# Guidelines for Artificial Lakes

## Before construction, maintenance of new lakes and rehabilitation of degraded lakes

## Prepared for Ministry of Building, Innovation and Employment

October 2012

**Authors/Contributors:**

Max Gibbs
Chris Hickey

**For any information regarding this report please contact:**

Max Gibbs
Limnologist and Environmental Chemist
Aquatic Ecology
+64-7-856 1773
max.gibbs@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

| | |
|---|---|
| NIWA Client Report No: | HAM2011-045 |
| Report date: | October 2012 |
| NIWA Project: | ELF11243 |

Cover Photo: Lower Nihotupu reservoir in the Waitakere Ranges, Auckland. [Photo by Max Gibbs]

# Contents

Reviewed by:

**Professor David Hamilton**
University of Waikato

**Dr Marc Schallenburg**
University of Otago

Formatting checked by
AB

Approved for release by:

**Dr David Roper**
Regional Manager
NIWA, Hamilton

# Executive summary

By installing a dam on a stream or river to retain water, the hydraulic regime is changed and a new set of conditions develop in the still waters of the resultant artificial lake. These conditions are usually predictable in general terms such that it is possible to design an artificial lake with minimal the risk of it having poor water quality or major environmental issues.

Throughout New Zealand there are many hundreds of man-made (artificial) lakes that have been built for a range of purposes including water harvesting under flood conditions for water supplies and irrigation, off-stream storage for irrigation, on-stream storage for urban water supplies, hydropower generation, and aesthetically pleasing water features in parks and urban developments. These artificial lakes may have high water quality when first filled but gradually the water quality declines as they are affected by nutrient enrichment from their catchment or a flaw in their design or management produces unexpected problems.

The purpose of the Guidelines for Artificial Lakes (the Guidelines) is to provide a repository of information about lakes, the limnological processes that affect their water quality and practical design considerations for avoiding pitfalls that could result in a degraded lake. The Guidelines also provide a range of management strategies required to produce the highest adequate lake water quality in the new lake and how to improve water quality in existing degraded artificial lakes. Many of the restoration measures suggested may also apply to natural lakes.

Constructing an artificial lake is a change in land use and therefore is covered by a range of legislation and rules. These Guidelines include a practical and easy-to-use guidance to all parties involved in the resource consent process for artificial lakes including dams and associated activities (e.g., water takes, discharges and diversions) under the Resource Management Act 1991 (RMA). As the Guidelines are intended for artificial lakes with a surface area of greater than 1 ha, the proposed artificial lake requires permitting under the Building Act 2004 and may require certification under the Building (Dam Safety) Act 2008 and the 2014 amendments.

Apart from the national legislation, the construction of an artificial lake is subject to the local active Regional Plan which will determine whether the lake is a permitted, discretionary, non-complying or prohibited activity in the region covered by the plan. The suitability of the land for the artificial lake, both geologically (proximity to fault lines) and in terms of landfills and waste dumps, should also be part of those considerations. The rules in the Regional Plan will then define the conditions of the resource consent that are applied to the artificial lake.

The consenting process should also be about responsibility including specifying who will manage or remove the artificial lake should it become degraded or no longer be needed. The consenting process should recognise the biosecurity risk associated with constructing an artificial lake where pest fish and aquatic plants and algae may proliferate and be transferred to other unaffected water bodies.

The Guidelines were written for both the applicant, who is required to prepare consent applications and assessments of environmental effects (AEE) for the construction of a new artificial lake, and for the council staff who have to audit and assess consent applications and develop consent conditions and monitoring plans. The Guidelines will also be of use to interested and/or affected parties who want to be involved in the consent approval process.

# 1 Introduction

**Definition:** An artificial lake is a body of freshwater greater than 1 ha in area created by human intervention in a location where a lake would not naturally exist.

There are a large number of lakes and ponds throughout New Zealand that have been created or modified by installing structures that impede the natural flow of water. These are artificial lakes. Their shapes (morphometry) and sizes are highly variable with no two artificial lakes being the same. The changing of its physical characteristics from freely flowing to static affects the quality of the water and all aspects of the environment that depend on that water. These effects occur within the artificial lake as well as within the river/stream bed and the groundwater field below the lake. Apart from water quality, there are issues of public safety around the stability of the retaining structures (dams/weirs/bunds) in adverse conditions (catastrophic failure) and the hazards posed by changing water levels and hydrodynamics both in the lake and downstream due to the operation of a dam.

There are comprehensive guidelines for dams (Foster et al. 2000; MfE, 2000) but there is currently no national guidance document to assist both developers and consenting authorities to identify potential water quality issues prior to and following the development of an artificial lake. Many of these issues, including the risks of catastrophic failure, are addressed in the guidelines for dams. However, those guidelines are not focused on the issues associated with artificial lakes which include recreational lakes and subdivision/golf course “water features”, filled disused gravel or opencast mining pits and irrigation water storage reservoirs. A number of problems can arise including water quality deterioration, algal blooms and proliferation of undesirable organisms including macrophytes and pest fish. These problems are not always foreseen by developers, or by local and regional authorities who authorise all or part of the development. *A posteriori* remediation of these problems is generally technically difficult and/or expensive.

To fill this gap, the Surface Water Integrated Management (SWIM) group meeting in 2008 proposed an Envirolink Tools project entitled “Guidelines for Artificial Lakes”. The project was approved by the Foundation for Research Science and Technology, now the Ministry of Business, Innovation and Employment (MBIE), in June 2010.

The “Guidelines for Artificial Lakes” document, hereafter referred to as “the Guidelines”, is intended to provide practical options or solutions to avoid, remedy or mitigate the potential issues associated with impounding water. In this respect the Guidelines provides a toolbox that brings together the pool of experience and knowledge available nationally and internationally on the best management practices/guidelines for the development and maintenance of the quality of artificial lakes.

## 1.1 Purpose of these Guidelines

The purpose of the Guidelines is to provide a repository of information about lakes, the processes that affect their water quality and practical design considerations for avoiding pitfalls that would result in a degraded lake. The Guidelines also provide a range of management strategies required to produce the highest possible lake water quality in the new lake and how to improve water quality in existing degraded artificial lakes.

Constructing an artificial lake is a change in land use and therefore is covered by a range of legislation and rules. These Guidelines include a practical and easy-to-use guidance for parties involved in the resource consent process for artificial lakes including dams and associated activities (e.g., water takes, discharges and diversions) under the Resource Management Act 1991 (RMA) and planning controls under Regional Plans that prescribe whether the development of an artificial lake is a:

- **Permitted activity**: No resource consent required.
- **Controlled activity**: Consent required but always granted.
- **Restricted discretionary activity**: Resource consent required.
- **Discretionary activity**: Resource consent required.
- **Non-complying activity**: Resource consent required.
- **Prohibited activity**: No resource consent will be granted.

The Guidelines were written for both the applicant, who is required to prepare consent applications and assessments of environmental effects for the construction of a new artificial lake, and for the council staff who have to audit and assess consent applications and develop consent conditions and monitoring plans. The Guidelines will also be of use to interested and/or affected parties who want to be involved in the approval processes.

The guidelines for dams (Foster et al. 2000) were produced in response to a need for a better understanding of how dams and dam safety issues should be addressed in the resource consent process. Dam design, construction, and operation are specialist fields and it is not common for councils in New Zealand to retain this sort of expertise in-house.

The guidelines for artificial lakes were produced in response to a need for a better understanding of how water quality and water quality management issues should be addressed in the planning and resource consent process. As with dam design, construction and operation, water quality management, monitoring and mitigation are specialist fields that councils may not have readily available in-house.

There are many water quality issues that are covered in a wide range of textbooks and scientific papers. It is the intension of the Guidelines to provide a summary of the relevant information in one place as a first stop for understanding the processes that occur in water when it is impounded in an artificial lake. For those wanting further information or details of specific issues, that information can be found in books such as the original Lake Managers Handbook (Vant 1987) and subsequent 2002 revision available on the Ministry for the Environment web site in four parts as Lake Manager’s Handbook: Fish in New Zealand Lakes; Alien Invaders; Land-Water Interactions; and Lake Level Management. Further information on New Zealand lakes can be found in books such as “Inland Waters of New

Zealand” (Viner 1987) and “Freshwaters of New Zealand” (Harding et al. 2004), and on lakes in general in textbooks such as “Limnology” (Wetzel, 1975).

Pre-empting water quality issues through good design is more important than mitigating major environmental issues. Notwithstanding this, these guidelines include management strategies to rehabilitate existing degraded lakes to improve their water quality and mitigate the flow-on effects to the downstream environment.

Of necessity, there is a strong overlap between the guidelines for dams and the guidelines for artificial lakes and information from the guidelines for dams has been included in the guidelines for artificial lakes where reproduction of that information is important for clarity rather than just referring to the former document.

In summary these guidelines have the following objectives:

- To provide a background understanding of key processes that occur in a lake and how to design an artificial lake to avoid an ecological disaster and to minimise off-site issues.
- To provide practical information on monitoring and management strategies required to maintain high water quality in the new lake and other existing lakes.
- To provide guidance on remedial actions that could be used to rehabilitate an existing degraded lake.
- To provide guidance on the environmental, legislative, cultural and safety issues that need to be considered when planning the development of an artificial lake.

Environmental issues covered in the Guidelines are applicable to the design of all artificial lake systems.

## 1.2 Limitations of these Guidelines

As no two artificial lake projects are going to be the same, these Guidelines can only provide general advice on the most common issues and potential effects that arise as a result of developing an artificial lake. While these guidelines provide the most up to date information at the time of publication, any change in legislation, or technological changes may need to be considered by those using the guidelines. For example, the Building (Dam Safety) Act 2008 amendments are due for release in July 2014.

The Guidelines do not provide all of the information required to prepare or audit a resource consent application for the development of an artificial lake. The Guidelines are also not a substitute for qualified specialists who remain important in ensuring accurate and reliable site-specific information. The Guidelines do, however, provide a starting point and check list of things to consider in relation to artificial lakes and a process which has been agreed by both representatives from lake owners and operators and the regional councils. The Guidelines serve to clarify roles and responsibilities in the consent process and provide guidance on ensuring a comprehensive and effective consent process.

While artificial lakes can come in many sizes, these Guidelines do not specifically deal with lakes smaller than 1 hectare (10,000 $m^2$) in area, without reference to depth or volume. This means that all artificial lakes formed by a dam or embankment must comply with the Building

Act 2004, which has a lower size limit of 0.6 hectares in area with a depth greater than 3 m deep and a volume of more than 20,000 $m^3$. All artificial lakes must also comply with the Building (Dam Safety) Regulations 2008, although these are currently being revised.

In general, wastewater treatment ponds (municipal and farm) are also excluded from these Guidelines. Farm wastewater treatment ponds are covered by guidelines for farm dairy effluent pond design and construction (IPENZ 2011). Ornamental freshwater ponds, dams and other small lakes are covered by guidelines for ponds (Boffa Miskell 2009). Wetlands are not specifically covered by these Guidelines although the catchment and margins of the artificial lake may include wetland features. Planting guidelines for these are provided by Tanner et al. (2006). Urban stormwater detention ponds are not covered as there are already reasonable guidelines available for these (e.g., Tasman District Council 2010).

## 1.3 Structure of these Guidelines

The guidelines are in three parts:

1. **The legislative background** which provides an introduction to the legal requirements when constructing an artificial lake and the legislative framework for dam construction and operation. This section provides definitions of what constitutes a large dam and where to find the information on requirements and responsibilities of the owner and the regional authorities, the permits and safety inspections required. Under the RMA each Regional Council is required to have a Regional Plan which will include rules for deciding whether the artificial lake is a permitted, controlled, discretionary, non-complying or prohibited activity under the Regional Plan. Each Regional Plan will have separate and specific requirements for artificial lakes, which might be different for different regions. The Guidelines will highlight areas of concern that may need to be covered in an assessment of environmental effects (AEE) report to support the consent application including but not limited to dam safety issues, analysis and evaluation of the likely environmental effects of dam construction and operation in the selected location, and ways to mitigate and manage environmental effects. The regional authority will need to set consent conditions and monitoring procedures.

2. **The ecological background** which provides a brief but specific overview of how lakes function, the biogeochemical processes that drive responses to cyclical change (day-night, seasonal), climatic events, and land-use in the catchment.

3. **Designing an artificial lake** which provides an overview of the practical aspects of design and maintenance, and when things go wrong, the restoration of artificial lakes. It includes practical issues that need to be considered when designing an artificial lake and design considerations that will avoid major pitfalls in a new artificial lake. It also provides information on the measurements that need to be made before the design phase begins and the monitoring that is required when the lake is constructed to manage the lake for maintenance of adequate water quality. Where appropriate, case studies are used to illustrate issues.

# 2 Legislative Background

Most developed countries have specific dam safety legislation, purpose-made together with the country's own administrative system. In New Zealand dam construction and operation are controlled by two main pieces of legislation; the Building Act, 2004, and the Resource Management Act, 1991. These Acts are not specifically designed and do not contain specific requirements for dams or other artificial lakes. In the past, this has often resulted in confusion and misunderstanding about the requirements and responsibilities of the parties involved in the resource consent process. The Building (Dam Safety) Regulations 2008 were designed to clarify these issues and were considered adequate to address all of the issues associated with dam structures, if the process is applied consistently.

The current New Zealand legislation that is likely to relate to the construction and operation of dams and other artificial lakes is:

- Resource Management Act 1991
- Building Act 2004
- Building (Dam Safety) Regulations 2008 and amendments
- Health and Safety in Employment Act 1992
- Freshwater Fisheries Regulations 1983
- Soil Conservation and Rivers Control Act 1941
- Civil Defence Act 1983
- Historic Places Act 1993

In addition, the following legislation may apply if the construction and operation of the artificial lake affects public conservation land, reserves or conservation covenants:

- Conservation Act 1987
- National Park Act 1980
- Reserves Act 1977

These guidelines focus on the approval processes under the RMA, which requires each Regional Council to produce a Regional Plan. These plans determine whether the development of the artificial lake is a permitted activity, a controlled activity, a discretionary activity, a non-complying activity or a prohibited activity in the region covered by the Plan.

The safety of dams is discussed in detail in the RMA section of the guidelines for dams (Foster et al. 2000). The dam safety provisions of the Building (Dam Safety) Act 2008 were to come in to force on 1 July 2010 but have undergone major revision and the release has been delayed until 2014.

## 2.1 Resource Management Act 1991

Part Three of the Resource Management Act 1991 contains duties and restrictions under the RMA. With respect to artificial lakes, these restrictions are broadly categorised as: uses of beds of lakes and rivers (section 13 of the RMA); taking, using, damming and diverting water (section 14 of the RMA); and discharging contaminants into water (section 15 of the RMA).

### 2.1.1 RMA section 13

#### Restrictions on certain uses of beds of lakes and rivers

Section 13 of the Act applies to the beds of rivers and lakes. The terms bed, river, and lake are defined in the Act.

Section 13 does not apply to riparian margins, artificial watercourses, river estuaries, or discharges to water:

- Rules about riparian margins are made under section 9 of the Act.
- Artificial watercourses (canals, races, etc.,) are not rivers (by definition in the Act).
- Rules about water in a river or lake or in an artificial watercourse (such as damming and diverting water) are made under section 14 of the Act.
- River estuaries are part of the coastal marine area. Rules about disturbing the beds of river estuaries are made under section 12 of the Act.
- Discharges to water in rivers, lakes or artificial watercourses are controlled in section 15 of the Act.

The presumption of subsection 13 (1) is restrictive. This means that a resource consent is required to do any of the activities described in this subsection unless they are specifically allowed by a rule in an operative regional plan.

The presumption of subsection 13 (2) is permissive. This means that anything described in section 13 (2) can be done as of right, unless it is specifically restricted by a regional rule.

The regional rules are grouped into the sorts of activities that are described in subsections 13 (1) and (2) of the Act. These activities are:

- Section 13(1)(a) structures in, on, under or over the bed of a lake or river.
- Section 13(1)(b) excavation, drilling, tunnelling or disturbance of the bed of a lake or river.
- Section 13(1)(c) introduction of plants in, on, or under the bed of a lake or river.
- Section 13(1)(d) deposition of substances in, on, or under the bed of a lake or river.
- Section 13(1)(e) reclamation or drainage of the bed of a lake or river.
- Section 13(2)(a) entry or passage across the bed of any river or lake.

- Section 13(2)(b) disturbance, removal, damage, or destruction of any plant or part of any plant (whether exotic or indigenous) or the habitats of any such plants or of animals in, on, or under the bed of any lake or river.

More detail on Section 13 is provided in Appendix B.

### 2.1.2 RMA section 14

#### Restrictions relating to fresh water

Section 14 of the Act restricts all taking, use, damming and diverting water, and using heat or energy from water, including water in the coastal marine area. "Water" is defined in the Act, and includes all water, whether it is in a river, lake, artificial watercourse, wetland, an underground aquifer or the sea. (Water in a pipe, tank or cistern is explicitly excluded). The presumption of subsection 14 (1) is restrictive. This means that a resource consent is required to do any of the activities described in this subsection unless they are specifically allowed by a rule in an operative regional plan.

