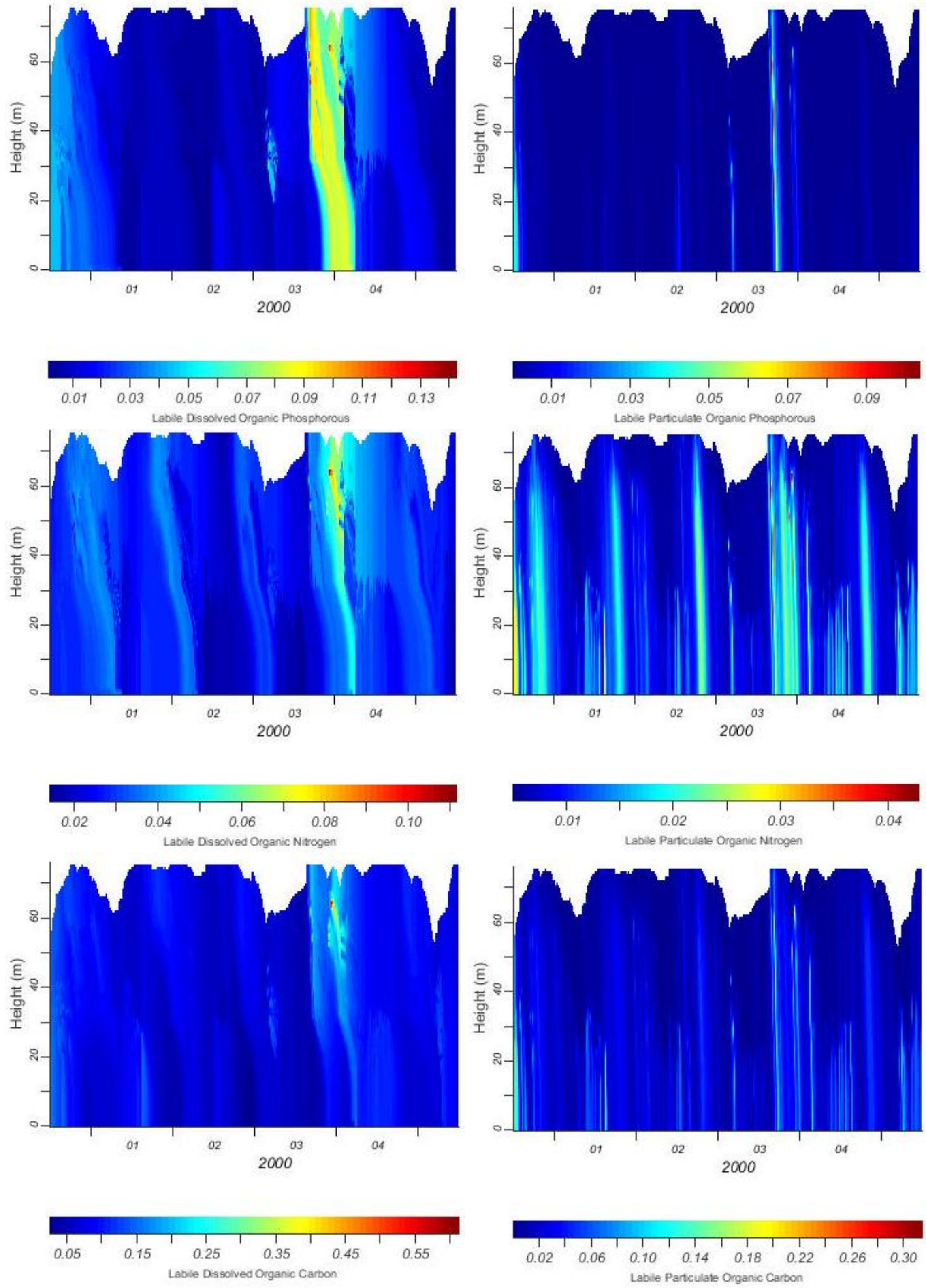


Figure 12. Simulated organic nutrient concentrations (mg L^{-1}) for the period 30/06/2000 to 30/06/2005, for DOPL, POPL, DONL, PONL, DOCL, POCL. Note that the colour scales are different for each plot.

Total nitrogen to total phosphorus mass ratios (based on concentrations) ranged from approximately 1 to 9 over the simulation period (Figure 13). When compared to the Redfield ratio (by mass) of 7.2:1 (White et al. 1985) phytoplankton growth in the reservoir appeared likely to be strongly nitrogen limited.

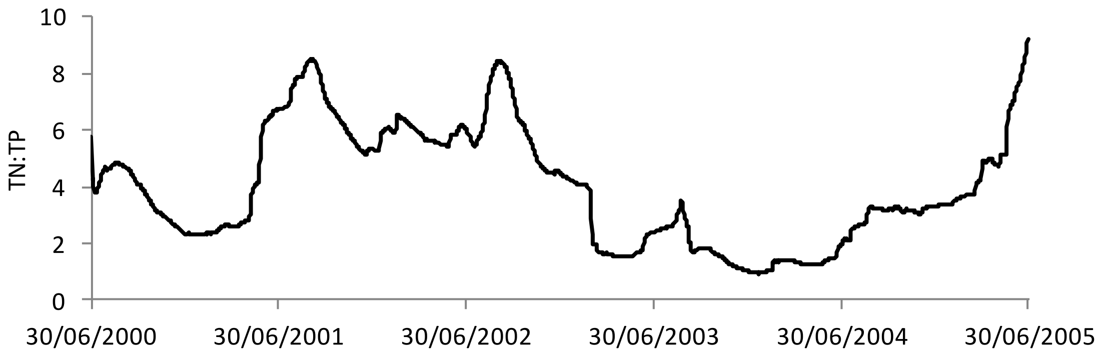


Figure 13. Basin average ratio of total nitrogen to total phosphorus (TN:TP) over the simulation period.

3.2.3. ***Phytoplankton***

Simulated daily maximum surface total chlorophyll *a* concentrations ranged from 0.3 to 9.5 µg L^{-1} over the simulation period. Diatoms were the dominant group (maximum 7.3 µg L^{-1}) followed by chlorophytes (maximum 2.8 µg L^{-1}) and relatively low concentrations of cyanobacteria (maximum 1.2 µg L^{-1}). Chlorophyll *a* concentrations were typically highest during spring (Figure 14).