The regional rules are grouped into the sorts of activities that are described in subsections 14 (1) of the Act. These activities are:

- Section 14(1)(a) taking, using, damming and diverting water.
- Section 14(1)(b) taking, using, damming and diverting heat or energy from water.
- Section 14(1)(c) taking, using, damming and diverting heat or energy from the material surrounding any geothermal water.

More detail on Section 14 is provided in Appendix C.

### 2.1.3 RMA section 15

#### Discharges to the environment

Section 15 of the Act restricts the discharge of water or contaminants to water, including water in the coastal marine area, and restricts the discharge of contaminants to land or air. The presumption of subsection 15 (1) is restrictive. This means that a resource consent is required to do any of the activities described in this subsection unless they are specifically allowed by a rule in an operative regional plan.

The regional rules are grouped into the sorts of activities that are described in subsections 15 (1) of the Act. These activities are:

- Section 15(1)(a) discharging contaminants to water (including water in the coastal marine area).
- Section 15(1)(b) discharging contaminants to land where they may enter water.

More detail on Section 15 as it is related to water is provided in Appendix D.

## 2.2 Regional Plans

Each Regional Council is charged under the RMA with developing a Regional Plan which regulates all aspects of the use of water in the region covered by the plan, including water takes, discharges and diversions. The Regional Plan will have a set of rules that can be applied in each situation for water take, use and management. The construction of an artificial lake may not be specifically included in the Regional Plan or it may be included in the overall water allocation strategy of the region. Fundamental to each Regional Plan are the definitions which specify what is considered to be a permitted, controlled, restricted discretionary, discretionary, non-complying, or prohibited activity in the region covered by the plan. These terms are defined in the RMA as:

A **permitted activity** may be carried out without the need for a resource consent so long as it complies with any requirements, conditions and permissions specified in the RMA, in any regulations, and in any applicable plans. A building permit is still required.

A **controlled activity** requires a resource consent before it can be carried out. The consent authority must grant the consent unless the consent relates to development of the artificial lake on land which is likely to suffer material damage from erosion, falling debris, subsidence, slippage, or if there is insufficient legal and physical access to the site.

The consent authority can impose conditions on the consent, but only for those matters over which the council has reserved control in the relevant plan or over which control is reserved in national environmental standards. The activity must also comply with any requirements, conditions and permissions specified in the RMA, regulations or relevant plan.

A **restricted discretionary activity** requires a resource consent before it can be carried out. The consent authority can exercise discretion as to whether or not to grant consent, and to impose conditions, but only in respect of those matters over which it has restricted its discretion in the plan or over which discretion is restricted in national environmental standards or other regulations. The activity must also comply with any requirements, conditions and permissions specified in the RMA, regulations or relevant plan.

A **discretionary activity** requires a resource consent before it can be carried out. The consent authority can exercise full discretion as to whether or not to grant consent and as to what conditions to impose on the consent if granted. An activity is discretionary if:

- the plan identifies it as discretionary
- a resource consent is required for the activity but the plan fails to classify it as controlled, restricted discretionary, discretionary or non-complying, or
- the activity is described as prohibited by a rule in a proposed plan which is not yet operative.

A discretionary activity must also comply with any requirements, conditions and permissions specified in the RMA, regulations or relevant plan.

A **non-complying activity** requires a resource consent before it can be carried out. A resource consent can be granted for a non-complying activity, but first the applicant must establish that the adverse effects of the activity on the environment will be minor or that the activity will not be contrary to the objectives of the relevant plan or proposed plan. Any effect on a person who has given written approval to the application will not be considered. In addition, the consent authority may disregard an adverse effect of the proposed activity if the plan permits an activity with that effect (the 'permitted baseline' test).

A **prohibited activity** may not be carried out. In addition, no resource consent can be granted to authorise the activity. Parties wishing to carry out a prohibited activity must apply for a change to the plan to reclassify the activity.

At present there is no consistent set of rules for artificial lakes in the Regional Plans across New Zealand and, consequently, what is a permitted activity in one region may be a non-complying activity in another. It would be beneficial to have a coherent national set of rules.

In regions where the artificial lakes were constructed before the local Regional Plan became active, some of those artificial lakes may now be non-complying or prohibited, in which case they may need to be removed or granted a restricted discretionary activity consent.

Because most artificial lakes of 1 ha in area will exceed the minimum size under the Building Act 2004, they will need a building permit and to be registered. This is likely to include a requirement for appropriate authorisation by the Regional Council. Even where the construction of an artificial lake of specific dimension is deemed to be a permitted activity, the rules in the Regional Plan are also likely to include a requirement for a notification of the intention to construct the dam prior to construction.

If the dam does not comply with all of the conditions of the permitted activity rule (for example, the size of the catchment upstream of the dam is too large, or the dam wall is too high) the applicant will need to apply for a resource consent under the rules for a discretionary activity or restricted discretionary activity.

Different rules may apply for **On Stream** and **Off Stream** dams. In general terms, a dam built on a permanent stream is an ‘on stream dam'. A dam constructed on an intermittent stream is an ‘off stream dam'. The definition of permanent and intermittent streams should be set out in the Definitions and Abbreviations section of the Regional Plan. In some regions it may be very difficult to obtain resource consent for an on stream dam unless there is a clear environmental benefit and there are no realistic alternatives.

Environmental issues could directly or indirectly affect whether an artificial lake is a permitted, discretionary or prohibited activity under the Regional Plan. For example:

- Damming water can alter stream hydrology and affect a stream's ability to deal with contaminants. It can become a habitat for nuisance or undesirable biota such as pest fish and invasive macrophytes. This can lead to poor water quality, excessive amounts of midge larvae, malodourous cyanobacteria and a reduction in available stream habitat. These factors not only affect freshwater ecosystems but also affect the availability and quality of water for downstream users. The rules for artificial lakes may include minimum flows below the dam as well as maximum temperatures, minimum dissolved oxygen, and a minimum water quality level discharged from the artificial lake.

- Dams built across streams can block fish from accessing upstream habitat. The damming of water is likely to be a contributing factor in the decline of New Zealand's freshwater fish populations. The rules for artificial lakes may require the inclusion of a fish pass in the dam structure.

- The construction or existence of even small dams can become a contentious issue between neighbours. The rules for artificial lakes in the Regional Plan may include obtaining letters of approval from neighbours before the application for a resource consent to build the artificial lake can be considered.
- The artificial lake that forms behind the dam wall will fill to the contours of the land, which may not coincide with the property boundaries. It is important that dam structures and the water they impound are located well within property boundaries so that they will not affect adjacent, upstream or downstream properties in any way.
- The presence of a large body of water on previously dry land may affect the flow in downstream springs and wells. Where the water from the artificial lake is used for irrigation, the interception of the stream/river flow may constitute abstraction. The rules for water abstraction and the maximum take may be part of the Regional Plan and would become part of the resource consent.
- Reservoir filling can induce seismicity as was reported when the level of Lake Pukaki was raised (Reyners 1988). Thus, some consideration of earthquake faults should be undertaken when creating large dams.

There is always a risk that a dam will fail. This can damage the downstream environment, including freshwater ecosystems, property, people, communities and infrastructure. Without exception, the artificial lake must comply with the Building (Dam Safety) Regulations 2008 and subsequent amendments.

Recently highlighted issues of unknown risks of earthquake fault lines beneath Christchurch City may need to be included in revisions of regional plans. Seismic surveys may be needed to ensure that the dam structure is not built across a fault line.

Finally, the artificial lake may have a finite lifetime and may need to be removed or renovated to meet the standards in future regional plans. The rules may require that the water quality in the artificial lake is maintained at the highest water quality adequate to meet the proposed use of the lake and downstream users into the future.

Checks should be made of the relevant Region Plan and the rules for artificial lakes contained or implied within those plans. If no specific provision is made in the plan for artificial lake, the fall-back position is the RMA and rules in the regional plan that apply to water take, use and management.

The location of the proposed artificial lake in the landscape may need to be aesthetically pleasing and fully compliant with the rules in the Regional Plan. The history of the location should be checked against the Regional Council’s register of land-fill and potentially toxic chemical disposal sites. For example, drums of toxic waste may be buried in the bottom of the gully chosen for the artificial lake development rendering it unsuitable for the lake until that material is removed and relocated in an appropriate disposal site.

## 2.3 Setting resource consent conditions

Robust resource consent conditions are fundamental to ensuring that actual or potential adverse environmental effects of an activity are appropriately avoided, remedied or mitigated. It is critical that resource consent conditions are drafted carefully to ensure that:

- they are within the law
- compliance with the conditions will result in any adverse effects being limited to the extent anticipated by the decision-maker
- the consent holder and other parties understand exactly what the requirements are, and
- if necessary, enforcement can be undertaken.

As a consequence, the drafting of resource consent conditions is extremely important. The Guidelines do not provide detailed information about the drafting, implementation, review, revision, or cancellation of conditions.

Section 108 of the RMA allows councils to include conditions on resource consents. Conditions include standards, terms, restrictions or prohibitions specified in a consent following the written decision to grant the consent. The scope of possible conditions of consent is very wide. For example, they may relate to:

- the design or appearance of structures
- landscaping
- hours of operation
- restrictions on the quality of a discharge
- restrictions on the amount of resource use
- monitoring and reporting, and
- the layout of a site.

Conditions may include the provision of:

- cash
- land
- works
- services, and
- a bond.

Specifying conditions of consent that are effective and enforceable is essential to the operation or development of the artificial lake and in ensuring that any adverse effects on the environment are avoided, remedied or mitigated. Therefore setting of appropriate conditions is essential. Best management practices and adaptive management approaches can be used to frame the consent conditions in positive terms of what can be done (permissive) rather than what can't be done (restrictive).

For example, the resource consent for rehabilitation work may be written in a way that is restrictive to the point that it actually prevents the success of the project. It may define the products and materials to be used and the treatment rates. These latter may have been the best estimates from a model but are required to be adapted in the “real world” to accommodate environmental variability. Consequently, the resource consent needs to be permissive to allow “room to manoeuvre” but not be a licence to do “whatever it takes”.

While it is possible to develop a standardised procedure for approving consents and setting of generic consent conditions (Appendix A), each artificial lake is a unique entity which may require a site specific set of consent conditions. Because the artificial lake does not exist in the chosen landscape, consent conditions are based on the anticipated potential effects on the environment. Consequently, council will need as much information as possible about the project from the developer.

Chapter 3 of these Guidelines provides descriptions of the processes occurring in a lake to assist the decision maker in approving the resource consent and setting the resource conditions.

## 2.4 Responsibilities

Within the legislative process, different agencies and people have different responsibilities:

**The developer** is responsible for initiating and facilitating the project, together with coordinating the design and environmental assessment requirements, either directly or by contracting an environmental resource consultant to perform that task, including consultation with local communities and iwi that might be affected by the placement of the artificial lake. The developer is responsible for providing true and accurate information about the project to the regulatory authorities, and holds the relevant permits and resource consents required to complete the project. With the exception of the engineering design, the developer is responsible for the health and safety and the work of all subcontractors to the project from site preparation through construction, to the final landscaping, as well as the on-going monitoring and management of the water quality in the lake as per the conditions of the resource consent. If the artificial lake is only required for a short period, the developer is also responsible for the decommissioning and removal of the artificial lake. This should be noted in the resource consent.

**The engineer** contracted by the developer will be responsible for the design of the dam structure to retain the water, to ensure that they comply with the regulations in the relevant sections of the Building Act. The engineer will also be required to supervise the construction and supply all appropriate compliance certificates.

**The Council Planner / consenting officer** is responsible for seeing that all the documentation required is supplied and completed and that it complies with the legislative requirements as set out in the Building Act, the RMA and the regional plan. The Council Planner / consenting officer is responsible for setting the conditions of the resource consent for those aspects of the project that require on-going management and monitoring.

## 2.5 Biosecurity

The biosecurity risk associated with storage of water in reservoirs and artificial lakes should also be considered when setting the conditions for the resource consent. Small lakes and reservoirs often become “hot spots” where pest fish and aquatic plants and algae may proliferate and can be transferred to other unaffected water bodies (de Winton & Champion 2011). The presence of the artificial lake where previously there was no lake can provide a pathway for pests to bypass the natural barriers (filters) to their natural spread or migration as indicated in the schematic (Figure 2-1).

For example, the construction of an artificial lake for jet boat racing through tight water-courses in the gravel bed next to a pristine river sounds like a great recreational resource and community amenity. However, it could bring pest species (aquatic macrophytes, *Didymo*) transported on boat trailers or as spores in the water-cooled jet boat engines, etc., into close proximity to the river. If these pests become established in the artificial lake then that lake becomes a “stepping stone” for introducing those pests into the pristine river or lake, e.g., Lake Dunstan increases the risk to Lake Wakatipu from *Lagarosiphon.*

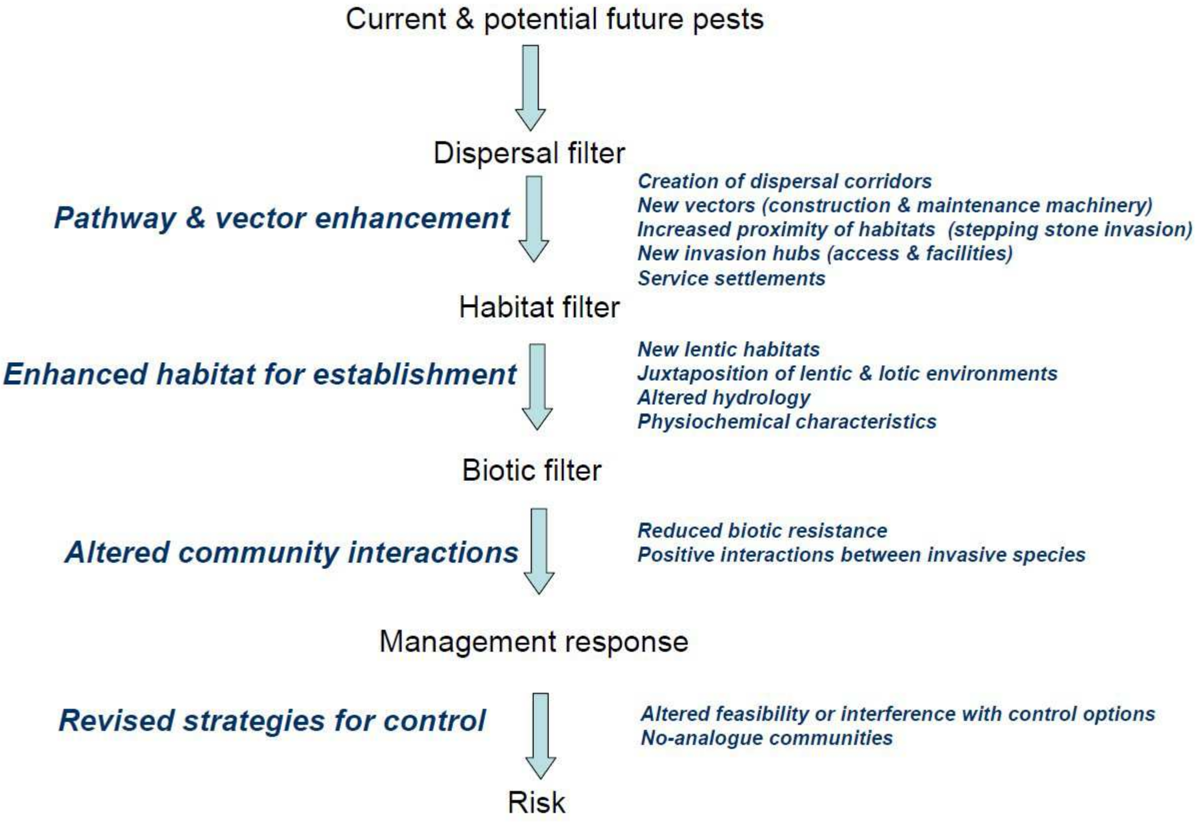


**Figure 2-1: The changed "riskscape" for freshwater biosecurity by waterway engineering.** Diagram shows how filters to pest introduction, establishment and control, can be reduced or bypassed by human activities relating to waterway engineering. [From de Winton & Champion, 2011].

Management of the risk in the resource consent conditions for the artificial lake development might require the construction of a cleaning station to wash boat trailers and flush boat engines before they are allowed onto the lake. Public notices may need to be placed at the entrance to the lake warning against the transfer of aquatic organisms – fish (including goldfish), snails, macrophytes including aquarium plants – and water including bilge water and cooling water in boats, and aquarium water.

**Glossary of terms used in the following section:**

| | |
|---|---|
| PIC | Potential impact classification. |
| PAR | Population at risk. |
| DSAP | Dam Safety Assurance Programme. |
| DCC | Dam Classification Certificate. |
| ADCC | Annual Dam Compliance Certificate. |

## 2.6 Large Dams

Artificial lakes differ in size and there is a distinction between small artificial lakes and large artificial lakes or dams in the legislation. The flow chart (Figure 2-3) gives an outline of the of the legal requirements for a large dam that are not required for a small dam.

The Building Act 2004 defines a large dam as “a dam that retains 3 or more metres depth, and holds 20,000 or more cubic metres volume, of water or other fluid”. The Act does not expressly define the terms “depth” and “volume”. The definition is important in situations where a dam has dimensions that are close to the threshold for a large dam. This matter has important implications for regulation and compliance because a dam that is not a large dam (Figure 2-3):

1. Does not require a building consent (being exempt under Clause (da) of Schedule 1).
2. Does not require the owner to submit an audited DCC with a PIC to the Regional Council or Unitary Authority.
3. Does not require the owner to submit an audited DSAP to the Regional Council or Unitary Authority.
4. Does not require the owner to submit an ADCC to the Regional Council or Unitary Authority.
5. Is not subject to the dangerous, earthquake-prone or flood-prone dams provisions of the Act (with the exception of the provisions of Section 157 in relation to immediate danger).

Notwithstanding this, all dams require a Certificate of Code Compliance for the building work.

### Amendment

Recommendations have been made to change the definition of a large dam in the Building (Dam Safety) Regulations 2008 under the Building Act 2004. The proposed changes will be included in an amendment to the act and are due to come into force on 1 July 2014. The preferred amendment has two categories of large dam - either a “classifiable dam” or a “referable dam” (Figure 2-2). There are also two definitions of large dam:

- The range of large dams that are automatically required to be classified (classifiable dams), include large dams that are over eight metres in height and 20,000 cubic metres in volume, or are three or more metres in height and 100,000 cubic metres in volume.

The preferred amendment defines large dams that are not classifiable dams as referable dams and provides regional authorities with tightly limited discretion to consider requiring these referable dams to be classified where there are reasonable grounds for doing so.

The Dam Safety Scheme as currently set out in the Building Act 2004 would affect an estimated 1150 dams. An independent review found the reach of the proposed 2008 Dam Safety Scheme was too broad, imposing rules and compliance costs out of proportion to the risk to New Zealanders.

Note that the present Dam Safety Scheme defines a large dam as retaining 3 or more metres depth of water. This means any structure on the outlet of a natural lake which has a depth greater than 3 m is classified as a large dam. The proposed changes refer to the height of the dam retaining the water (Figure 2-2).

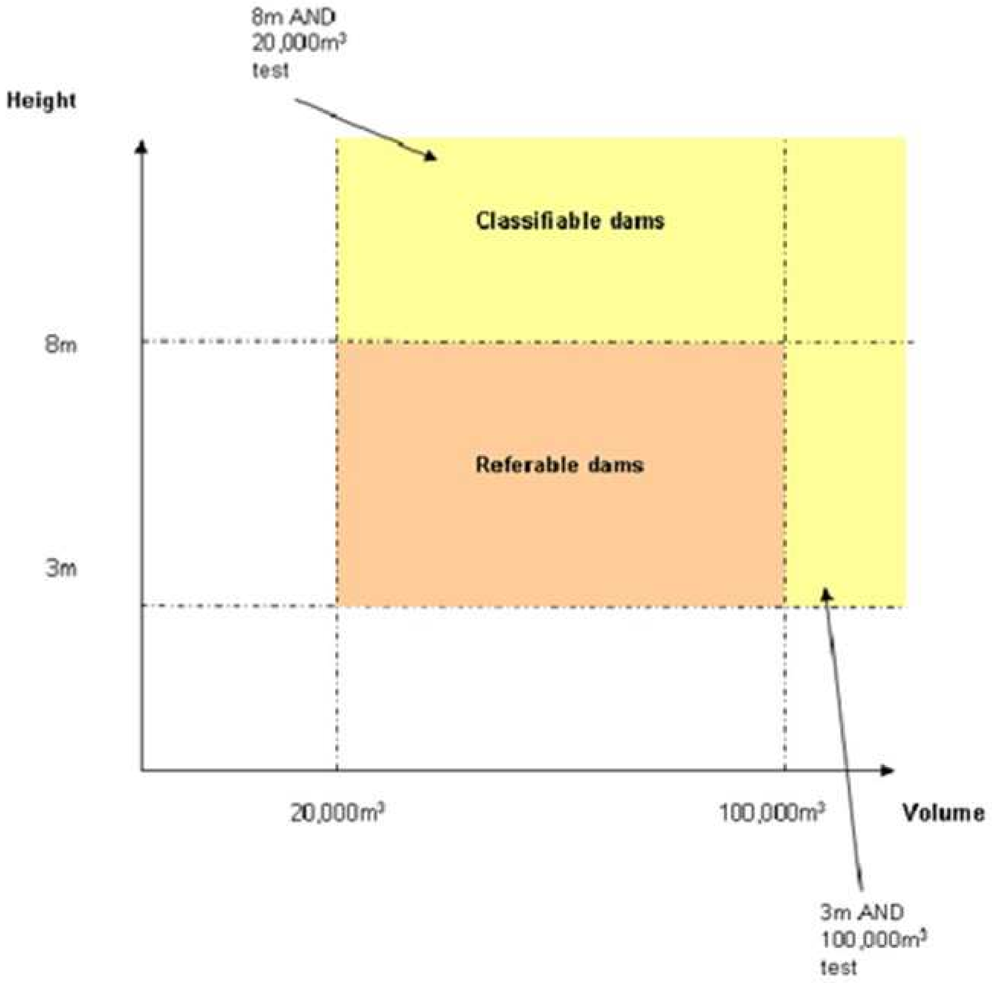


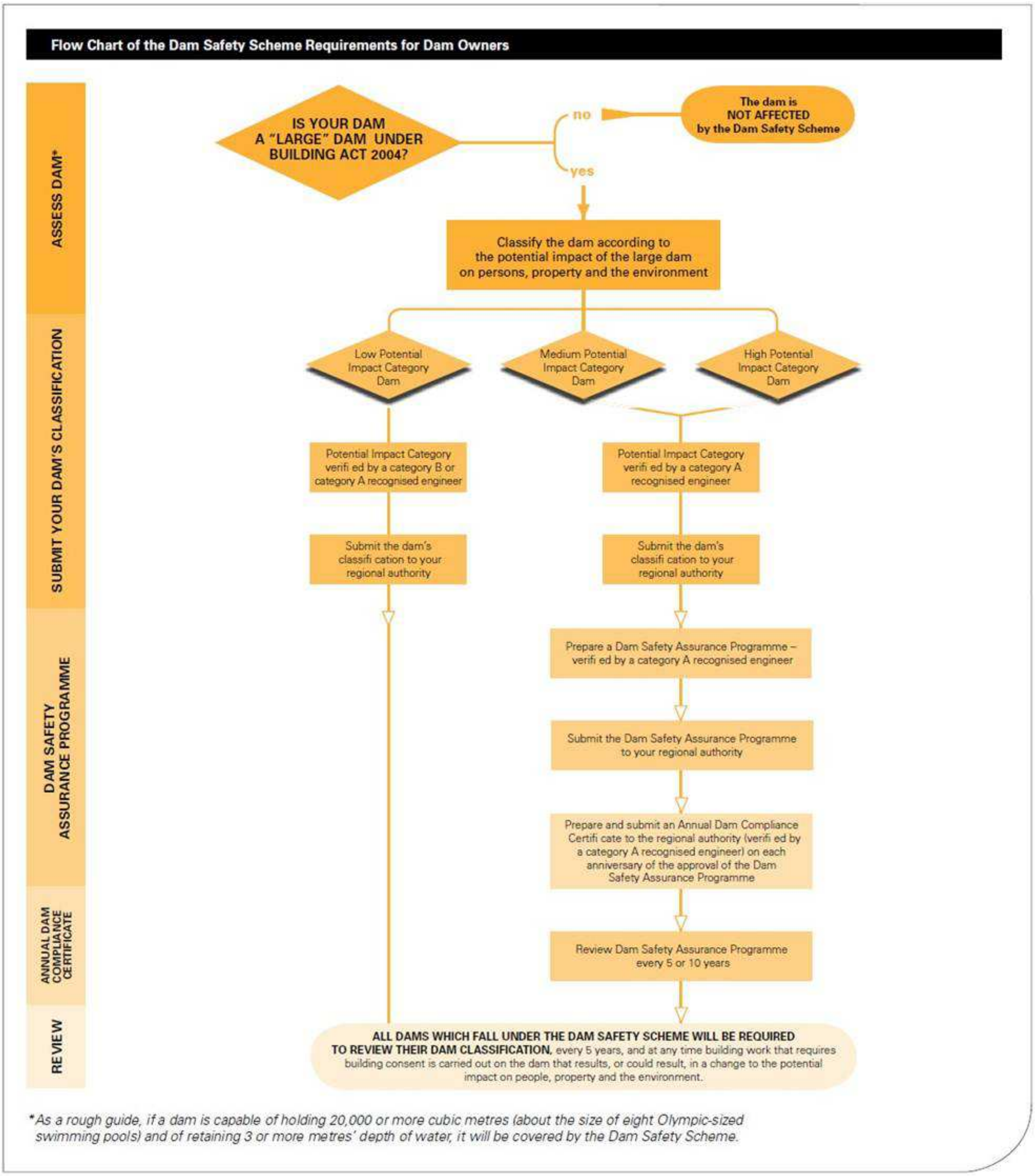
**Figure 2-2: Concept of Classifiable and Referable dams.** As proposed in the dam safety cabinet paper on the internet at http://www.dbh.govt.nz/dam-safety-cabinet-paper#fn1

Dam safety had been a concern for a number of years and was brought to recent attention by the Opuha Dam in South Canterbury failing during construction in February 1997 and various flood events around the country during the late 1990s. These events demonstrated that a dam failure could result in loss of life and damage to property, infrastructure and the environment. It also highlighted that the potential impact of a dam can change over time due to downstream developments and that there were no regulatory systems in place to manage these changes prior to the Building (Dam Safety) Regulations 2008.

Relevant documents on dam safety include:

Dam Safety Scheme: Guidance for regional authorities and owners of large dams. Department of Building and Housing 2008.

Dam Safety Scheme: An overview for rural owners of large dams. Department of Building and Housing 2008.



Flow Chart of the Dam Safety Scheme Requirements for Dam Owners

*As a rough guide, if a dam is capable of holding 20,000 or more cubic metres (about the size of eight Olympic-sized swimming pools) and of retaining 3 or more metres' depth of water, it will be covered by the Dam Safety Scheme.

**Figure 2-3: Flow chart for determining whether a dam is a large dam.** From "Dam Safety Scheme: Guidance for regional authorities and owners of large dams. Department of Building and Housing 2008".

## 2.7 Types of dams

The Dam Safety Scheme only applies to large dams. A large dam is defined by section 7 as being a dam that retains three or more metres depth, and holds 20,000 or more cubic metres volume of water or other fluid.

The types of dam that are in the definition of 'dam' in section 7 of the Act:

(a) meaning an artificial barrier, and its appurtenant structures, that –

  (i) are constructed to hold back water or other fluid under constant pressure so as to form a reservoir, and

  (ii) are used for the storage, control, or diversion of water or other fluid; and

(b) includes –

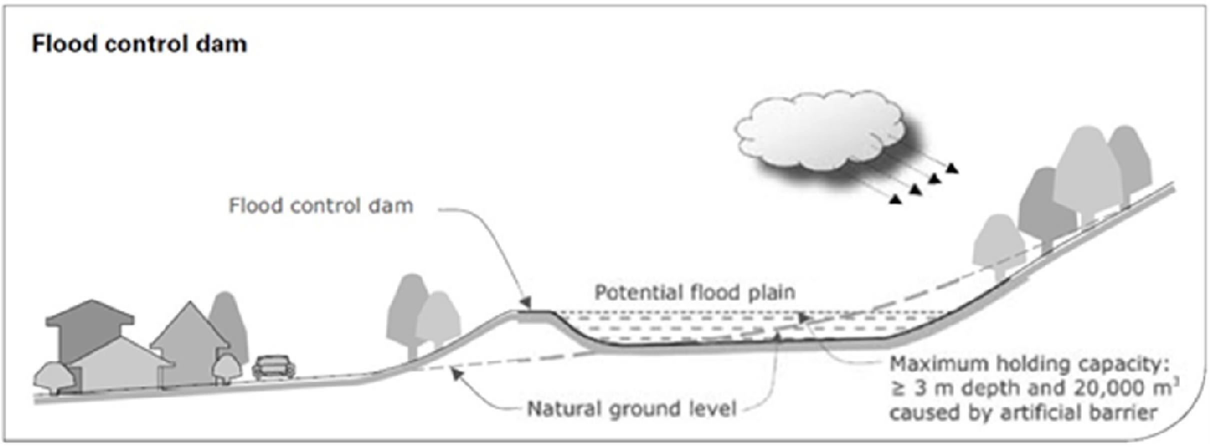
  (i) a flood control dam, and

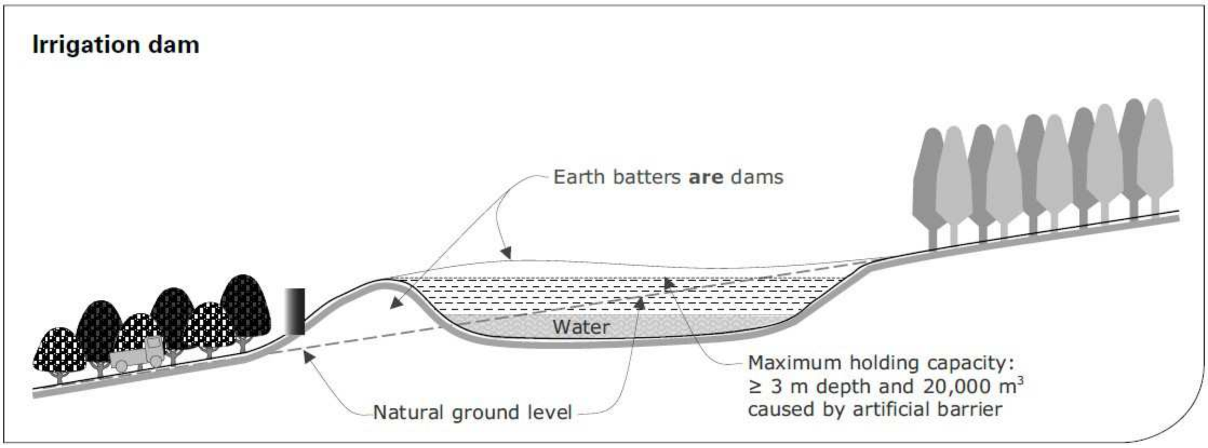
  (ii) a natural feature that has been significantly modified to function as a dam, and

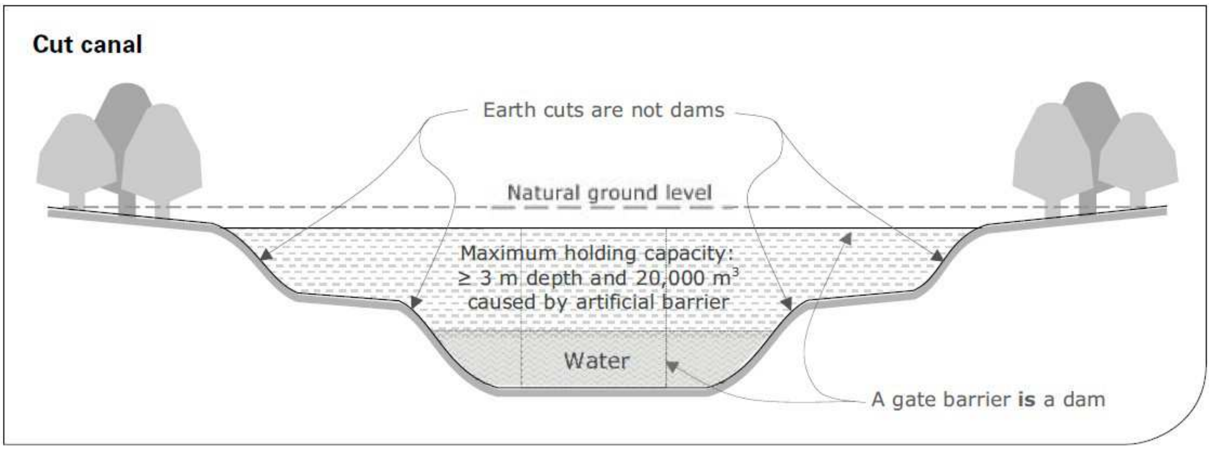
  (iii) a canal, but

(c) does not include a stopbank designed to control floodwaters.

The following examples (Figure 2-4) are extracts from "Dam Safety Scheme: Guidance for regional authorities and owners of large dams", Department of Building and Housing 2008.