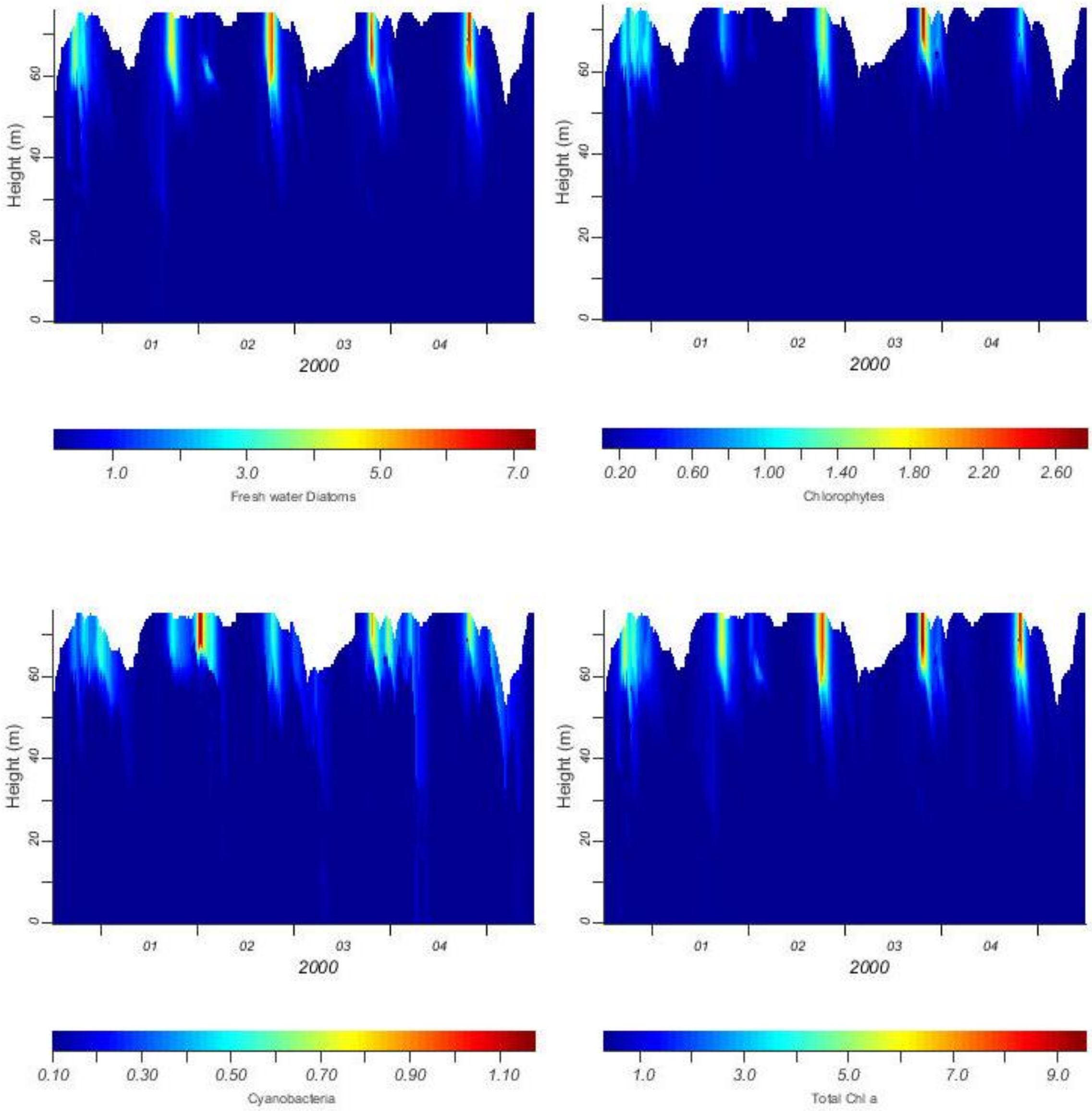


Figure 14. Simulated total chlorophyll concentrations as a sum for three generic phytoplankton groups concentrations for the period 30/06/2000 to 30/06/2005, representing diatoms, chlorophytes, cyanophytes, and total chlorophyll for all genera. Note that the colour scales are different for each plot.

3.3. Outflows

3.3.1. *Dam overflow*

Based on the supplied daily reservoir offtake volumes (Appendix 2.4), incoming water occasionally exceeded the capacity of the reservoir. On these days, water spilled over the crest of the dam, and was recorded within DYRESM as overflow (Figure 15).

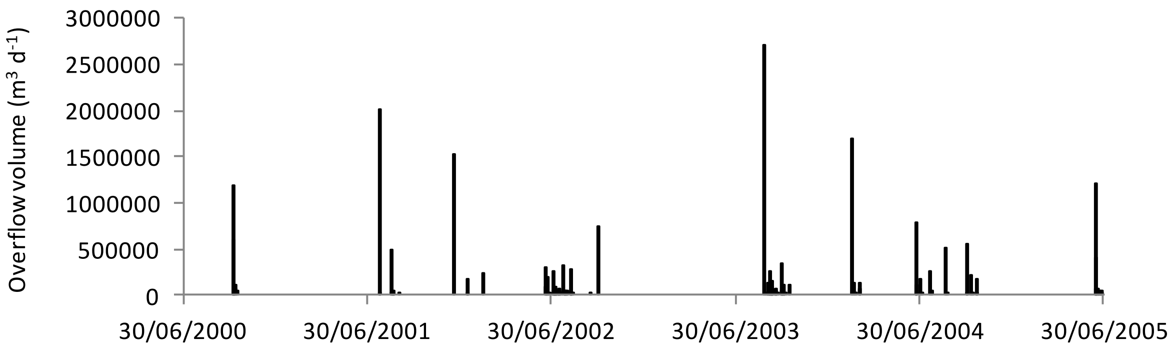


Figure 15. Daily overflow volume ($m^3 d^{-1}$).

3.3.2. *Water quality of withdrawn dam water*

Dissolved oxygen concentration in the two dam outtakes was frequently low during periods of reservoir stratification, especially at the dam toe outtake (Figures 16 & 17). Dissolved nutrient concentrations were typically low, although slightly higher at the dam toe outflow, due to release of ammonium and phosphate from reservoir sediments into bottom waters.

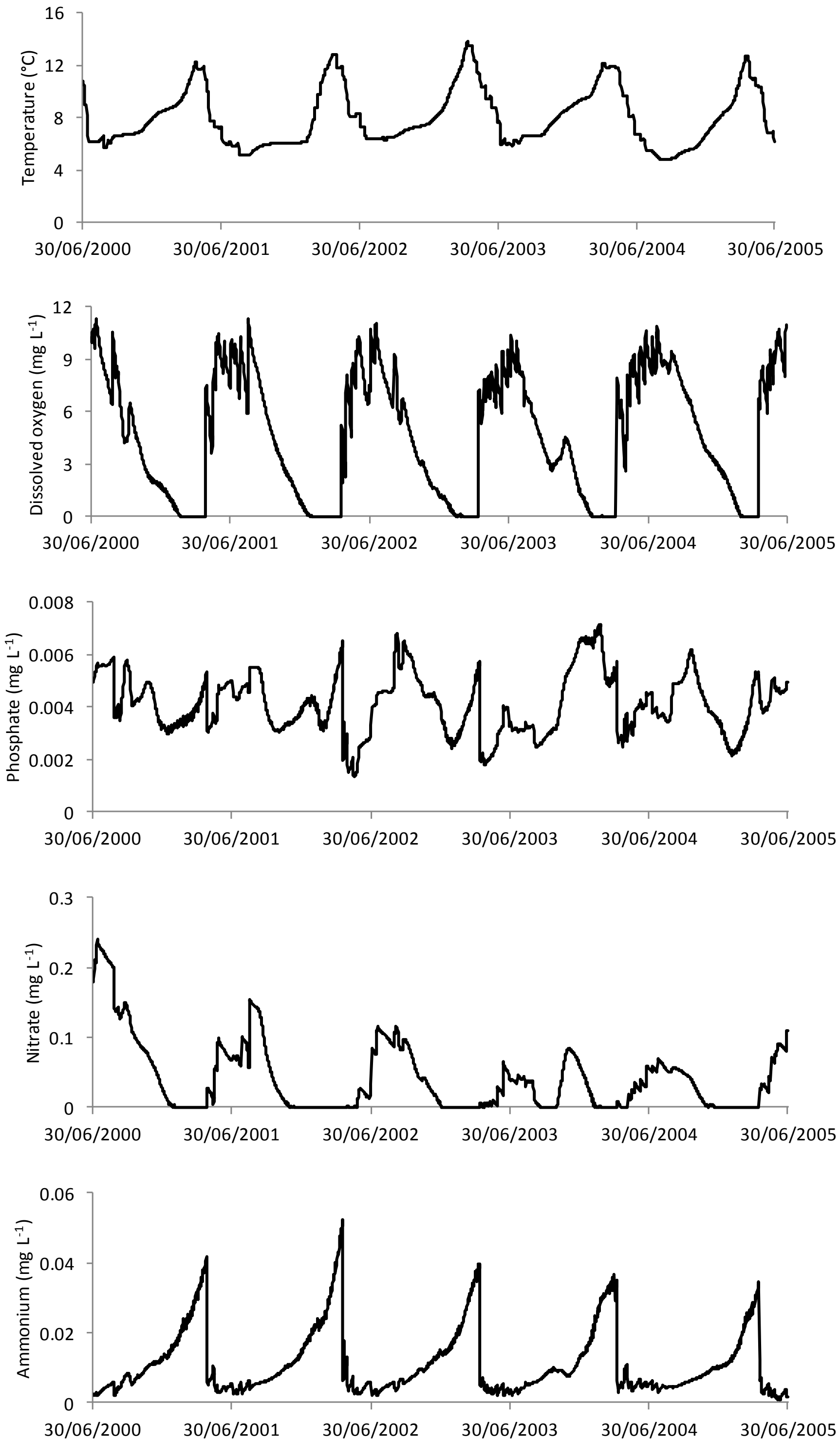


Figure 16. Simulated water quality of the dam toe outlet (elevation 395 m) for water temperature. dissolved oxygen, phosphate, nitrate, and ammonium.