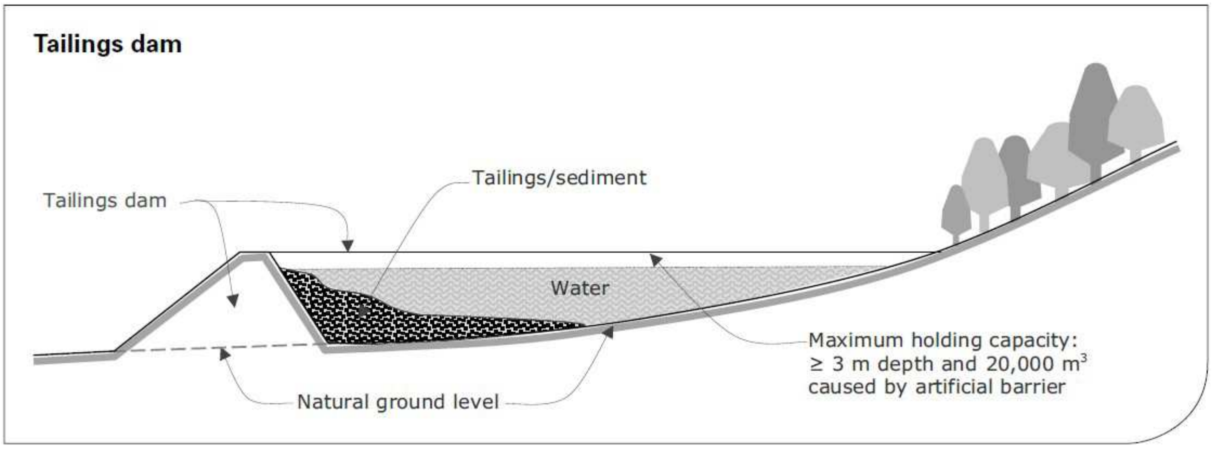


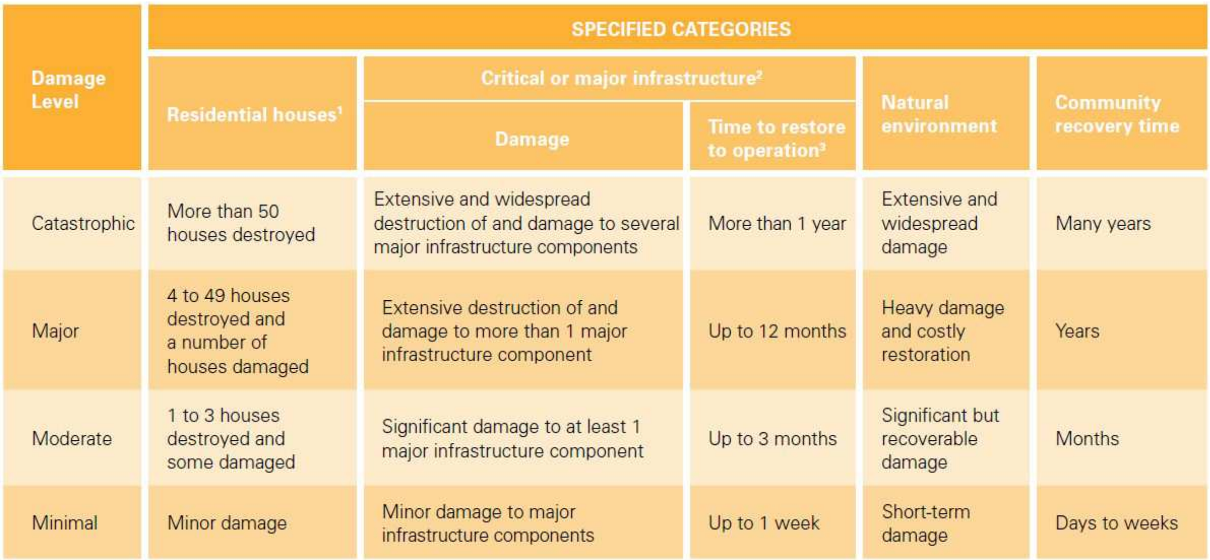
**Figure 2-4: Examples of dam types.** Flood control; Irrigation; Cut Canal; Tailings from "Dam Safety Scheme: Guidance for regional authorities and owners of large dams" Department of Building and Housing 2008.

Also not included under the Dam Safety Scheme are artificial lakes formed by flooding a quarry or mine, provided there is no physical structure used to retain the water. For example, Weavers Lake near Huntly is a flooded coal mine (Figure 4-7).

## 2.8 Dam classification

Large dams can be classified by the level of damage they would cause if they failed (Table 2-1) and the risk of human injury or death (Table 2-2). The following are extracts from "Dam Safety Scheme: Guidance for regional authorities and owners of large dams" Department of Building and Housing 2008.

**Table 2-1: Determination of Assessed Damage Level.** (From "Dam Safety Scheme: Guidance for regional authorities and owners of large dams" Department of Building and Housing 2008).



| Damage Level | SPECIFIED CATEGORIES | | | | |
|---|---|---|---|---|---|
| | Residential houses[1] | Critical or major infrastructure[2] | | Natural environment | Community recovery time |
| | | Damage | Time to restore to operation[3] | | |
| Catastrophic | More than 50 houses destroyed | Extensive and widespread destruction of and damage to several major infrastructure components | More than 1 year | Extensive and widespread damage | Many years |
| Major | 4 to 49 houses destroyed and a number of houses damaged | Extensive destruction of and damage to more than 1 major infrastructure component | Up to 12 months | Heavy damage and costly restoration | Years |
| Moderate | 1 to 3 houses destroyed and some damaged | Significant damage to at least 1 major infrastructure component | Up to 3 months | Significant but recoverable damage | Months |
| Minimal | Minor damage | Minor damage to major infrastructure components | Up to 1 week | Short-term damage | Days to weeks |

The damage level needs to be assessed by considering the impact on:

- residential houses
- critical and major infrastructure (both damage caused and estimated time to restore to normal operation)
- natural environment
- community recovery time.

a) The dam owner must determine and/or estimate the damage that would be caused by an uncontrolled release of the reservoir when full, due to a dam breach – that is, if the dam fails, what would likely occur?

b) The dam owner may do the assessment themselves and use a Recognised Engineer to verify the classification, or the dam owner may use a Recognised Engineer to handle the whole classification process. The Recognised Engineer must be either a Category A or Category B Recognised Engineer, as discussed in 4.10 of "Dam Safety Scheme: Guidance for regional authorities and owners of large dams" Department of Building and Housing 2008.

c) In some situations an estimate of flood areas may be carried out using the downstream topography – i.e., valley shape and slope – as it may be obvious whether the flow is going to impact on houses, infrastructure, or the natural environment, or find its way to a larger water course and not cause much damage.

For straightforward dam layout and topography, it will be a matter of examining where the water might flow using an on-site assessment. If required, a suitably qualified professional engineer will be able to create an inundation/ flood map.

Note: More complex layout or topography may require engineers experienced in hydraulic modelling to map the inundation level. Once the flood map has been created, it can be used to assist in classifying the PIC of the large dam.

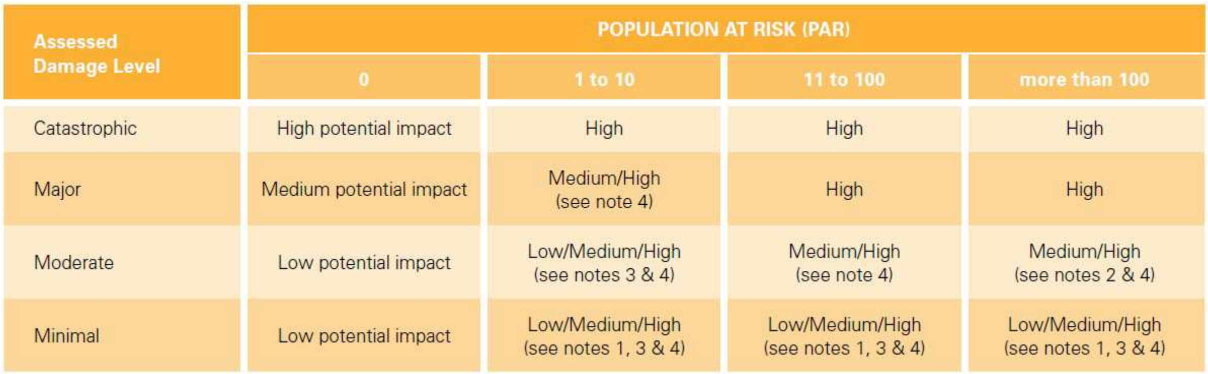
d) The overall damage level is determined by assessing whether the damage level in each of the specified categories is catastrophic, major, moderate or minimal, and then selecting the highest damage level.

Example: An assessment determines that in the event that a particular dam failed, it would result in:

- three houses becoming uninhabitable with the likely loss of two or more lives
- minor damage to a state highway
- flooding of a protected ecosystem resulting in destruction of the habitat of endangered species
- extensive damage to the natural environment and costly restoration
- damage requiring several months for the community to recover.

In this example, the damage to residential houses is moderate, damage to critical and major infrastructure is minimal, and time for the community to recover and damage to the natural environment is major. The damage to the natural environment is the highest out of all of the columns, so the assessed damage level is ‘major’.

**Table 2-2: Determination of Dam Classification.** (From "Dam Safety Scheme: Guidance for regional authorities and owners of large dams" Department of Building and Housing 2008



| Assessed Damage Level | POPULATION AT RISK (PAR) | | | |
|---|---|---|---|---|
| | 0 | 1 to 10 | 11 to 100 | more than 100 |
| Catastrophic | High potential impact | High | High | High |
| Major | Medium potential impact | Medium/High (see note 4) | High | High |
| Moderate | Low potential impact | Low/Medium/High (see notes 3 & 4) | Medium/High (see note 4) | Medium/High (see notes 2 & 4) |
| Minimal | Low potential impact | Low/Medium/High (see notes 1, 3 & 4) | Low/Medium/High (see notes 1, 3 & 4) | Low/Medium/High (see notes 1, 3 & 4) |

Dams must be classified as high, medium or low PIC. Using Table 2-2, the classification depends on the population at risk (PAR) and on the assessed damage level (as determined in Table 2-1).

The assessor determines:

(1) how many people would likely be affected by inundation greater than 0.5 metres in depth, and

(2) how many lives would be lost (this can be done at the same time as estimating the assessed damage level).

Example: In the example above, the three houses indicate a PAR in the range of 1-10. With a ‘major’ damage level from Table 2-1 the dam could be either medium or high PIC from Table 2-2. The location of the houses indicates that two or more lives are likely to be lost. The dam is classified as high PIC. This assessment is submitted to a Category A Recognised Engineer for review and certification, before being submitted to the regional authority.

The PAR and the potential damage must be determined on the basis of a breach or failure of the dam. For this purpose, a breach or failure of a dam occurs when it is at full service level and all retained fluid is released over a short period of time. The PAR is determined as those likely to be affected by a flood greater than half a metre deep. When considering PAR, the following issues should be taken into account:

- groups of dwellings
- camping areas and occupancy times
- allowance for temporary populations (e.g., fishermen, bushwalkers, birdwatchers, picnickers)
- river crossings and bridges
- the number of people using nearby schools, hospitals and other institutions (e.g., prisons) as well as commercial and retail areas.

# 3 Ecological background information

Fundamental to the development of a new artificial lake, management of an existing lake or rehabilitation of a degraded lake is an understanding how lakes function. Lakes are nature's accumulators. Apart from retaining water, they trap sediment and detritus, and store nutrients from inflows. Lakes are also nature's biological reactors, providing enough time for microbial processes to convert particulate organic matter into soluble biologically available nutrients which support the proliferation of algae (phytoplankton) and water weeds (aquatic macrophytes). From a human perspective, lakes can provide reservoirs of potable water and are aesthetic features in the landscape. However, when they become degraded, the water quality declines and the lake becomes less attractive or a liability. The transition from a high water quality and an aesthetically pleasing landscape feature, to a nutrient enriched unpleasant lake occurs via a process called eutrophication (Figure 3-1).

## 3.1 Eutrophication

Eutrophication (Figure 3-1) is "the process by which a body of water acquires a high concentration of nutrients, especially phosphorus (P) and nitrogen (N). These nutrients typically promote excessive growth of algae (phytoplankton). As the phytoplankton die and decompose, high levels of organic matter and the decomposing organisms deplete the water of available oxygen, potentially causing the death of other organisms, such as fish. Eutrophication is a natural, slow-aging process for a water body, but human activity greatly speeds up the process." (Art, 1993).

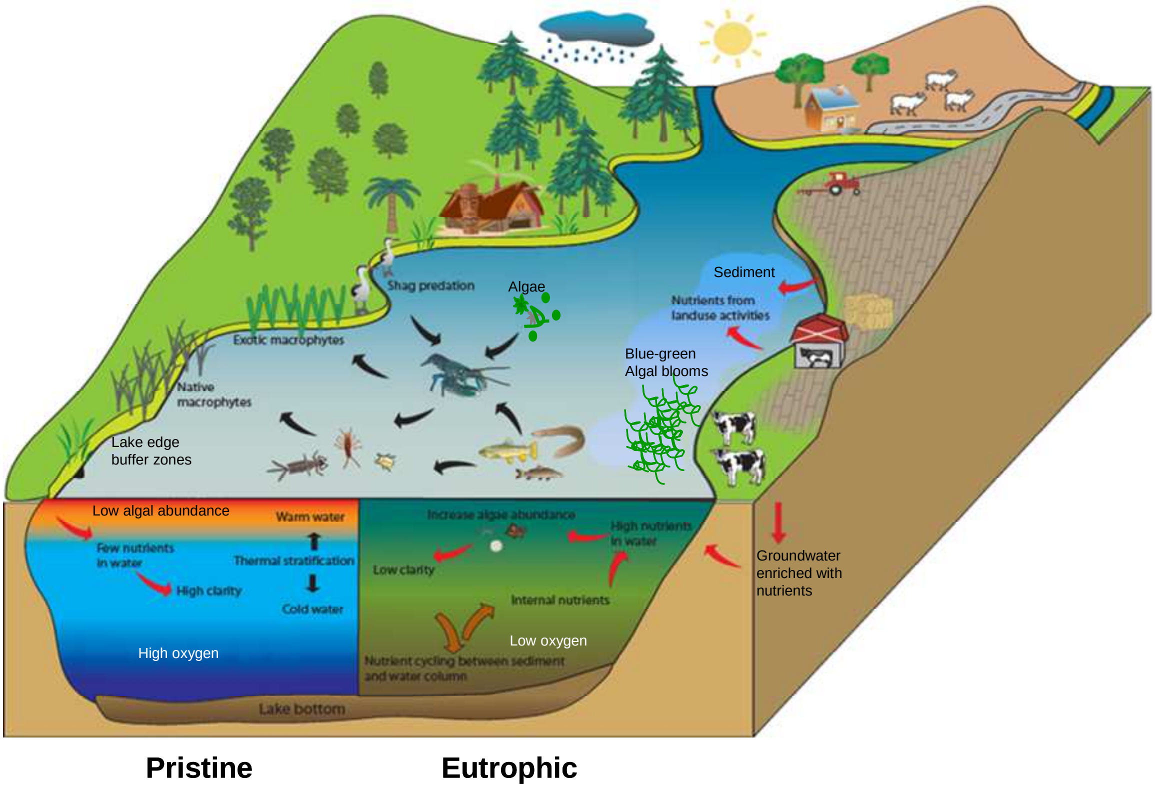


**Figure 3-1: Schematic of characteristics of a pristine versus eutrophic lake.** Eutrophication is accelerated through activities in the catchment.

### 3.1.1 Rate of eutrophication

The rate of eutrophication is a function mostly of the nutrient load and lake size. A low nutrient load to a large lake will have less impact on water quality than the same input to a smaller lake, because of dilution. However, an important part of the nutrient budget is the mass of nutrients exported from the lake via the outflow i.e., the rate of flushing. This determines how much is retained in the lake to drive the eutrophication process. Because the lake is a natural sediment trap, under normal conditions, the mass of nutrients exported will always be less than the mass input to the lake. Where the balance between input and output is comparable, the rate of eutrophication will be slow. However, where the input is increasing at a greater rate than can be exported, the rate of eutrophication will be high.

The quantity of nutrients retained in the lake is a function of lake size and hydraulic residence time. In general, large lakes will retain a greater proportion of nutrient input than smaller lakes because the hydraulic residence time is longer, giving the particulate material more time to settle and the biological processes in the lake more time to assimilate the nutrients.

### 3.1.2 Flipping lakes

While the transition from pristine to eutrophic water quality is generally a gradual process in deep lakes, in shallow lakes it can be a non-linear process where a sudden catastrophic regime shift can cause the lake to rapidly change or “flip” between alternative stable states. These stable states are a relatively clear water phase with macrophyte dominance or a decline to a turbid water phase with phytoplankton dominance. Because the elevated turbidity and phytoplankton proliferation reduce light penetration to the lake bed, it is very difficult to re-establish the macrophyte beds i.e., to reverse the flip. Essentially the threshold “tipping” point to degrade from a macrophyte to phytoplankton dominated system is easier to reach than the tipping point to go from a phytoplankton dominated system back to a macrophyte dominated system. This difference is known as hysteresis and restoration of degraded lakes often struggles against the system hysteresis (Schallenberg & Sorrell, 2009). Lake Omapere is an example of a flipping lake.

## 3.2 Hydraulic residence time

The hydraulic residence time in a lake is the theoretical time it would take for the average drop of water entering a lake to leave it via the outflow. It is calculated as the volume of the lake divided by the mean annual discharge of water from the lake. This is an approximation to the true residence time, which is a function of the circulation currents in the lake and is linked to the morphometry of the lake.