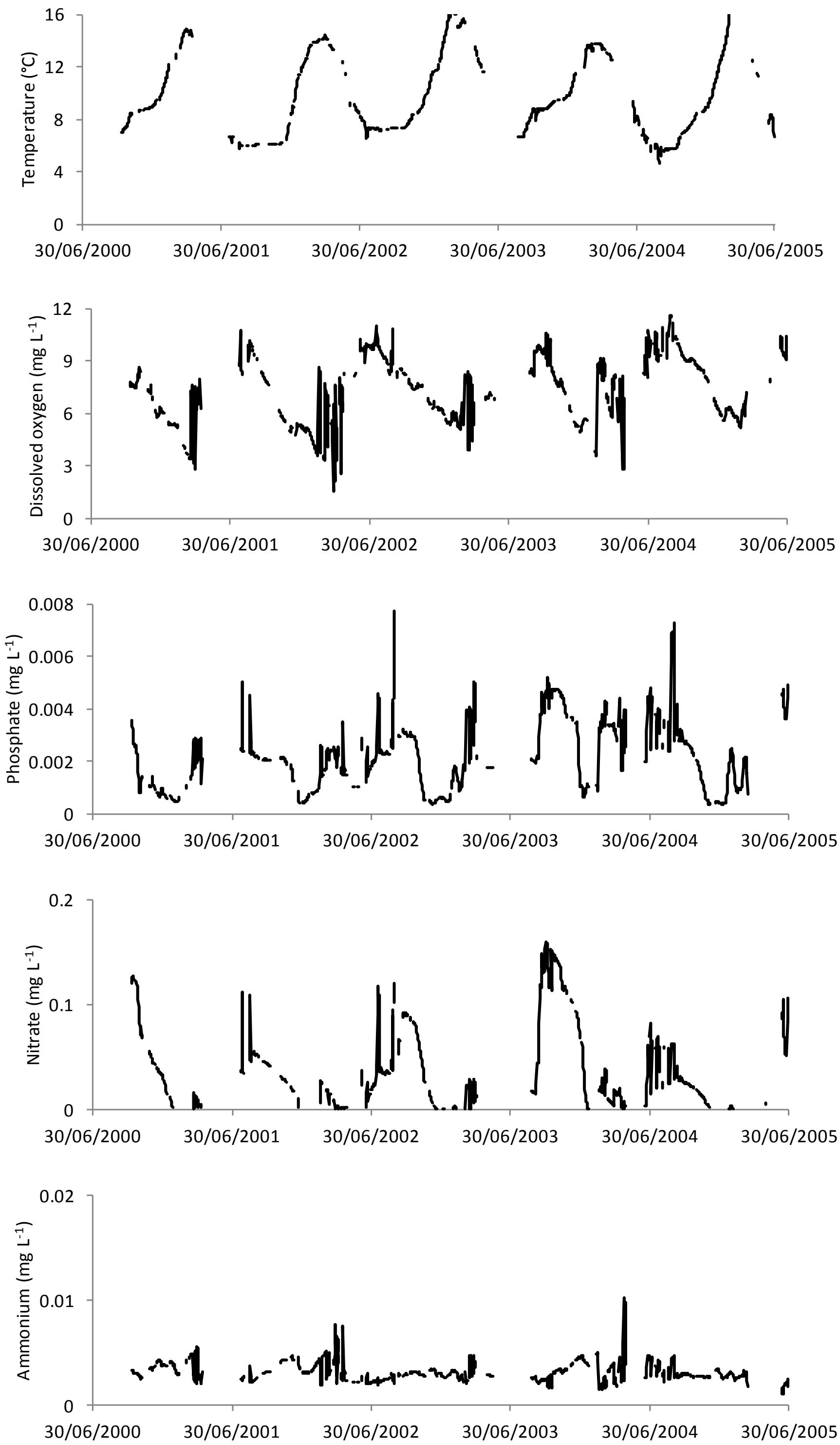


Figure 17. Simulated water quality of the main dam outlet (elevation 426 m) for water temperature. dissolved oxygen, phosphate, nitrate, and ammonium. Gaps in the lines represent days when no water is withdrawn via the main dam outflow.

3.4. Sensitivity analyses

3.4.1. *Filling time*

In order to assess potential variation in reservoir filling time according to when the reservoir construction is complete, a simulation was run with a start date of 11 January 2000. Relatively low rainfall during summer resulted in a large increase in filling time to approximately 185 days, compared with 95 days for the default start date of 30 June 2000 (Figure 17).

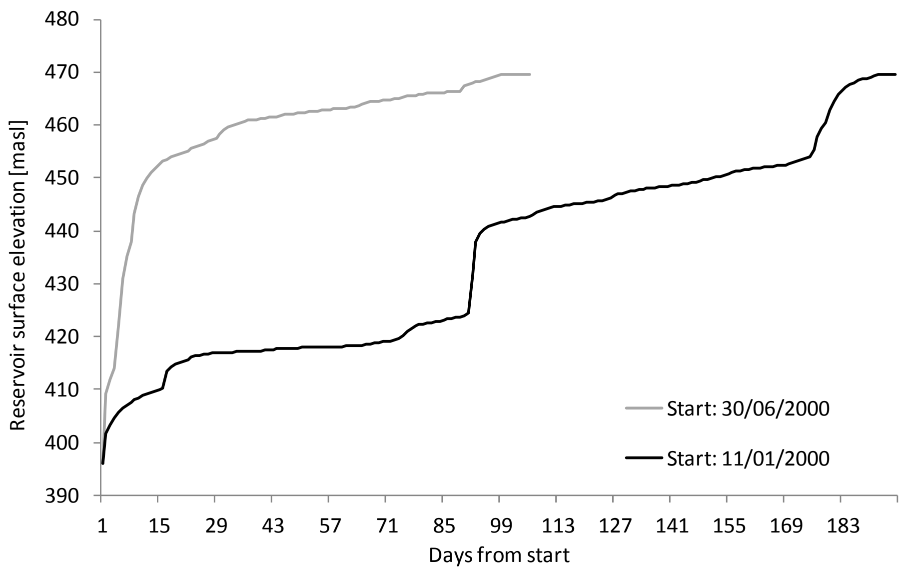


Figure 18. Comparison of water level through time for summer (11/01/2000) and winter (30/06/2000) start dates for reservoir filling.

3.4.2. *Thermal stratification*

The DYRESM parameter 'effective surface area coefficient' (ESAC) can affect the stratification dynamics within a lake or reservoir. For the baseline simulations, the effective surface area coefficient was set to the surface area of the reservoir when at full capacity (ESAC = 3.6×10^6 m^2). A further scenario was simulated, using the minimum simulated surface area of the reservoir during the 5-year baseline simulation (surface elevation = 446.6 masl, ESAC = 1.73×10^6 m^2). In the current reservoir model, very little change was observed in the water column thermal structure due to the change in the effective surface area coefficient (Figure 19).

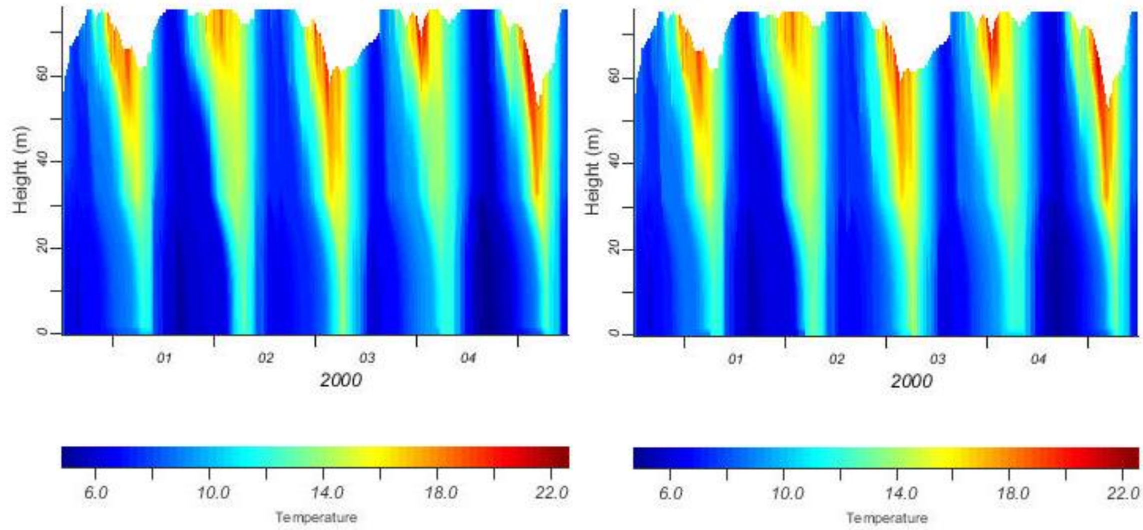


Figure 19. Sensitivity analysis for simulated water temperature over the period 30/06/2000 to 30/06/2005, using two values for the DYRESM parameter 'effective surface area co-efficient' (ESAC). (Left) baseline simulation, with ESAC representing the surface area of the reservoir when at capacity, and (Right) with ESAC equal to the surface area at the minimum water level over the simulation period.