Artificial lakes such as dams on rivers and streams typically have short residence times of a few days to weeks, while larger lakes may have residence times measured in months to years. If the artificial lake is a drowned valley, the flow through the lake is likely to be along the axis of the lake and the residence time is likely to be described by the approximate calculation. If there is a side-arm with minimal inflow, the side-arm will have a longer residence time than the main channel. If the inflow is close to the outflow from the lake, the inflow may short-circuit to the outflow without passing through the main body of the lake.

Residence time is important as it gives an indication of the potential resilience of the lake to an event. A short residence time means that a pulse of nutrients entering the lake is likely to be flushed out of the lake quickly, reducing the magnitude of any potential impact such as development of nuisance algal blooms. As the residence time increases, there is more time for in-lake processes to occur and the potential for a phytoplankton proliferation response to nutrient inputs increases. When the residence time is longer than one year, in-lake processes can incorporate those nutrients into the annual nutrient cycle within the lake. This means that the pulse of nutrients accumulates in the lake bottom sediments and will enhance the amount of nutrients recycled from the sediments the following year. Under these conditions there is a loss of direct coupling of the input to the output and the nutrients exported from the lake become increasingly a function of the in-lake processes.

#### Case study example

For many years the outflow from Lake Rotorua discharging via the Ohau Channel into the western basin of Lake Rotoiti was thought to short-circuit directly to the Kaituna River bypassing the main body of Lake Rotoiti. That flow passage did occur for about half the year. For the rest of the year, the Ohau Channel discharge was colder than Lake Rotoiti and flowed as a density current along the bed into the main eastern basin of Lake Rotoiti (See section 3.10 for details on density currents). This flow pattern resulted in a short residence time in the western basin but a long residence time in the eastern basin of Lake Rotoiti in summer, with the residence time reducing substantially in autumn and winter.

Annually, about 25% of the volume of Lake Rotoiti was replaced with eutrophic Lake Rotorua water. Because it entered into the bottom of Lake Rotoiti, it displaced the cleaner near-surface water out of the lake and this caused the degradation of Lake Rotoiti. Under this flow regime, the net residence time of the eastern basin was around 4 years. Recently a diversion wall has been installed in the Okere arm of Lake Rotoiti to enforce a permanent short circuit of the Lake Rotorua water away from Lake Rotoiti. The residence time of water in the eastern basin of Lake Rotoiti doubled but the water quality improved dramatically.

Note that Lake Rotoiti has a water level control structure on the outlet and may be regarded as an artificial lake, although it otherwise retains many of the features of a natural lake, including relatively long residence time.

### 3.2.1 Flushing rate

Flushing rate is the inverse of hydraulic residence time, being the number of times the lake water is exchanged each year by the inflow water. A short residence time of 1 month is equivalent to a flushing rate of 12 times per year.

## 3.3 In-lake processes

The biogeochemical processes occurring in a lake, and the timing of their occurrence, are a function of the lake morphometry (shape, depth, size), the orientation of the lake to the prevailing wind, the elevation of the lake in the landscape (water temperatures), and the geographical position within New Zealand (a temperate maritime climate). Two key parameters regulating biogeochemical processes are the water depth and water column structure.

- **Water depth** attenuates light penetration and thus biological processes that use light. Phytoplankton and aquatic plants (macrophytes) require light for growth. Consequently, the depth to which macrophytes can grow is determined by light limitation. Phytoplankton are free floating plants that get carried by the lake water – potentially upward under turbulent mixing conditions but they can sink when the water is calm. If they sink below the depth at which light can sustain their growth (euphotic zone) and are not carried back up by water column turbulence, they will die (senesce).

- **Water column structure** has two main conditions: (i) when the water column is mixed with a uniform temperature throughout (isothermal). Under these conditions the water is likely to be turbulent with uniform dissolved oxygen (DO) and nutrient concentrations. (ii) when the water column has formed layers (stratified) that isolate processes occurring in one layer from those occurring in another. Under these conditions the water is likely to have low turbulence with different concentrations of DO and nutrients in each layer. Such stratification is mostly caused by density difference and exists because the wind mixing energy is insufficient to overcome the difference in density between layers. Although there are special cases, the most common form of stratification in freshwater lakes is thermal stratification where warmer water, being less dense than cold water, will float on top of the cold water.

### 3.3.1 Thermal stratification

Thermal stratification occurs in most deep lakes in summer due to the much higher solar heating rate of the surface waters relative to the bottom waters. Thermal stratification typically begins in spring and remains stable throughout summer and autumn until the surface waters cool sufficiently that the lake becomes isothermal, and the lake water can fully mix once more (Figure 3-2). (See **Monomictic lakes** below).

Thermal stratification may also occur in shallower lakes for shorter periods in calm weather especially during the heat of summer. Wind events between the calm periods cause the water column to mix until the next calm period allows the lake to stratify once more. (See **Polymictic lakes** below).

In either situation the process is the same. The upper lake water (epilimnion) becomes warmer than the bottom waters (hypolimnion) and the boundary between these layers (metalimnion) becomes a thermocline. The thermocline is a gradient and the rate of change in temperature through the thermocline defines its strength as a barrier between the epilimnion and hypolimnion. As a barrier, the thermocline resists mixing and regulates the diffusion of heat, nutrients and DO between the epilimnion and the hypolimnion.

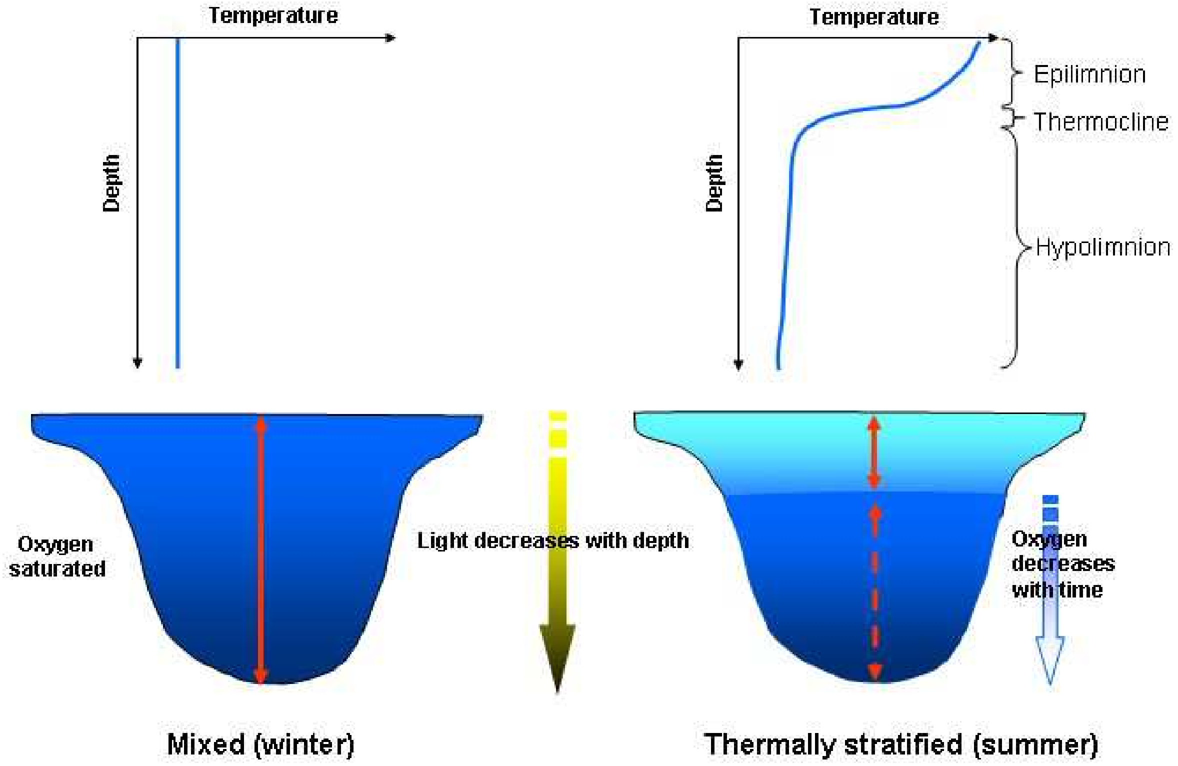


**Figure 3-2: Schematic diagram of a lake showing the concept of fully mixed and thermally stratified.**

As the lake cools in winter, the temperature difference between epilimnion and hypolimnion reduces and the resistance to mixing decreases. When the epilimnion temperature equals the hypolimnion temperature, the water column is said to be isothermal (has the same temperature throughout the lake depth) and has virtually no resistance to wind-induced mixing. If wind mixing doesn’t occur and the epilimnion cools further, the surface water will become denser (heavier) than the water below and mixing will occur with the epilimnion falling to the bottom and the hypolimnion rising to the top as the water column turns over. Because of this phenomenon, the mixing phase at the end of a stratified period, be it temperature driven or driven by a wind mixing event, is referred to as “turnover”.

New Zealand lakes can be classified into several types as defined by thermal stratification:

1) **Shallow lakes**, which do not develop stable thermal stratification for prolonged periods (> a few days). These lakes are typically < 3 m deep and exposed to the prevailing winds. They may develop a temperature gradient during the course of a day during summer but this will be rapidly dissipated by light to moderate winds or night time cooling.

2) **Dimictic lakes**, which have a warm stratification phase in summer and a cold inverse stratification phase in winter, often associated with a temporary ice cover. There is a turnover mixing period between each stratification phase. These lakes mostly occur in the South Island and are usually relatively small, high altitude lakes.

3) **Monomictic lakes** which stratify once in spring and remain stably stratified through the summer season before winter turnover. These lakes are generally deep (>20m)

although shallower lakes may be monomictic if they are protected/sheltered from the effects of strong winds.

4) **Polymictic lakes** which thermally stratify for short periods before being mixed by wind, and will experience several episodes of thermal stratification over the summer. They are typically relatively shallow (3 m to 20 m depth) and exposed to the wind.

5) **Meromictic lakes** which remain stably thermally stratified throughout the year. These lakes are usually small but deep and protected/sheltered from the wind. Flooded quarries are often meromictic.

In each of these types of lake, the mechanism for stratification is driven by the temperature-induced density difference between the different layers. The larger the density difference, the stronger the stratification and the resistance to wind-induced mixing. Strong thermal stratification also increases the strength of the thermocline as a barrier to the transport of oxygen from the epilimnion to the hypolimnion and the diffusion of nutrients from the hypolimnion to the epilimnion.

A special case occurs where heated water from geothermal sources or industrial cooling water enters the lake and forms a warm layer on the surface. Lake Aratiatia, the first hydro-power dam on the Waikato River, is an example where the lake receives a warm cooling water discharge from the Wairakei Geothermal Power Station and the lake becomes thermally stratified. [The Wairakei Geothermal Power Station draws cold river water into its cooling water system and returns it to the river without addition of any geothermal fluid.] In this case the thermal stratification occurs at night when the flow through the Aratiatia Power Station is low allowing the water level in the lake to rise ready for peak generation in the morning. When peak generation occurs, the lake is rapidly mixed with the cold water from the Waikato River and it cools again.

### 3.3.2 Density stratification

Stratification can also occur where there is a difference in the density of an inflow to an otherwise freshwater lake. The most common causes of density differences are:

1) Suspended sediments during flood events. The suspended matter give the water a higher density and that water flows to the bottom of the lake as a density current. It can be a problem in water supply reservoirs where there is no provision for changing the depth of the take-off valve. Given time, the suspended matter settles and the lake will mix again.

2) Salinity differences that occur when seawater enters the lake as a salt wedge either flowing up the outflow from a coastal lagoon or seeping through the ground as a saline intrusion into a dune lake. Lake Aratiatia is a special case where the slightly saline hot water from the Wairakei Stream enters the lake and sinks to the bottom because the density of the stream water is greater than the lake water despite it being hot (~35˚C) when it enters the lake.

Because of the two very different hot water inflows to Lake Aratiatia, at night Lake Aratiatia develops a three-layered system – a warm, oxygen depleted surface layer, a cold, well oxygenated middle layer, and a warm, oxygen depleted slightly saline layer on the bottom.

Consequently, at night the trout in Lake Aratiatia are restricted to the cold middle layer, or the bottom of the few small cold-water inflows.

### 3.3.3 Depth of mixing

The depth of thermal stratification is an important factor for phytoplankton growth. When the lake is fully mixed in winter, the average phytoplankton cell will travel through the full depth of the water column with the vertical mixing currents. This means that the phytoplankton cell will be carried below the euphotic zone where there is insufficient light to support phytoplankton growth and will stop growing until the circulation current brings it back up into the euphotic zone again. All else being equal, the growth of phytoplankton is therefore dependent on the average light level to which the cells are exposed.

The amount of time spent in the euphotic zone determines the rate at which phytoplankton biomass increases while the time spent in the dark determines the loss of phytoplankton biomass through cell death. The theoretical depth at which phytoplankton growth in the euphotic zone is matched by losses of phytoplankton biomass in the dark is known as the “critical depth” (Sverdrup 1953).

In contrast to the fully mixed lake in winter where the phytoplankton are exposed to low average light, thermal stratification in summer prevents phytoplankton from being carried below the epilimnion and they are exposed to high average light levels. Consequently, phytoplankton in the epilimnion of a thermally stratified lake tend to grow faster than in a fully mixed lake (Figure 3-3). The exceptions are very large clear lakes such as Lake Taupo.

Destratification is a management option to control algal proliferation in some lakes.

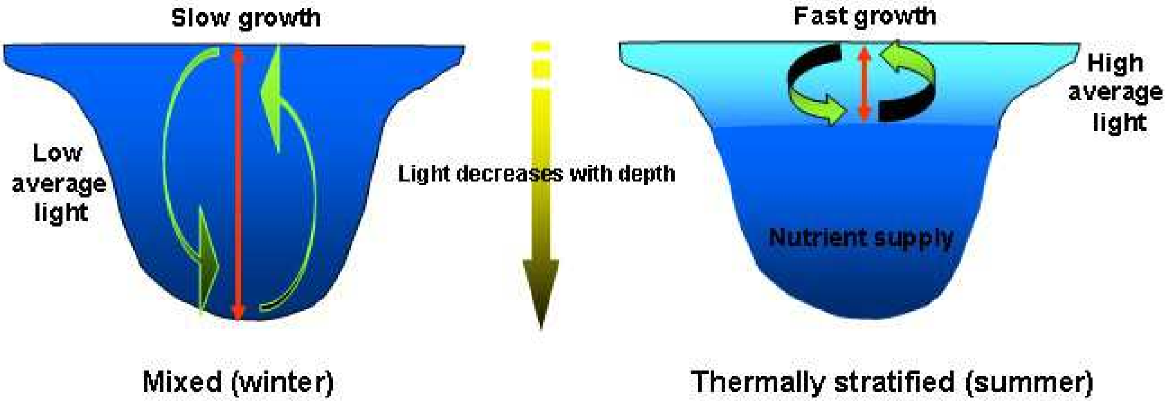


**Figure 3-3: Schematic diagram illustrating the effect of thermal stratification on the growth of phytoplankton in a lake.**

## 3.4 Dissolved oxygen

Dissolved oxygen (DO) is a key indicator of the “health” of a lake (Burns 1995) with high DO concentrations in both the hypolimnion and epilimnion being associated with good health.

Oxygen solubility in water is a function of temperature and pressure. At sea level, oxygen saturated warm water at 25°C has a DO concentration of 8.2 g $m^{-3}$ which is 27% less oxygen than in colder water at 10°C which has a DO concentration of 11.3 g $m^{-3}$. Lakes at an altitude of 400 m above sea level will have a saturation concentration 4% lower than at sea level due to the lower atmospheric pressure. Increasing salinity also decreases DO solubility in water.

Oxygen in water is derived from air dissolved in the lake water and it is that process which defines the maximum or 100% saturation value for DO. Aquatic plants including phytoplankton and macrophytes can increase the DO concentration due to photosynthesis during the day, producing supersaturated water. At night, plant and microbial respiration processes can consume some of the DO, which is not replenished by photosynthesis, reducing the DO concentration to less than 100%. This is called oxygen depletion. Over a 24 hour period (diel cycle) the DO concentration will rise and fall with the highest DO concentrations in the mid-afternoon and lowest concentrations just before dawn.

In a healthy lake these diel fluctuations in DO concentration will be small. As the lake becomes eutrophic the rate of oxygen depletion exceeds the re-oxygenation due to photosynthesis and the DO concentration in the lake falls below 100%. Wind-induced mixing events (storms) can re-oxygenate the water column when DO is below saturation. Conversely, during calm periods which support thermal stratification, the thermocline can reduce or completely block the transfer or diffusion of oxygen from the epilimnion to the hypolimnion. Under these conditions, DO concentrations can become severely depleted and may fall to zero. The oxygen consumed is released as carbon dioxide ($CO_2$) which dissolves in the water or escapes as gas bubbles.