3.4.3. *Effects of removing versus retaining vegetation within the reservoir basin; sediment oxygen demand.*

3.4.3a. *Baseline scenario*

At the elevation of the dam toe outlet, hypoxia (considered here to be DO < 2 mg L^{-1}) was observed for between 85 and 141 days annually. At the elevation of the main dam outlet, hypoxic conditions were only observed for between 1 and 8 days annually (Table 5). Despite the low number of hypoxic days at the main outlet elevation, oxygen levels well below saturation were persistent during periods of stratification (Figure 20).

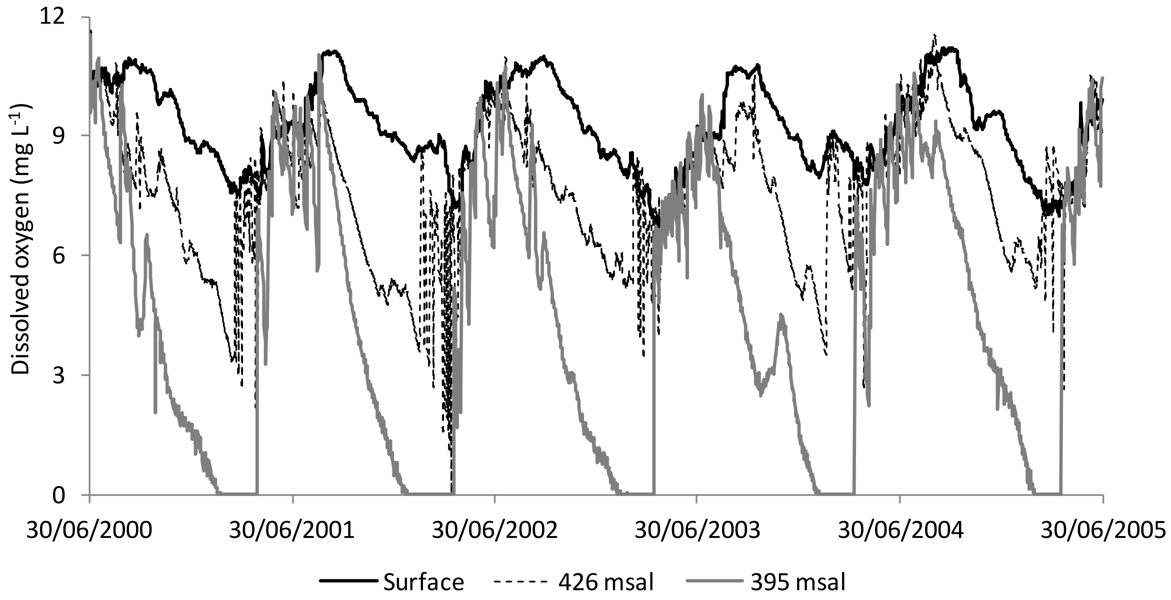


Figure 20. Simulated dissolved oxygen at the reservoir surface, and at the elevation of the two simulated dam outlets.

3.4.3b. *Modified SOD scenarios*

A 20% increase in SOD resulted in longer periods of hypoxia in bottom waters, but had only a small effect on dissolved oxygen levels at the main dam outlet. Reducing the SOD by 20% reduced by nearly half the number of hypoxic days each year in bottom waters (Table 4).

Table 4. Annual count of hypoxic days (DO < 2 mg L^{-1}) for the baseline simulation (SOD = 2.5 g m^{-2} d^{-1}) and three alternative values of sediment oxygen demand based on percentage departures from the baseline SOD.

	Baseline		SOD +10%		SOD +20%		SOD -20%	
Period	**395 masl**	**426 msal**	**395 masl**	**426 msal**	**395 masl**	**426 msal**	**395 masl**	**426 msal**
2000-2001	141	1	160	4	170	6	74	1
2001-2002	139	8	157	8	171	9	83	4
2002-2003	134	0	142	1	160	2	67	0
2003-2004	106	0	122	5	168	0	69	0
2004-2005	85	0	106	0	129	0	48	0

3.4.4. ***Removal of dam toe outflow***

Moving the daily extraction of 90% 7-day MALF from the toe of the dam to the main dam outlet after reservoir filling had dramatic effects on the physical structure of the water column. Mixing was much reduced, and the reservoir remained stratified for several years over the 5-year period. Subsequently, dissolved oxygen levels in reservoir bottom waters were more severely and persistently low (Figure 21).

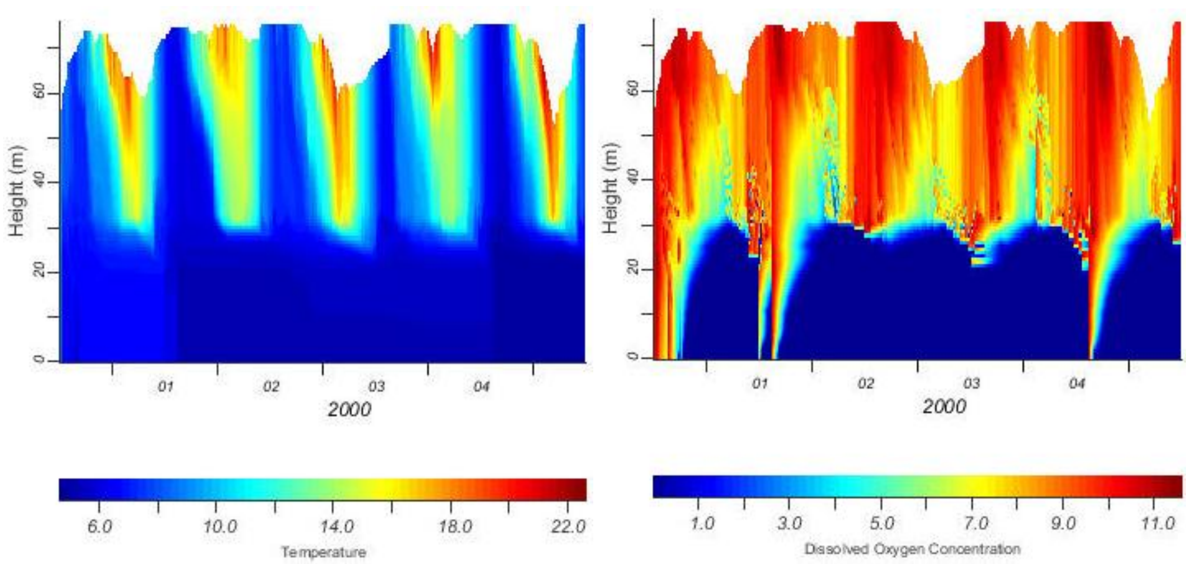


Figure 21. Simulated water temperature (°C) and dissolved oxygen (mg L^{-1}) in the Ruataniwha reservoir for a dam operation scenario without extraction of outflow from the toe of the dam.

4. Discussion

4.1. Hydrodynamics

Hydrodynamic simulations showed that the Ruataniwha Reservoir would take a relatively short time to reach full capacity (c. 95 days if filling began in winter). Filling time was shown to be strongly modified by the date chosen to begin filling but was still considerably less than one-year even when filling began in summer.

Thermal stratification plays a central role in determining water quality in reservoirs. Under the inflow and outflow regimes provided, the current model application has shown that the proposed Ruataniwha Reservoir is likely to be monomictic (i.e. one sustained period of mixing each year), with stratification periods typically about 195 days per year. During stratification, the colder hypolimnion waters of a lake tend to behave relatively independently from the warmer eplimnion, with very little exchange of heat and nutrients between these layers. Therefore, stratification is a strong influence on oxygen levels and hence nutrient concentrations in bottom waters.

A simple sensitivity analysis showed that the effective surface area coefficient (i.e. representing wind energy transfers due to catchment topography) had an insignificant influence on the thermal structure of the reservoir. By contrast, modifying the outflow regime at the dam, specifically removing the dam toe outflow (395 masl) and combining it with the main outflow (426 masl) had a dramatic effect on stratification dynamics, and actually prevented the reservoir from mixing over several years. Because stratification is one of the most important drivers of oxygen depletion in bottom waters, with flow-on effects for water quality, the outflow regime needs careful consideration, and may warrant further investigation.

4.2. Reservoir water quality

Low oxygen concentrations in the reservoir can have detrimental effects on aquatic biota, such as fish and macroinvertebrates (Kolar & Rahel 1993). Oxygen depletion in the bottom waters and/or near the sediment-water interface also has a major influence on the solubility of metal cations and associated phosphorus sorption, as well as other inorganic nutrients such as ammonium, which can be re-released from the bottom sediments into the overlying water column (Beutel 2001).

Oxygen depletion in the bottom waters of stratified lakes has been linked directly to the production of organic matter in the water column and organic matter deposited at the sediment-water interface where oxygen is largely consumed through mineralisation of particulate and dissolved organic matter by a number of microbiological pathways (Beutel et al. 2007). In the current model application it was difficult to ascertain conclusively the effects of retaining versus removing the existing vegetation within the reservoir basin on bottom water oxygen depletion rates. The sensitivity analysis of SOD, however, has shown that an increase in organic matter (i.e. carbon content) may lead to an increase in the duration of hypoxic conditions in the bottom waters, while decreased organic matter content may lead to a decrease in days of hypoxic conditions. To better understand the effects on oxygen consumption in the bottom waters of the diverse vegetation in the reservoir basin, it is recommended that measurements be made of carbon content for different vegetation types. An improved definition of the sediment oxygen demand in relation to the available organic matter and its breakdown rate would be useful to reduce uncertainty in the model simulations.

The inclusion of inorganic suspended solids in the conceptual model could not be justified because of a lack of input data from National River Water Quality Network (NRWQN) monitoring data. High suspended solids loads, however, have the potential to carry high loads of particulate nutrients to the reservoir with subsidiary effects, for example, on water column light climate and phytoplankton growth. The reservoir model in its present form may require further refinement if inorganic suspended solids were deemed necessary to include in the model application. Quantifying a site-specific relationship between turbidity and total suspended solids in the Makaroro River could enable the use of the available NRWQN turbidity data for this purpose.

The Redfield ratio of 7.2:1 by mass is often considered as a threshold indicator of TN:TP below which N is likely to limit phytoplankton growth (e.g. Downing and MacCauley 1992; Elser et al. 2007). Based on the model simulations of the proposed Ruataniwha Reservoir, the average TN:TP ratio is predicted to be below this threshold for the majority of the simulation period, with an average of 3.97, indicating that phytoplankton in the reservoir may often be N-limited. The low TN:TP ratio can mostly be attributed to relatively low TN concentration in the Makaroro inflow, but is exacerbated by occasional high TP loads, for example, associated with sustained high rainfall as for the period 2003 to 2004. Also, linear interpolation of monthly inflow nutrient measurements may have exaggerated the duration of high P-load events.

Periods of N-limitation could potentially promote dominance of N-fixing cyanobacteria (Smith, 1983; Schindler et al., 2008) potentially resulting in proliferation of cyanobacteria, especially when there are high levels of P, as was the case in the Ruataniwha Reservoir simulations for the period 2003 to 2004. The conceptual model of the Ruataniwha Reservoir included cyanobacteria only as a generic phytoplankton group and was not assigned an N-fixation function, which is difficult to parameterise. Ecosystem models, including CAEDYM, cannot predict ecosystem changes that may occur due to the introduction of a new species such as N-fixing cyanobacteria species (e.g. *Anabaena planktonica*) which have been observed to form mono-specific blooms. Furthermore, cyanobacteria were assigned neutral buoyancy in the present simulations. The potential for blooms of cyanobacteria may be further increased by the presence of persistently buoyant species. Despite the shortcomings of this conceptual simplification, the model simulations have shown the potential for moderate concentrations of cyanobacteria to occur in Ruataniwha Reservoir during stratification when surface waters are warmer.

4.3. Downstream water quality

Outlet depths can have obvious effects on the hydrodynamics and thermal structure of reservoirs. For example, a deep water withdrawal results in replacement of deep water in the hypolimnion with warmer water from above the outlet depth, and thus facilitates weakening of the strength of stratification (Ma et al. 2008). By contrast, the sensitivity analysis on the effect of outflow heights on stratification and water quality in the current model application has shown that the thermocline could be shallower when the outflow height is closer to the surface. This could also result in a larger volume of hypoxic and nutrient-rich hypolimnetic water.

Removing hypolimnetic water from the reservoir could have a beneficial outcome for the reservoir water quality by removing water that is depleted in oxygen and the associated nutrient-rich water which would have otherwise been mixed into surface waters following the breakdown of stratification. As shown in this modelling application, however, removing hypolimnetic waters can have unfavourable effects on the river water quality downstream. There is an opportunity to more carefully optimise the balance of outflow water quality and reservoir water quality by carefully adjusting the balance of discharges in the outflows. For this purpose it may be worthwhile considering assigning water quality limits for the reservoir and discharge, and running model simulations that balanced the limit-based approach.

4.4. Recommendations

Based on model simulations, finding a balance between acceptable water quality in the dam outflow and maintaining a beneficial thermal regime within the reservoir may prove difficult. A more detailed modelling investigation of a variety of possible inflow volumes, irrigation schemes, and outtake extraction heights, could help to inform these decisions.

Because carbon content of the reservoir basin will influence oxygen depletion in bottom waters, a more comprehensive estimation of aerial average carbon/biomass contained within the vegetation cover of the reservoir basin could help reduce this uncertainty. A consideration of the labile component of this organic matter, based on small-scale measurements of underwater oxygen depletion rates, may assist with important decisions relating to the scale of vegetation removal. Outflow water from the reservoir is frequently low in dissolved oxygen, therefore, ensuring adequate aeration of extracted water may be desirable for downstream water quality. Nutrient status of extracted water may be variable, and comprehensive monitoring of river quality downstream of the dam will be essential.

Process-based models such as DYRESM-CAEDYM are an excellent tool for assessing potential hydrodynamics and water quality in theoretical ecosystems. However, because of the impossibility of empirical observations with which to calibrate the model, and to quantify model error in order to ensure a high degree of accuracy, there is a relatively high degree of uncertainty in the model output. It will be essential, once the dam is constructed and filled, that comprehensive and regular water quality monitoring is undertaken, in order to ensure the health of the Ruataniwha Reservoir, as well as downstream water quality in the Makaroro River. Repeated applications of the model would likely help to guide and refine a monitoring program.

5. Conclusions

The DYRESM-CAEDYM simulations presented here highlight important issues regarding water quality of the proposed Ruataniwha Reservoir. While overall water quality is like to be good-to-fair, an often low TN:TP ratio indicates a potential for nitrogen-fixing cyanobacteria to be a substantial component of the phytoplankton assemblage and for blooms to occur if phosphorus concentrations are not managed carefully from the reservoir catchment.

Deviations from the flow regime provided for this study may have significant consequences for water quality. Careful attention should be paid to the effects of outflow regime on stratification dynamics, due to the cascading effects of extended stratification, oxygen depletion, and subsequent nutrient release that can drive algal growth. Furthermore, the reservoir will ultimately determine downstream water quality, and the height of outflow extraction will strongly influence the oxygen and nutrient status of the Makaroro River downstream of the dam. Striking a balance between downstream water quality and maintaining regular turnover of the reservoir water column may prove a difficult task, and further modelling could aid with the optimisation of the outflow regime.

6. References

Benson B.B. & D. Krause Jr., 1980. The concentration and isotopic fractionation of gases dissolved in freshwater in equilibrium with the atmosphere. Limnology and Oceanography 25: 662-671.

Bruce L.C, Hamilton D., Imberger J., Gal G., Gophen M., Zohary T. & K.D. Hambright, 2006. A numerical simulation of the role of zooplankton in C, N and P cycling in Lake Kinneret, Israel. Ecological Modelling 193: 412-436.

Burger D.F, Hamilton D.P. & C. Pilditch, 2007. Modelling the relative importance of internal and external nutrient loads on water column nutrient concentrations and phytoplankton biomass in a shallow polymictic lake. Ecological Modelling 211: 411-423.

Burns, N.M., Rutherford, J.C.; Clayton, J.S., 1999. A monitoring and classification system for New Zealand lakes and reservoirs. Journal of Lakes Research & Management 15(4): 255-271.

Downing J.A., McCauley E., 1992. The nitrogen:phosphorus relationship in lakes. Limnology and Oceanography 37(5): 936-945.

Gal G., Hipsey M.R., Parparov A., Wagner U., Makler V. & T. Zohary, 2009. Implementation of ecological modelling as an effective management and investigation tool: Lake Kinneret as a case study. Ecological Modelling 220: 1697-1718.

Hamilton D.P., 2005. Land use impacts on nutrient export in the Central Volcanic Plateau, North Island. New Zealand Journal of Forestry 49: 27-31.

Ma S., Kassinos S.C., Kassinos D.F. & E. Akylas, 2008. Effects of selective water withdrawal schemes on thermal stratification in Kouris Dam in Cyprus. Lakes & Reservoirs: Research and Management 13: 51-61.

Mohseni O., Stefan H.G. & T.R. Erickson, 1998. A nonlinear regression model for weekly stream temperatures. Water Resources Research 34: 2685-2692.

Mortimer C.H., 1981. The oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. Balogh Scientific Books, ISBN 978-3-510-52022-0, 23p.