The zero oxygen condition occurs in the sediment first, as that is where the carbon source is that supports the microbial process of decomposition and oxygen consumption. Sediment conditions with zero DO but with molecules with oxygen such as nitrate ($NO_3$) and sulphate ($SO_4$) are defined as **anoxic**. Further microbial processing strips the oxygen atoms from these molecules, releasing it as $CO_2$. When all of the molecular oxygen is gone the sediment condition is defined as **anaerobic**.

The distinction between anoxic and anaerobic conditions is important because it defines the microbial processes that can occur. For example, microbial denitrification only occurs in anoxic conditions because there is $NO_3$ present. However, while surface layers of the sediment are anoxic, deeper into the sediment anaerobic conditions will prevail. Under anaerobic conditions, organic nitrogen is mineralised into ammonium ($NH_4$-N) and hydrogen sulphide ($H_2S$) and black iron and manganese sulphides are the main form of sulphur.

When microbial processes deplete the oxygen to zero in the lake water overlying the sediments, the hypolimnion becomes anoxic and geochemical processes of mineral reduction occur. Under these conditions, insoluble metal oxides such as iron (Fe) and manganese (Mn) dissolve to release these trace elements into the water column. When the hypolimnion becomes re-oxygenated again, the metal oxides form and precipitate down into the sediment once more i.e., the reduction – oxidation (REDOX) cycle is reversible.

The REDOX process mostly occurs in the sediment of an oxygenated lake. Metals in their soluble reduced form occur deep in the sediment below insoluble metal oxides near the surface that have formed through contact with oxygen in the overlying lake water. Between these two conditions there is an equilibrium between the soluble and insoluble components. However, the soluble component tends to diffuse up through the sediment towards the oxygenated water where it is oxidised to the insoluble form. This changes the balance in the equilibrium state and more of the soluble component diffuses up towards the surface. The result of this process is that the concentration profile in the sediment changes with the deeper sediment becoming depleted and the near surface sediments becoming enriched in that compound. This process is known as diagenesis and it is important in the recycling of the nutrient phosphorus from the sediment.

## 3.5 Nutrient cycling

The general function and processes occurring in lakes are well known and the sediment-water interface processes have been variously described in numerous papers and text books (e.g., Wetzel 1975; Spears et al. 2007; Beutel et al. 2008) since the first detailed study by Mortimer (1941; 1942). In general, nutrients nitrogen (N) and phosphorus (P) from catchment sources enter a lake mostly via surface river inflows and groundwater. If the hydraulic residence time is long, particulate organic matter, including the phytoplankton that grew on the dissolved N, P, and $CO_2$ in the inflows and lake, will settle out of the lake water and accumulate in the sediments. Microbial decomposition processes in the sediment use the carbon for energy and consume oxygen, often causing the sediment to become oxygen depleted and eventually, in degraded lakes, anoxic. During this process both N and P are mineralised and released into the anoxic sediment pore-water in soluble inorganic forms. Nitrogen is released in the ammoniacal form, $NH_4$, which is then oxidised to the nitrate form, $NO_3$, by nitrifying bacteria (nitrification) as it diffuses up and out of the sediment into the oxygenated overlying water. At the sediment-water interface, the $NO_3$ produced may be further transformed into nitrogen gases ($N_2O$ and $N_2$) by denitrifying bacteria (denitrification) and permanently lost from the lake. The rate of this process is regulated by temperature and requires the oxic/anoxic boundary to be in or on the sediment, which provides a physical substrate to support the bacterial populations. The $NO_3$ found in the lake water is the sum of the net excess released from the sediment after denitrification, plus new $NO_3$ from the river inflows and in the groundwater entering through the bed of the lake.

In contrast to N, P released into the sediment pore-water as dissolved reactive phosphorus (DRP) only remains in solution under anoxic conditions. As the DRP diffuses up out of the sediment towards well oxygenated overlying lake water, it is sequestered by metals such as iron (Fe), manganese (Mn), aluminium (Al) and calcium (Ca) in the sediment and adsorbed onto the surface of their oxides. Consequently, in a well oxygenated lake, there is generally very little DRP available in the lake water for the growth of phytoplankton. The difference between these diffusion pathways and thus the sediment release rates of N and P, leads to the storage of P in the sediments near the surface. Because some N is lost through denitrification, over time there is a shift in the N:P ratio from the fresh plant material ratio of around 7.2:1 by weight (Redfield 1958) to generally less than 5:1 in the sediments.

In a well oxygenated eutrophic lake there will be low concentrations of DRP, $NH_4$ and the trace metals Fe and Mn but high concentrations of $NO_3$.

The sequestration of P from the water column by P-to-metal interactions, is regulated by oxygen. As the DO concentration in the hypolimnion falls towards zero, REDOX potential becomes less positive and insoluble metal oxides dissolve, releasing any DRP that was bound to their oxide form. Because these geochemical transformations occur at specific REDOX potentials, they can be linked to the DO concentration in the lake water at a pH of around 7 (Stumm & Morgan 1995). For example, the dissolution of manganese oxide to $Mn^{2+}$

begins when the REDOX potential falls below 0.55 Eh Volts, which equates to a DO concentration of about 5 g $m^{-3}$ (Figure 3-4), but the dissolution of iron oxide to $Fe^{2+}$ begins when the REDOX potential falls below 0.1 Eh Volts, which equates to a DO concentration of about 2 g $m^{-3}$ (Achterberg et al. 1995; Stumm & Morgan 1995). When the DO concentration reaches zero, nitrification stops and $NH_4$ can diffuse into the hypolimnion. Any $NO_3$ left in the lake water will gradually be removed by denitrification and the hypolimnion will be found to have elevated concentrations of DRP and $NH_4$-N. Consequently, in the anoxic bottom waters of an eutrophic lake there will be elevated concentrations of DRP, $NH_4$-N and the trace metals Fe and Mn but very low concentrations of $NO_3$-N.

Based on the different Eh volts associated with different metal, the presence of elevated concentrations of Mn in the water column would be an indication that a reservoir was becoming oxygen depleted (Figure 3-4). An example of where this has occurred is in the Maitai reservoir, which is part of the Nelson City water supply system. Periodic elevated concentrations of Mn were reported in the Maitai River below the reservoir in summer (Holms, 2010) and the potential for metal toxicity in the downstream invertebrate community was investigated. Examination of the seasonal change in temperature, dissolved oxygen and Mn concentrations showed that the reservoir (depth 27 m) thermally stratified in summer and the DO in the hypolimnion fell to < 2 g $m^{-3}$ by March (Olsen, 2010). As the DO concentrations fell, the Mn concentration increased to >1.2 g $m^{-3}$ (Holms, 2010).

A possible solution to this problem would be to install an aeration system in the reservoir to maintain a DO concentration above 6 g $m^{-3}$, which would keep the Mn in the reservoir sediment. (See section 3.11).

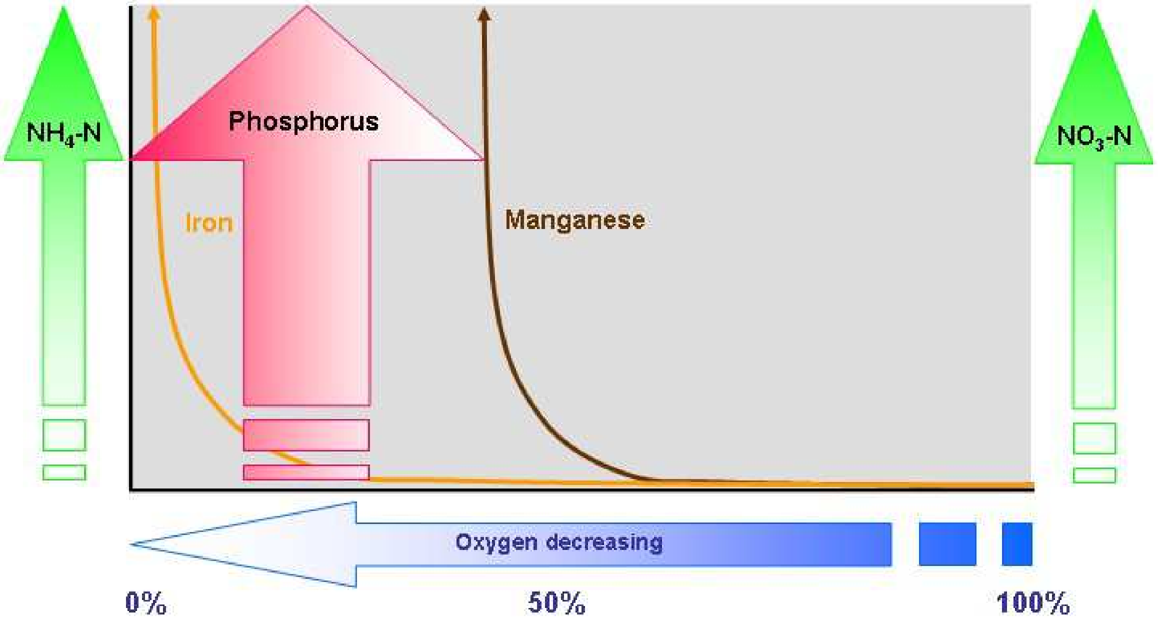


**Figure 3-4: Biogeochemical processes in a lake that are directly controlled by oxygen.** Upward arrows indicate increasing concentration while their horizontal position indicates the level of oxygen for transitions. Under fully oxygenated conditions phosphorus is bound to oxides of manganese and iron but, as the oxygen concentrations fall, the phosphorus is released from these metals (manganese first then iron) as they are reduced to their soluble forms. Ammonium-N ($NH_4$-N) is continuously released from the sediment at all oxygen levels but is oxidised (nitrified) to nitrate-N ($NO_3$-N) under well oxygenated conditions. Without oxygen $NH_4$-N appears in the water column.

## 3.6 Phytoplankton growth

Phytoplankton are free floating microscopic plants commonly known as algae. As with vascular plants they require light, nutrients and a suitable substrate for growth. For phytoplankton the substrate is water, and freshwater phytoplankton species will not tolerate brackish or saline conditions. In general, phytoplankton require the plant nutrients N and P and $CO_2$ in the atomic C:N:P ratio of 106:16:1 which equates to a mass ratio of 42:7.2:1 (Redfield 1958). The C:N ratio in a phytoplankton cell can vary considerably depending on the species, but all have the same basic minimum requirement for N:P in the ratio of 7.2:1 by weight.

### 3.6.1 Phytoplankton classification

The basic phytoplankton classes comprise Diatoms (Bracillariophyceae), Greens (Chlorophyceae), Blue-greens (Cyanophyceae), Dinoflagellates (Dinophyceae), Desmids (Desmidiaceae) and Chrysophyta (Chrysophyceae), the latter two classes being generally minor components of the phytoplankton community. Each phytoplankton species has a “niche” which allows them to compete with other species and survive.

- **Diatoms** have a heavy silicon sheath structure which causes them to sink rapidly in calm conditions but helps them capture light and survive during deep mixing events. They become dominant under turbulent conditions in winter but they have little or no control over their position in the water column. They use dissolved N and P nutrients for growth but also require silicon for their sheath. Growth for all groups can be limited by a lack of any one of these three nutrients and occasionally by micronutrients such as cobalt or molybdenum.

- **Greens** do not have silicon sheaths and require only dissolved N and P nutrients for growth – a lack of either nutrient can limit their growth. They also prefer turbulent conditions but have the ability adjust their depth in the water column in calm conditions through the production of mucilage and lipids. They often form large colonies, some of which can float in the upper water column e.g., *Botryococcus*. They possess flagella, which in some species allow limited capacity for movement.

- **Blue-greens — cyanobacteria** — also do not have silicon sheaths and require only N and P for growth. However, unlike other phytoplankton species some cyanobacteria have the ability to use atmospheric nitrogen as their N supply when dissolved inorganic N is in low supply. When there is a surplus of P in the water column, cyanobacteria can store additional P as a “luxury uptake” for use when P is less abundant. Cyanobacteria prefer calm conditions and often have gas vacuoles to allow them to be buoyant in the water column. Heavy carbohydrates (sugars) produced by photosynthesis cause them to sink. If they sink below the euphotic zone, these sugars are utilised for respiration (producing $CO_2$), and the buoyancy imparted by gas vesicles becomes dominant over sinking from sugars, causing them to rise to the surface. In high abundance, cyanobacteria can shade other phytoplankton species reducing their growth rate and thus out-competing them. Their nitrogen-fixing capability and ability to regulate their position in the water column allow them to out-compete most other species. The major problems with cyanobacteria are: that several species can produce toxins which put an unpleasant taste and odour in the water and make the water toxic to humans and other animals, and they form nuisance blooms which result in wind drift scums along the lake shore which produce unpleasant odours as they die.

- **Dinoflagellates** are phytoplankton with thick carbon sheaths or theca around each cell. They use dissolved N and P and fix carbon as an energy source. Some species can predate other organisms, enveloping them and digesting them. They are motile using flagella to move in the water column. Some species have the ability to move up and down through the thermocline as dinoflagellates have two flagella. This allows them to go down into the hypolimnion where they can obtain nutrients then move up into the epilimnion to get enough light for growth. Dinoflagellates can produce toxins and impart unpleasant taste and odour in the lake water.

Mucilaginous species, such as some diatoms, and the super abundance of others phytoplankton can cause problems when they bloom by blocking water supply filters.

### 3.6.2 Phytoplankton blooms

A rapid seasonal growth of any phytoplankton species over and above their mean annual biomass is referred to as a bloom. A bloom is a special condition because it is usually not a sustainable growth condition and is likely to collapse. When it does collapse, the phytoplankton decompose and release the nutrients from their cells. The decomposition process will also consume DO and may result in anoxic conditions with a subsequent release of nutrients from the sediment that could, in turn, stimulate the growth of another phytoplankton species.

Not all apparent "blooms" are the result of rapid growth. Buoyant phytoplankton species (e.g., cyanobacteria; *Botryococcus braunii*, a colonial green algae) that can float to the surface under calm conditions may form nuisance scums on the lake surface without sudden growth (Figure 3-5). Under windy conditions, the phytoplankton cells are relatively evenly dispersed throughout the mixed depth of the water column and the water appears clear. When the turbulent mixing due to the wind stops, the cells float to the surface where they aggregate. A light breeze causes the aggregation to drift inshore where it forms a scum.

The apparent bloom can be present one day and gone the next, only to appear somewhere else when the wind stops and light breezes come from a different direction.

To cope with this type of algal proliferation in water supply reservoirs, especially when the dominant species is a cyanobacteria species, water can be drawn from a deep offtake valve which is well below the depth of the surface scum layer.

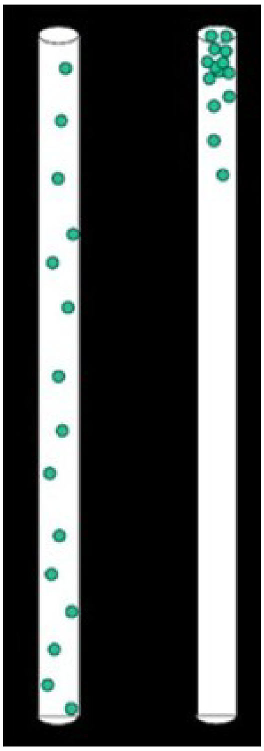


**Figure 3-5: Schematic showing the formation of a cyanobacterial scum in calm conditions without any change in cell abundance or growth.** Left = mixed, Right = calm. [Conceptual schematic diagram redrawn from Prof D. Hamilton, University of Waikato].

When phytoplankton blooms reach the shore line they can wash up leaving malodourous decaying material on the beach. When they become trapped in marginal buffer zone plants, their decomposition provides additional nutrients for those plants. Usually the proliferation of any phytoplankton species is prevented from reaching bloom proportions by grazing by herbivores such as herbivorous fish or zooplankton.

## 3.7 Zooplankton

Zooplankton are tiny organisms that cannot produce their own food and thus consume phytoplankton to survive. The abundance of zooplankton in a lake is a direct function of the available food supply i.e., the abundance of phytoplankton and bacterioplankton (mostly flagellates and ciliates) in the microbial loop (Pomeroy et al. 2007) (Figure 3-6). Zooplankton numbers increase after the phytoplankton proliferation, and continue to increase after the phytoplankton abundance declines due to the large biomass in the microbial loop. As phytoplankton senesce they release dissolved organic carbon in the form of proteins, carbohydrates, lipids and nucleic acids, which are utilised by bacteria. Bacterial production is very important and can be more than 30% of primary production. The microbial loop is functionally intertwined with the “food web” (Figure 3-6). Phytoplankton are just one of the prey items of zooplankton and this idealised predator-prey scenario rarely eventuates. As the food supply declines the zooplankton abundance declines. Consequently, there is always a lag between the phytoplankton and zooplankton growth cycles.