Özkundakci D., Hamilton D.P. & D. Trolle, 2011. Modelling the response of a highly eutrophic lake to reductions in external and internal nutrient loading. New Zealand Journal of Marine and Freshwater Research 45: 165-185.

Redfield A.C., 1958. The biological control of chemical factors in the environment. American Scientist 46: 205-221.

Schladow S.G., Hamilton D.P., 1997. Prediction of water quality in lakes and reservoirs: Part II: Model calibration, sensitivity analysis and application. Ecological Modelling 96:111-123.

Schmidt M. & H. Lipson,2009. Distilling free-form natural laws from experimental data. Science 324(5923): 81-85.

Tonkin & Taylor, 2009. Prefeasibility Study of Water Augmentation Opportunities - Ruataniwha Plains. Report prepared for the Hawke's Bay Regional Council, T&T Ref: 25916.000, 35p.

Trolle D., Hamilton D.P., Pilditch C.A. & I.C. Duggan, 2011. Predicting the effects of climate change on trophic status of three morphologically varying lakes: Implications for lake restoration and management. Environmental Modelling & Software 26: 354-370.

Trolle D., Skovgaard H. & E. Jeppesen, 2008. The Water Framework Directive: Setting the phosphorus loading target for a deep lake in Denmark using the 1D lake ecosystem model DYRESM-CAEDYM. Ecological Modelling 219:138-804.

Tennesse Valley Authority, 1972. Tennesse Valley Authority, heat and mass transfer between a water surface and the atmosphere. TVA Reprot 0–6803, Norris, TN.

White E., Law K., Payne G. & S. Pickmere, 1985. Nutrient demand and availability among planktonic communities - an attempt to assess nutrient limitation to plant growth in 12 central volcanic plateau lakes. New Zealand Journal of Marine and Freshwater Research 19:49–62.

7. Appendices

See attached CD for the following appendices in electronic form:

7.1. Appendix 1. Source files: NIWA

7.1.1. *Virtual climate data*

7.1.2. *Dannevirke (D06212) climate data*

7.1.3. *Takapau Plains (D06024) climate data*

7.1.4. *NRWQN data: Makaroro at Burnt Bridge*

7.2. Appendix 2. Source files: Tonkin & Taylor

7.2.1. *Map of proposed Ruataniwha reservoir*

7.2.2. *Reservoir bathymetry and storage*

7.2.3. *Dam wall design*

7.2.4. *Daily reservoir inflow and outflow*

7.2.5. *Extract from report on compensation flows*

7.2.6. *Memo on production of synthetic flow record*

7.2.7. *Land use data and soil chemistry*

7.3. Appendix 3. DYRESM-CAEDYM parameter and input files

7.3.1. *DYRESM files (hydrodynamics)*

7.3.2. *CAEDYM files (ecology)*

MEMO

TO: Max Gibbs (NIWA)

FROM: Chris McBride (Limnotrack)

DATE: 06/01/2012

SUBJECT: DYRESM-CAEDYM simulations of alternative offtake regimes for Ruataniwha Reservoir at dam wall.

Introduction

Model simulations of hydrodynamics and water quality have previously been applied for the proposed Ruataniwha Reservoir in the Hawke's Bay Region, using the coupled model DYRESM-CAEDYM (Center for Water Research, Australia). McBride et al. (2011) provide a comprehensive summary of the model development, parameterisation and simulation results. One recommendation of McBride et al. (2011) was to pursue further analysis of alternative dam wall offtake elevations. This document describes modelling results for three such additional scenarios.

Methods

The present dam design (Appendix 1) has an upper offtake at 443 masl, and a lower offtake consisting of a box structure with trashracks and an internal lift gate at about 400 masl. Lower levels of the offtake box can be blocked off as required, for example to reduce sediment load in the extracted water. Because offtake elevation in DYRESM is fixed, for the scenarios presented, an elevation of 405 masl was specified for the lower offtake, as a suitable compromise (Max Gibbs, *pers. comm.*).

Table 1 shows offtake elevations (reservoir bottom elevation = 394 masl) for the two scenarios in McBride et al. (2011), as well as the three scenarios simulated for the present document. All scenarios were simulated for the five-year period 30-June-2000 to 30-June-2005. For scenario M1, all water (Tonkin & Taylor Makororo Scenario 16, see McBride et al., 2011) was extracted from the lower offtake at 405 masl. For scenario M2, all water was extracted from the upper offtake, at 443 masl as per Appendix 1. For scenario M3, a minimum baseflow (equal to 90% of 7-day mean annual low flow (7-day MALF), see McBride et al. 2011) was extracted from the lower offtake, and the remainder was extracted from the upper offtake.

Table 1. Water extraction from offtake elevations for two previously simulated scenarios from McBride et. al (2011) ('Baseline' and 'Sensitivity analysis'), and the three scenarios of the present document. Grey areas represent offtake elevations not included in the dam design on which the model scenario was based.

Elevation	Scenario				
(masl)	Baseline (days)	Sensitivity analysis (days)	M1 (days)	M2 (days)	M3 (days)
395	1 - 1825*	1 - 90*			
405			3 - 90* 91 - 1825**	3 - 90*	3 - 1825*
426	91 - 1825***	91 - 1825**			
443			-	91 - 1825**	91 - 1825***
455	-	-			

*Compensation flow (90% of 7-day MALF = 106099.2 m^3 d^{-1})

**Tonkin & Taylor Makoro Scenario 16

***Tonkin & Taylor Makoro Scenario 16 minus compensation flow

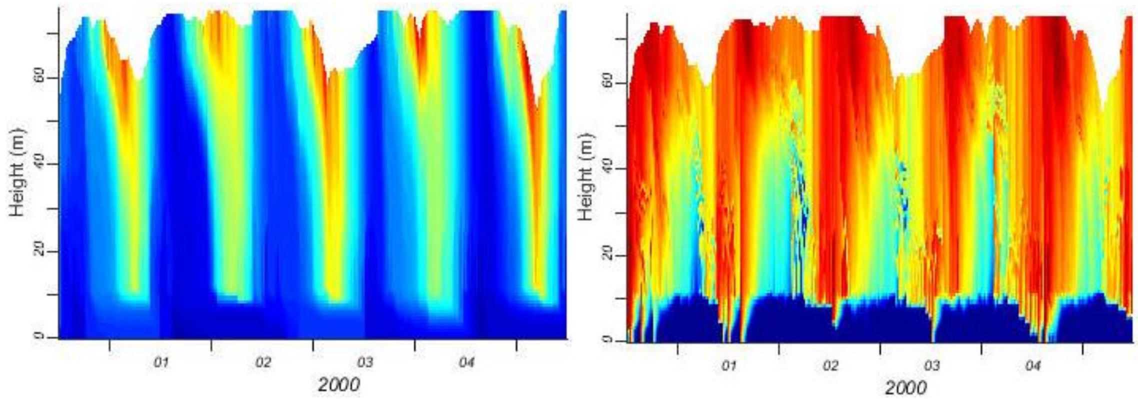
Results

Withdrawing all outflow water from the lower offtake (Scenario M1) resulted in a deep thermocline with a small volume of water below the thermocline (i.e., hypolimnion water). Oxygen depletion was observed below the offtake elevation, with sustained hypoxia (i.e. < 2 mg O_2 L^{-1}) between 2001 and 2003, when the water column was not mixed fully (Figure 1). Plots of simulated water quality in Scenario M1 are presented in Figure 2. Nutrient and chlorophyll *a* levels were generally comparable to those of the baseline scenario presented in McBride et al. (2011), however, build-up of ammonium and phosphate in the dead storage zone (i.e. < 405 masl) was increased due to reduced mixing of bottom waters relative to the baseline scenario.

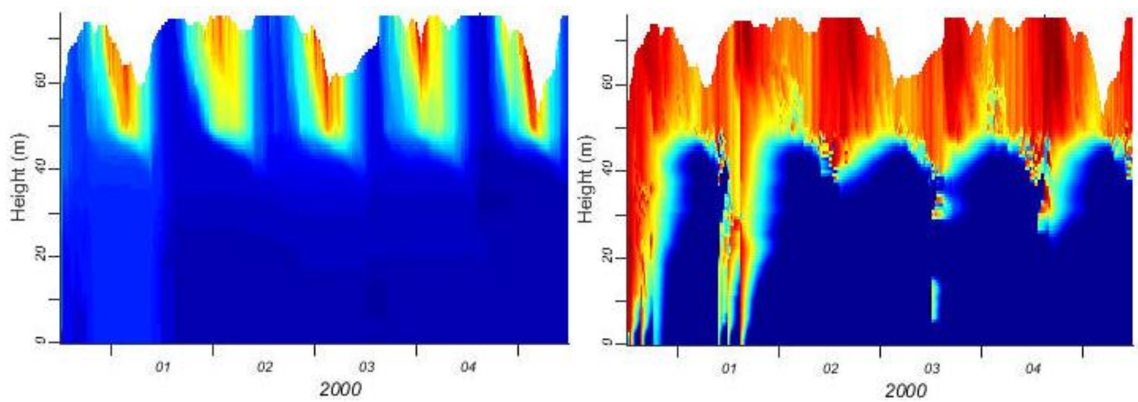
Withdrawing all water from 443 masl (Scenario M2) resulted in drastically reduced reservoir mixing, persistent hypoxia through more than half the water column depth, and poorer water quality relative to the baseline scenario presented in McBride et al. (2011).

Withdrawing a baseflow from a level of 405 masl, and the remainder of Scenario 16 offtake flow from 443 masl (Scenario M3) resulted in greater mixing relative to Scenario M2, and slightly less than Scenario M1 (Figure 1). However, because most offtake water in Scenario M3 would be withdrawn much higher in the water column, offtake water quality may at times be better than for Scenario M1 (see example; Figure 4).

Scenario M1



Scenario M2



Scenario M3

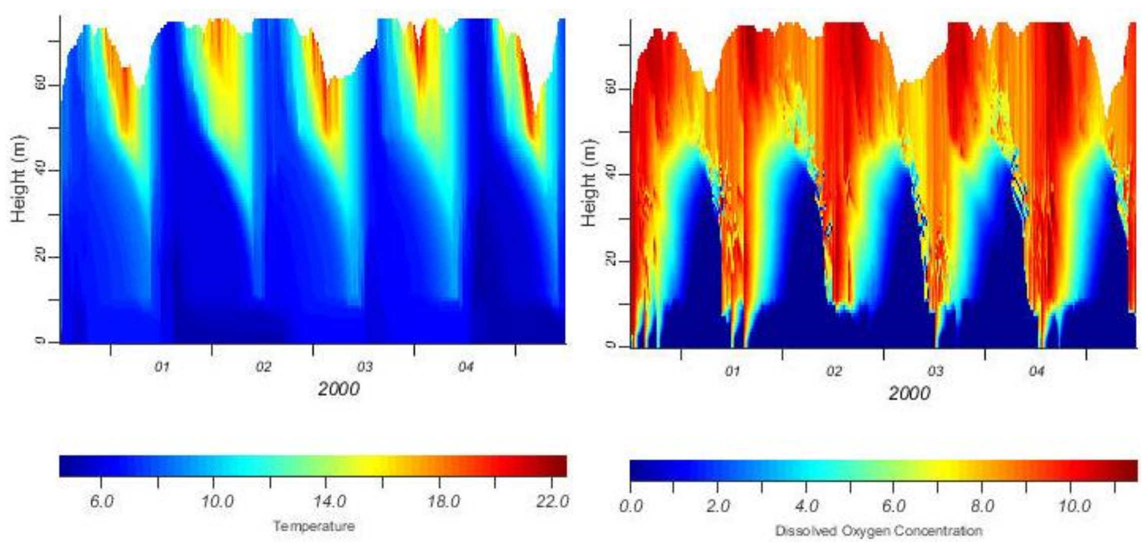


Figure 1. Simulated temperature (ºC; left) and dissolved oxygen (mg L^{-1}; right) for the period 30-06-2000 to 30-06-2005, for three scenarios (M1, M2 and M3) of offtake water extraction. Details of each scenario can be found in Table 1.

Scenario M1

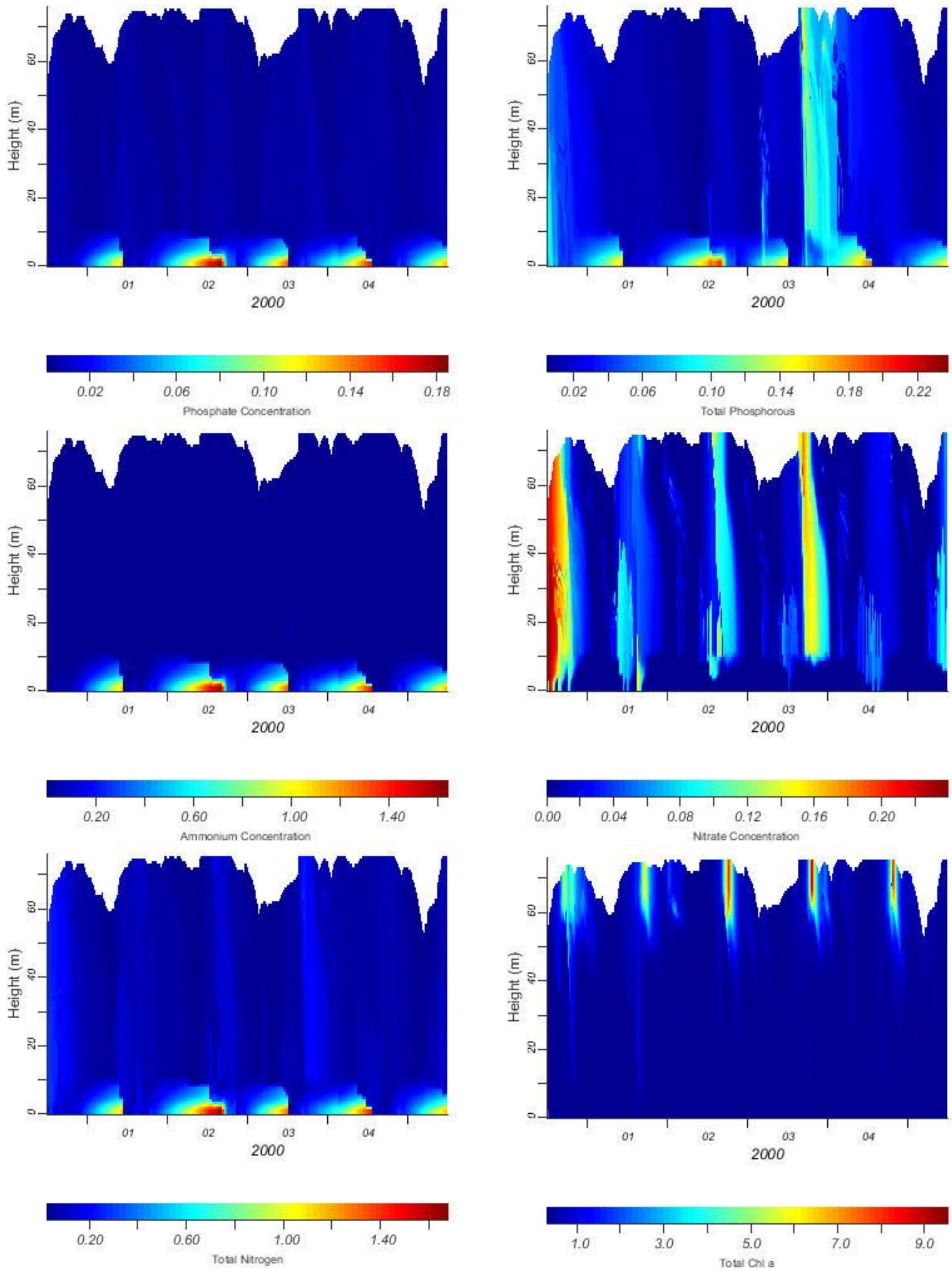


Figure 2. Simulated nutrient concentrations (mg L^{-1}) of phosphate, total phosphorus, ammonium, nitrate, total nitrogen and total chlorophyll *a* concentrations (µg L^{-1}) for the period 30/06/2000 to 30/06/2005, for scenario M1. Note that the colour scales are different for each plot.