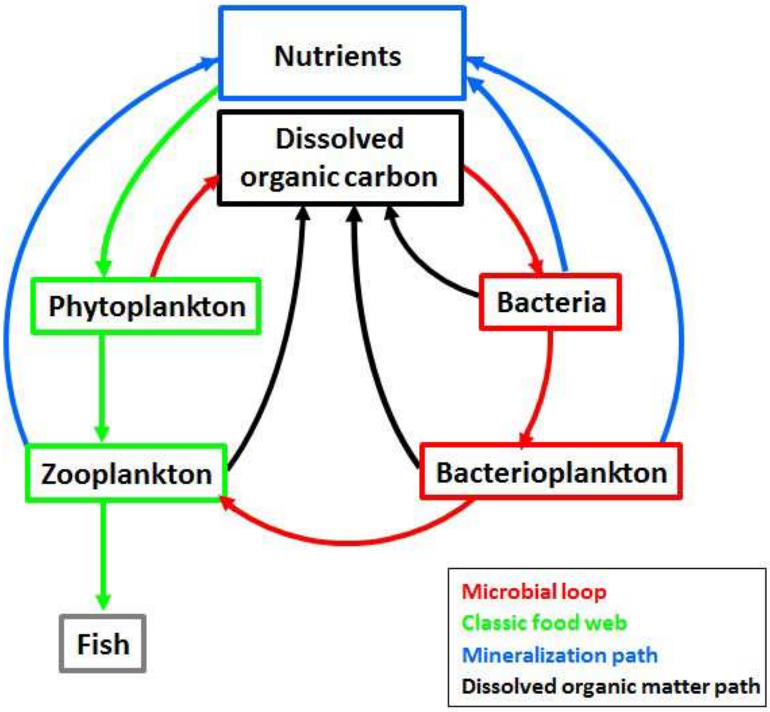


**Figure 3-6: Schematic diagram of the microbial loop and the classic food web.**

Zooplankton are part of the food web and consequently they are food/prey for juvenile fish. When fish numbers increase, zooplankton numbers decrease and phytoplankton can utilize the nutrients including those released from the microbial loop to increase in abundance.

## 3.8 Invertebrates and polychaetes

Invertebrates (aquatic insects) and polychaetes (worms or nematodes) are also part of the food web in a lake. They are widely distributed through most lakes in New Zealand, but they become more abundant near a source of food in eutrophic lakes. Polychaetes live in the sediments and are likely to be most abundant around waste water effluent discharges and “polluted” inflows. The most common invertebrate are chironomids commonly known as “lake flies” (Forsyth, 1971, 1978, 1986; Forsyth & James 1988). Although they look similar to mosquitoes and have a similar life cycle, chironomids have no biting mouth parts. Chironomid larvae spend their life in the surficial sediments and are commonly known as “blood worms” because of their bright red colour. They can tolerate very low oxygen and are more abundant in eutrophic lakes where the sediments are organically rich. However, their presence does not imply the lake is degraded e.g., they can be found in the bottom of Lake Taupo from the shallows to depths of more than 160 m. The blood worms pupate in the sediment then rise to the surface where they emerge / hatch together to mate. At this time they are an important food for juvenile fish and other predatory invertebrates in the lake and for spiders and birds such as swallows and fantails above the lake.

The lake fly hatch can be spectacular as the myriads of insects form swirling clouds above the lake. They are short-lived and, after laying eggs, they die. During the time of the hatch they become a serious nuisance to local residents and users of the lake.

In newly filled artificial lakes e.g., Lake Dunstan, the first macroinvertebrate species to colonise the lake bottom are likely to be predatory species of beetles, boatmen, damsel flies and dragonflies (Brain Smith, NIWA, pers. comm.). After that, the chironomids will begin to colonise the lake sediments.

## 3.9 Macrophytes, microphytes and periphyton

Apart from phytoplankton, lakes support a range of larger plants which are mostly not free floating and require a substrate such as sediment or another plant for support. The largest of these are macrophytes, commonly called “lake weeds”. Free floating macrophytes that can cause problems include hornwort (*Ceratophyllum demersum*) which is a large submerged macrophyte, and duckweed (*Lemna minor*) and azolla (*Azolla rubra* and *A. pinnata*), which are small surface plants that can cover large areas and are mainly a problem in smaller ponds. Macrophytes are typically vascular plants and share many of the characteristics of terrestrial plants including being annuals or perennials and having a well-defined seasonal growth cycle. Different species have different tolerances to turbulence and in shallow lakes they can cover the entire bed of the lake holding the sediment against disturbance by lake currents. In larger deeper lakes they cannot become established along exposed shorelines due to wave action.

They have different depth tolerances with native charophyte species producing low growing meadows which extend down to the light limitation depth of the euphotic zone. Exotic macrophytes such as the “oxygen weeds” *Lagarosiphon major*, *Elodea canadensis* and *Egeria densa* are more robust than the native species and are regarded as pest species, as is *Ceratophyllum demersum*. These plants can grow though several metres water depth smothering the native plants. Periphyton are smaller attached plants that can grow on rocks (lithophytes) or on larger plants (epiphytes). They are often filamentous producing long strands in sheltered embayments. Microphytes are benthic phytoplankton that live on or in the surface of the sediment where they have access to the nutrients seeping into the lake with the groundwater.

In their growth phase, macrophytes can take nutrients from both the sediment and the water column but when they collapse, those nutrients are returned to the lake water column. Where this collapse occurs in shallow lakes, the decaying leaves lying on the lake bed block oxygen diffusion into the sediment and causing nutrient releases which, in turn, can stimulate phytoplankton proliferation or blooms. Established macrophyte beds can be disturbed or destroyed by pest fish such as rudd and tench, leaving the lake bed vulnerable to sediment re-suspension and the generation of highly turbid conditions.

*Egeria densa* has a “boom and bust” growth cycle. Initially, the macrophyte grows rapidly, spreading across the lake, out competing all other macrophyte species (boom phase). When it collapses it releases all the nutrients in its cells and smothers the sediment causing localised anoxic conditions at the sediment water interface (bust phase). The rapid release of nutrients stimulates phytoplankton growth which, in conjunction with re-suspended sediment can block light to support macrophyte growth causing the lake to “flip” from a clear water macrophyte-dominated system to a turbid phytoplankton-dominated system. Lake Omapere is a classic example of this phenomenon.

## 3.10 Density currents

### 3.10.1 River inflows

Temperature differences between the river inflow and the receiving lake water result in density differences with the warmer water being less dense than the colder water. This density difference affects where inflowing water will mix in a lake. When the inflow water is warmer than the lake water, the inflow water will enter the lake as a buoyant plume flowing over the cooler lake water until mixing occurs through turbulence due to wave action.

If the inflow water is colder than the lake water, the inflow water will plunge as it enters the lake and underflow as a density current down the sloping bed of the lake until it reaches a depth where the temperature differential is zero. At that point the density current will lift off the bottom and insert as an intrusion layer across the lake (e.g., Spigel et al. 2005). If an equal temperature is not found, the density current will continue to flow down the bed of the lake displacing the existing water as the inflow water pools in the deepest part of the lake (Figure 3-7). As the density current plunges, it entrains surface water into the flow, increasing the volume of the density current and changing the nutrient content of the flow from the original inflow nutrient content, depending on the quality of the surface water entrained.

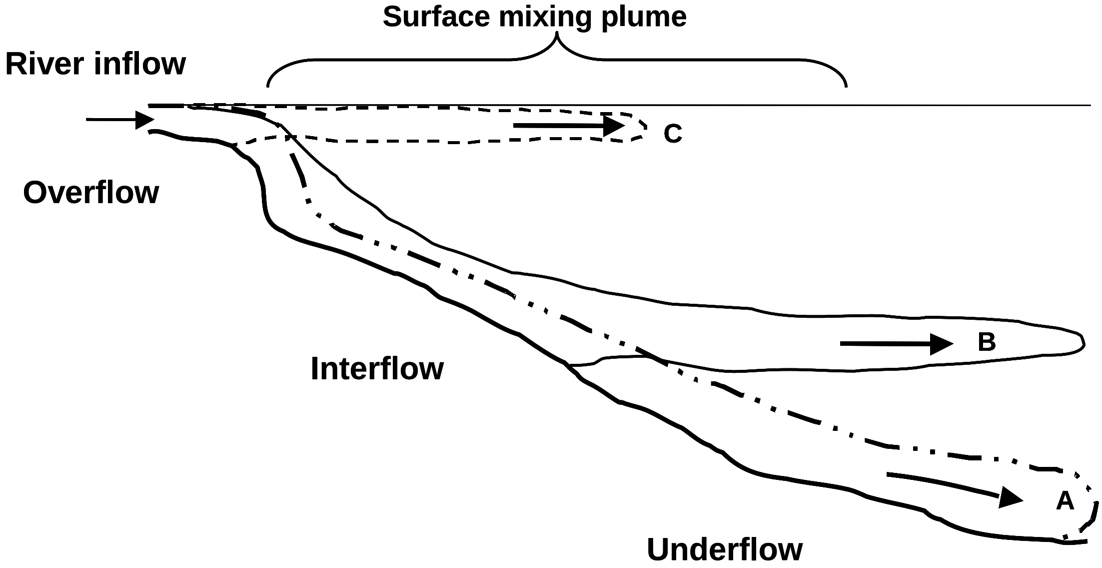


**Figure 3-7: Density currents.** A) Very cold water will become an underflow along the lake bed, B) medium temperature water will plunge to a depth of equal density where it becomes an interflow, C) warmer water enters the lake surface as a buoyant overflow which may form a visible plume on the surface. Both interflow and underflow entrain surface water with the flow.

In Lake Rotoiti, the underflowing density current from Lake Rotorua displaced about 25% of the volume of Lake Rotoiti annually (Vincent et al. 1991) and caused the accelerated eutrophication of Lake Rotoiti. The stronger the inflow the further the intrusion layer will move. In Lake Taupo the density current intrusion layer associated with the Tongariro River inflow has been detected as a discrete layer >20 km from the river mouth. Intruding density currents also occur in Lake Ohakuri, associated with saline geothermal inflows, and in Lake Maraetai, associated with Kinleith pulp mill.

The importance of density currents is that, as they plunge, they entrain surface lake water into the current which increases the size of the flow and thus the hydraulic inertia of the flow. The entrainment factor is dependent on the density difference and the velocity of the inflowing water. Field observations in Lake Rotoiti and Lake Taupo indicate that the entrainment factor may be 5 to 10 times the inflow. This means that a river inflow of 5 $m^3 s^{-1}$ can induce a density current with a flow of 25 to 50 $m^3 s^{-1}$. The entrained water will warm the density current so that it does not insert at the depth expected by equating the inflow and lake temperatures at a given depth. Furthermore, because the inflow temperature will warm and cool on a daily cycle, the density current may change from being a cold underflow in the morning to being a warm overflow by afternoon (Vincent et al. 1991).

Because of the large component of surface lake water in that flow, the water quality of the density current will be dominated by the water quality of the lake at the plunge point (e.g., DO, suspended solids, nutrients, phytoplankton). These water quality components will be transported through the lake by the density current. The depth of insertion then becomes important where an underflow carries oxygen into the hypolimnion thus reducing the degree of oxygen depletion and thus nutrient release from the sediment. This may occur mainly at night when the inflow temperature is colder. The entrained oxygen will offset respiration rates which are likely to be highest at that time.

Whereas the cold underflow may carry the nutrients in the inflow below the euphotic zone at night and in the morning during the spring growth phase, warm overflowing water will inject those nutrients into the epilimnion where they can support or stimulate phytoplankton growth in the euphotic zone. This effect can lead to phytoplankton proliferation during the summer stratified period when the epilimnion would otherwise be depleted in nutrients.

### 3.10.2 Turbidity currents

A turbidity current is a special form of density current where the density is strongly altered by the amount of sediment in the water. It is defined as a current of rapidly moving, sediment-laden water moving down a slope through water, or another fluid. The current moves because it has a higher density and turbidity than the fluid through which it flows. The driving force of a turbidity current is obtained from the sediment, which renders the turbid water heavier than the clear water above. It is commonly associated with floods events where mud slips have entered the river entering the lake. A turbidity current can deposit a large amount of sediment in the bottom of the lake and in extreme cases can over whelm the offtake structure.

### 3.10.3 Groundwater

Unlike stream and river inflows which flow out into the body of the lake as a “jet”, groundwater slowly seeps into the lake around the shoreline margins and in the near-shore waters when there are deep groundwater inflows. Groundwater may have order of magnitude higher nutrient concentrations than the surface inflows and, unlike stream and river inflows, the temperature of the groundwater remains almost constant throughout the year as it is thermally buffered by the soil through which it flows. Consequently, the temperature of the lake water will determine how the groundwater and associated nutrients mix in the lake.

In summer, when the lake water is warmer than the groundwater, the groundwater will flow as a thin density current layer across the lake bed. Because this is a high light area, nutrients in the groundwater will support and stimulate the growth of periphyton and microphytes on the lake bed in sheltered areas. In exposed areas, this inshore (littoral) zone is subjected to wave action which will disperse the nutrients and prevent the growth of periphyton and microphytes. In winter, when the lake may be colder than the groundwater, the groundwater and associated nutrients will rise from the bed of the lake and disperse with minimal local effect.

### 3.10.4 Selective draw

Selective draw-induced stratification is a man-made effect in a water supply reservoir or hydro-power dam (See the case study in section 6.1). Under normal conditions the reservoir or dam lake would have a temperature profile which continuously decreases with increasing depth. If water is drawn from a take-off valve at a mid-water column depth rather than flowing over the surface spillway, water will be drawn down from the top but not up from the bottom. This is because the draw requires a hydraulic head to force the water out of the valve and it cannot get that driving force from the water below the valve. The result is that the upper water column is drawn down towards the take-off valve and, because the upper water column is generally warmer that the bottom, the water column becomes thermally stratified at the depth of the draw. This type of stratification is likely to result in the water below the draw depth becoming stagnant, anoxic and nutrient enriched if there are high levels of productivity. It is often referred to as the “dead” volume of the lake (Figure 3-8).

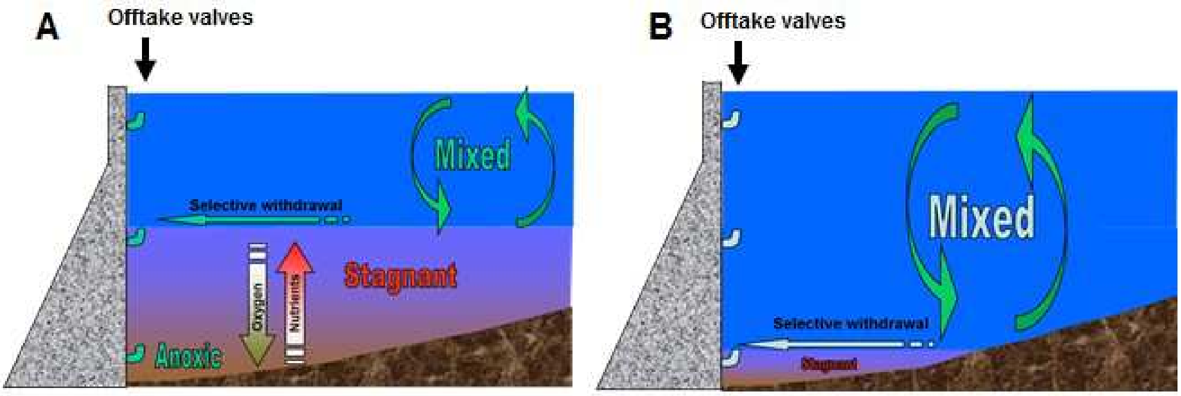


**Figure 3-8. Selective draw** from a mid-depth (**A**) causes stagnation or dead volume in the water below that depth because there is no mechanism for mixing oxygen below the draw depth. In practice it is better to draw from the lowest depth (**B**) so that the dead volume is minimal.

Placing the draw depth as deep as possible in the water column reduces the dead volume and the area of lake bed affected by stagnant water. The influence of density currents may ameliorate the water quality in the dead zone or even flush it. Conversely, under flood conditions, the density current may transport muddy water along the bottom applying new silt to the bed in the dead zone and causing the deep intake to draw muddy water. Consequently, the offtake structure in a reservoir often has offtake valves at more than one depth. A scour valve is often set at the deepest point through the dam wall to allow sediment build up to be reduced. This valve may also provide compensation water as required to maintain minimum flows in the downstream river if the normal operation of the reservoir does not provide enough water for that purpose.

However, even with a bottom draw depth, very deep lakes may still become oxygen depleted in the bottom water for a short period over the summer. An anoxic water discharge would adversely affect the downstream aquatic biota. To prevent this, well oxygenated water from the upper water column is blended with the bottom water to maintain a minimum DO concentration in the discharge water. This can be further aerated by engineering structures that cause the discharged water to have a high degree of turbulence or even spray into the air so that it can adsorb oxygen from the air.

Alternatively, an aeration system can be installed in the lake to mix the water column and prevent oxygen depletion occurring.

## 3.11 Aeration and oxygenation

For lakes and reservoirs that stratify in summer and develop an anoxic hypolimnion, aeration and oxygenation techniques can be used to replenish the DO concentration in the water. Aeration makes use of the oxygen in the air while oxygenation uses pure oxygen to achieve re-oxygenation. The aeration system used depends on whether the thermal stratification is to be removed through mixing or retained and just the hypolimnion is to be oxygenated.