Scenario M3

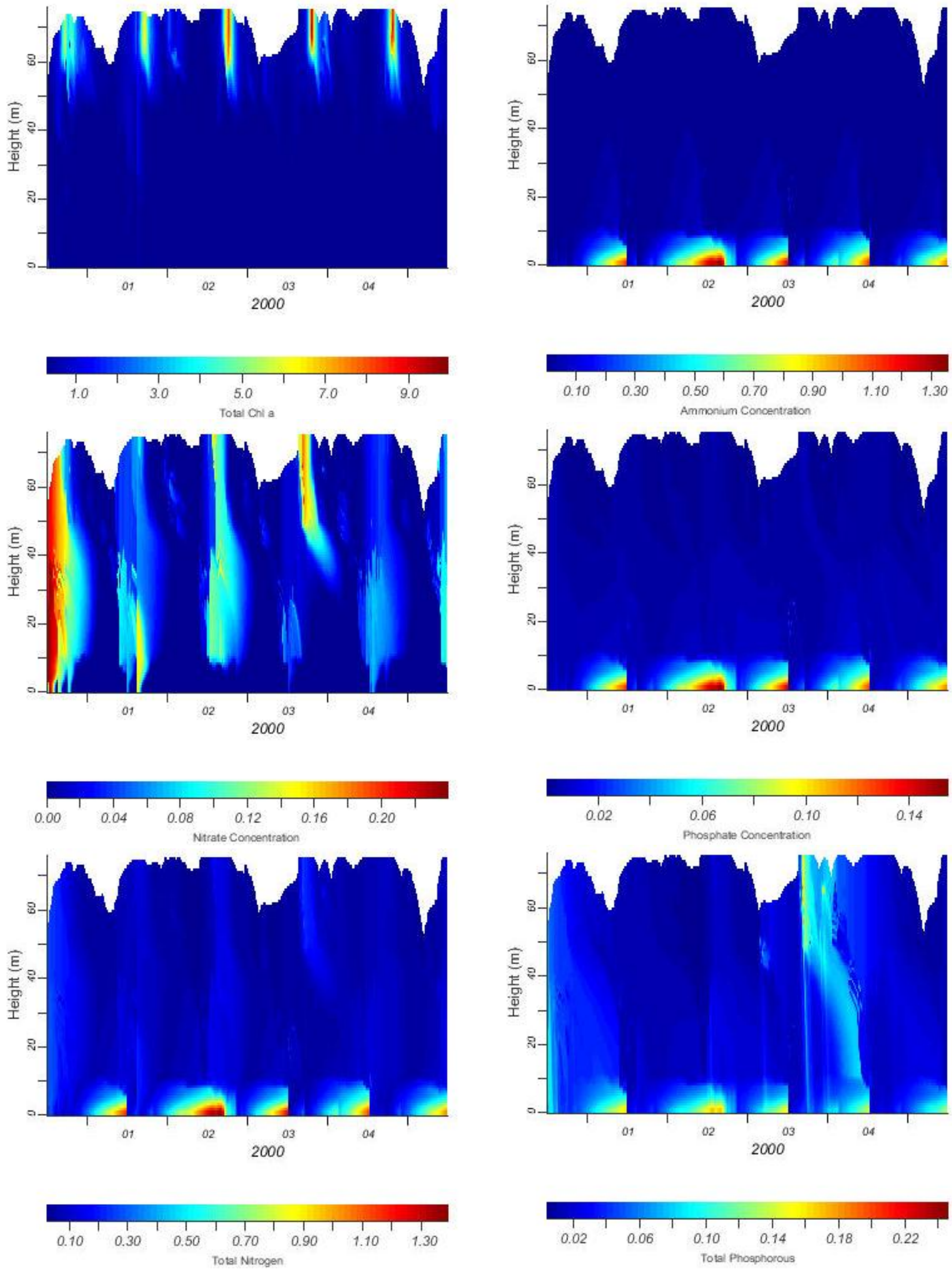


Figure 3. Simulated nutrient concentrations (mg L^{-1}) of phosphate, total phosphorus, ammonium, nitrate, total nitrogen and total chlorophyll *a* concentrations (µg L^{-1}) for the period 30/06/2000 to 30/06/2005, for scenario M3. Note that the colour scales are different for each plot.

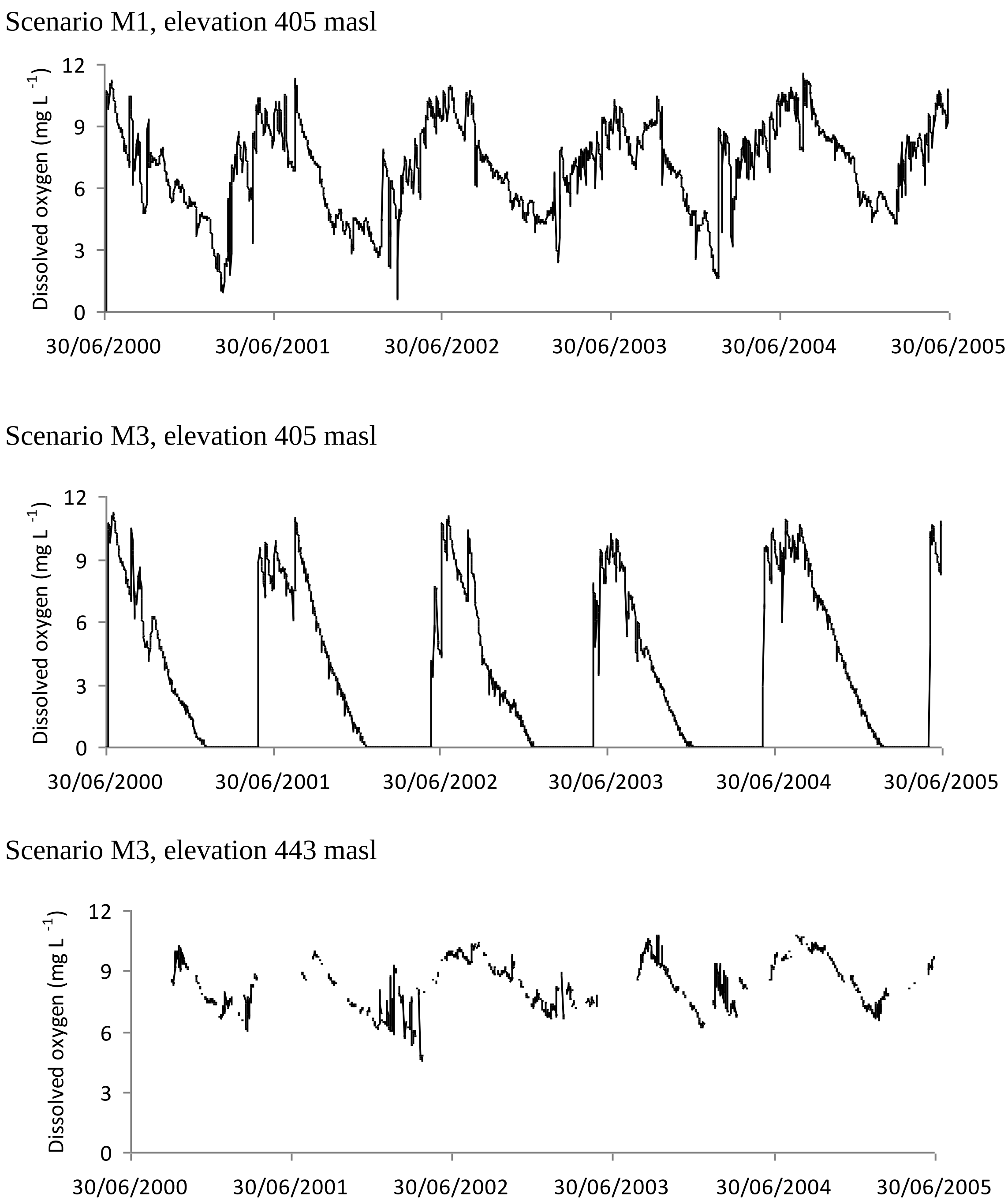


Figure 4. Simulated dissolved oxygen concentrations (mg L^{-1}) in extracted water at 405 masl for scenario M1, and 405 masl and 443 masl for scenario M3.

Conclusions

In the absence of a baseflow extraction at or near the very foot of the dam, it appears that the proposed Ruataniwha Reservoir would be at some risk of not consistently attaining complete water column turnover on a yearly basis. Scenario M1 resulted in the most favourable reservoir water quality, however, under all scenarios there appeared to be potential for offtake water quality with low dissolved oxygen and elevated nutrient concentrations, particularly prior to winter mixing. It is likely that some form of aeration immediately below the offtake, using the gravitational head of the water being extracted, would be valuable to raise levels of dissolved oxygen and decrease the likelihood of elevated levels of reduced metal cations such as iron II and manganese II and III. Extracting most water from the upper offtake would possibly improve downstream water quality, however, if the upper offtake is to be used, it may be necessary to withdraw the 7-day MALF (at least) from the lower offtake every day, in order to improve water quality in the reservoir itself by increasing the likelihood of water column mixing within each year and reducing the proportion of the water column that is deoxygenated. Increasing the flow at the lower offtake may further improve mixing and water quality in the reservoir; additional modelling would be valuable to refine the depth, timing and operational regime used for this type of deep offtake.

References

McBride C.G., Özkundakci D., & Hamilton D.P. 2011. DYRESM-CAEDYM modelling of proposed Ruataniwha Reservoir. Limnotrack Client Report, New Zealand.

Appendix 1

Present dam design. Refer to the file “Intake Arrangement.pdf”