### 3.11.1 Aeration with mixing

In many reservoirs, it is important to maintain well oxygenated water as a potable supply. In temperate regions these lakes can be managed for full DO saturation by placing an aeration bubbler (aerator) as a long strip at the outlet end of the lake (Nordin & McKean 1982). When compressed air is pumped into the aerator, it produces a curtain of bubbles that rise to the surface. Because water with air bubbles is less dense than normal water, that water rises and sets up a circulation current. The rising water disperses laterally through the upper water column while near bottom water is drawn towards the aerator by the entrainment current. Aeration is achieved by mixing the bottom water into the surface where it can dissolve oxygen from the air. The excess water above the thermocline forces the thermocline down until it reaches the lake bed and the whole lake is mixed (Figure 3-9A).

The placement of the aerator near the dam wall in the reservoir causes the current generated by the rising bubble plume to move upstream at the lake surface. This is because the dam wall constrains the current flow – it cannot move downstream through the dam wall. If the reservoir is elongated as in narrow riverine reservoirs, the current flow will be further constrained on each side and the efficiency of mixing will increase.

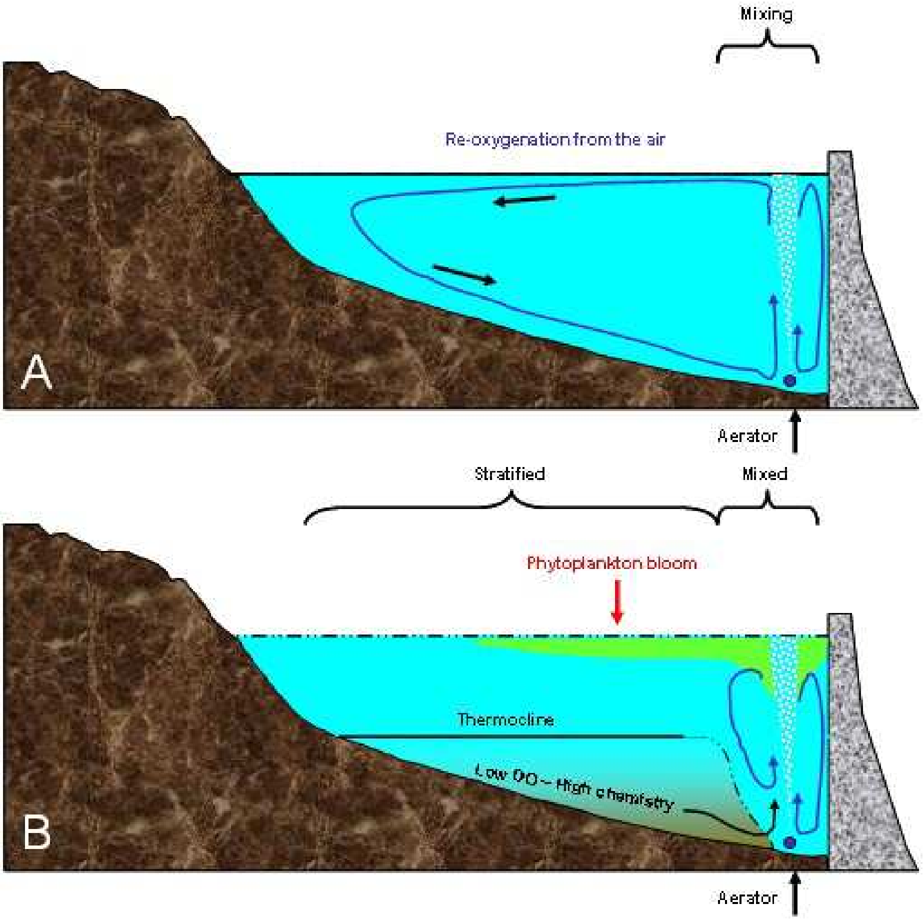


**Figure 3-9: Aeration in reservoirs.** A) Timed correctly, aeration generates a circulation current that allows the lake water to absorb oxygen from the air before moving to the bottom of the lake. B) Starting after thermal stratification, aeration can mix nutrients from the hypolimnion into the epilimnion where they can stimulate phytoplankton growth.

Start-up timing for aeration is important (Figure 3-9B). If the hypolimnion has already gone anoxic, mixing the water column will send high concentrations of nutrients up into the surface water where they may stimulate a phytoplankton bloom. An example of this is from a water supply reservoir (Figure 3-10) where, after many years of operation with medium water quality achieved by switching between offtake valves at different depths, an aerator was installed in 2000. The aerator was turned on in January and stimulated a major cyanobacteria bloom. In this example, black arrows indicate that the turn on was at the wrong time while green arrows indicate turn on at the correct time. In 2005 the aerator was left on for the full year and it sustained the cyanobacteria bloom. After 2007, the aerator was turned on before the DO levels had fallen below 6 g m$^{-3}$ and there have been no major blooms since. (See the case study in section 6.1).

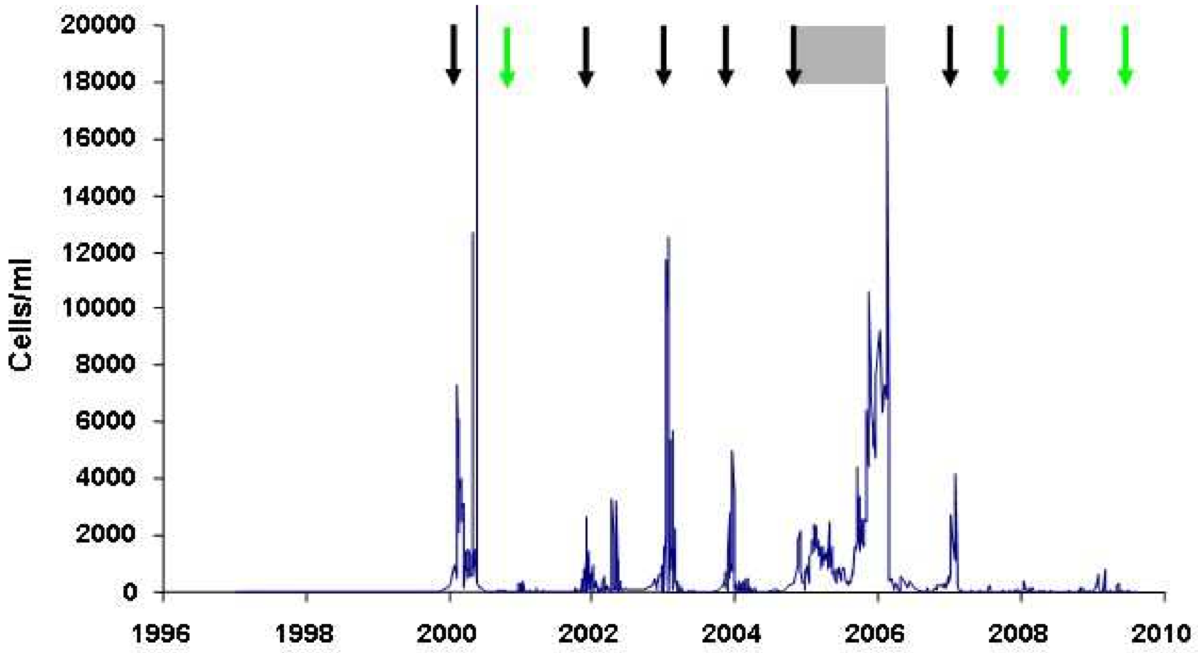


**Figure 3-10: Example of how aeration at the wrong time can stimulate a phytoplankton bloom (black arrows) but at the right time prevents the development of a bloom (green arrows). Data provided by Watercare Services Ltd.**

It is best to start the aeration system before the DO concentration has fallen below 6 g m$^{-3}$ in the bottom water. At this time thermal stratification will be weak and it will be relatively easy to break the stratification to achieve full depth mixing. Once mixing is achieved, the air supply can be adjusted from continuous to intermittent – enough to maintain the mixing and circulation at a minimum cost.

Detailed aeration protocols are presented in section 4.4.1.

The downside of aeration with mixing is that it also mixes the warmer water down into the lake bed and removes the cold water refugia required for some fish species e.g., trout. In a drinking water reservoir, warm water may not be acceptable to the consumer and an alternative strategy is required.

HAZARD WARNING: The water in the bubble plume associated with the aerator has a lower density than ambient water and a boat will have less freeboard. Swimmers are near-neutrally buoyant in water and would most likely sink if they entered the bubble plume. Notices need to be displayed warning about swimming near the plume or diving off a boat into the plume.

### 3.11.2 Oxygenation without mixing

Where the cold bottom water layer is important, special aeration equipment that aerates just the hypolimnion is used. There two main types (Figure 3-11):

1) The device is mounted in the hypolimnion so that it stirs the hypolimnion only. The equipment is installed in the hypolimnion with a small vent tube extending to the surface. The bubbles rising up through the water are caught within the device and directed to the surface through the vent tube while the entrained water is dispersed back into the hypolimnion below the thermocline without breaking the thermal stratification.

2) The device is surface mounted and incorporates a return tube to carry the aerated water back down to the hypolimnion before it is dispersed. In these systems, pure oxygen is more effective than compressed air, which has only 20% oxygen.

In both systems, if they are used in deep lakes, the aerator tube component needs to be a heavy walled tube to prevent ambient lake water pressure crushing the tube. Air bubbles inside the tube occupy some of the volume and this reduces the density of the water. Consequently, the pressure inside the tube is less than outside. Placement of the hypolimnetic aerator should be central at the deepest part of the lake. That will allow water to be drawn into the aerator from all directions and be dispersed back into the hypolimnion in all directions.

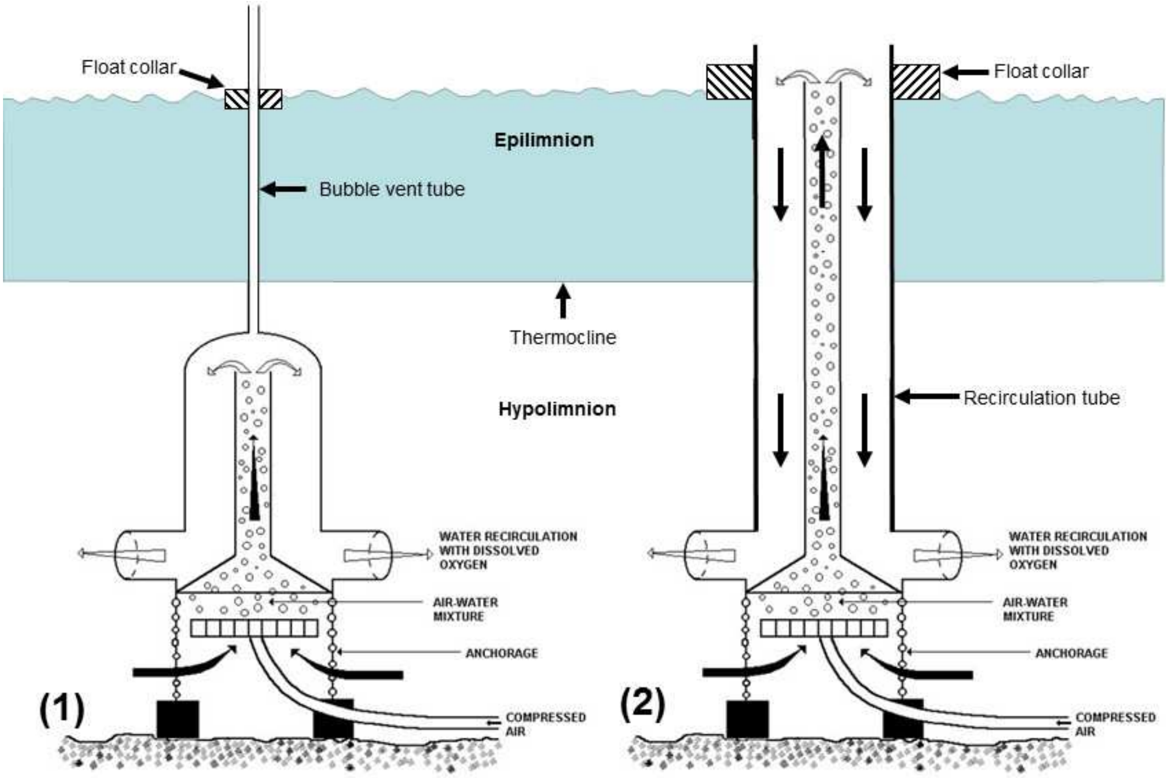


**Figure 3-11: Hypolimnetic aerators.** (1) Mounted in the hypolimnion; (2) Suspended from the surface. Both systems do not warm the hypolimnion while they re-oxygenate the water.

## 3.12 Catchment effects

New Zealand lakes are not substantially different from other lakes world-wide with the exception of lakes in the Taupo volcanic zone (TVZ) of the North Island. The TVZ is a zone of volcanic and geothermal activity extending from Tongariro National Park (Mount Ruapehu) northwards and off-shore to White Island in the Bay of Plenty, and includes Lake Taupo and the Rotorua lakes. Because of the nature of the pumice soils in the TVZ, which have low metal (Fe and Mn) but high P content, natural DRP concentrations in streams are high and DRP is often measurable in the lake water when dissolved inorganic nitrogen (DIN) concentrations are very low. The source of this P is dissolution of the pumice soil (Timperley 1983) and phytoplankton growing in many of the TVZ lakes may have their growth limited by N, i.e., they are considered to be N-limited lakes (White & Payne, 1977; Abell et al. 2010). This is in contrast to New Zealand lakes outside the TVZ and Northern Hemisphere lakes where there is often a large surplus of N and algal growth is limited by the availability of P, i.e., they are considered to be P-limited lakes.

Because most of the world-wide research into lake restoration has been done in the Northern Hemisphere, and it is easier to enhance the P-limitation of a lake than to remove the N to control algal growth (Schindler et al. 2008), almost all remediation strategies for the reduction of internal nutrient loads in lakes focus on the management of P (Figure 3-12). This approach is also valid in the TVZ lakes of New Zealand. However, just removing P from a lake, without regard to the N, leaves the potential for algal blooms if P management is not maintained. Consequently, remediation strategies for reducing the internal cycling of nutrients in a lake need to consider both N and P wherever possible (Lewis & Wurtsbaugh 2008).

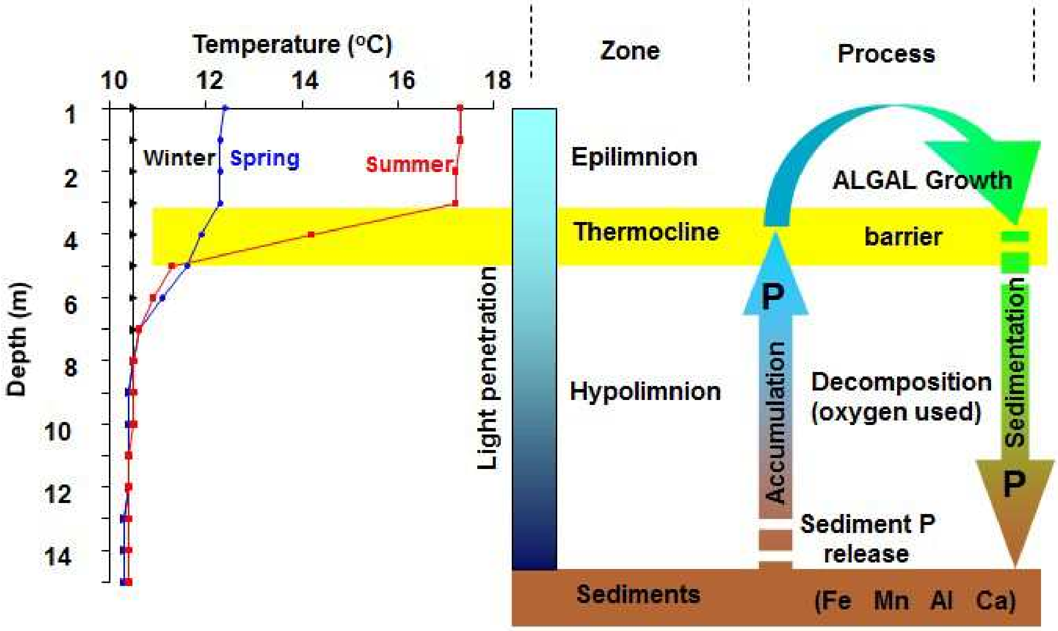


**Figure 3-12: Schematic diagram of the internal phosphorus (P) cycle in a lake relative to summer thermal stratification and the water column structure.** Interrupting the cycle by re-aeration of the hypolimnion will confine the P to the sediment, but will not solve the problem of increasing P storage in the sediment and its subsequent release if the aeration system stops.

While in-lake management strategies such as aeration may alleviate the problem of P release from the sediment, they are not a permanent solution and may only work while the aeration system operates. The source of the problem needs to be managed to prevent or reduce the amount of P and N getting into the lake from the catchment.

## 3.13 Overview

It is apparent from the above that lakes are complex and dynamic features in our landscapes rather than just a basin filled with water. A lake is part of the catchment and cannot be separated from that catchment. The water quality in a lake is the net result of a set of interactive and interdependent equilibrium conditions with over-arching physical controls driven by climate and weather, and diel and seasonal cycles. Because lake processes change over the seasonal cycle, it is likely that they will respond to long-term changes in climate. Shifting the balance of one equilibrium condition may cause others to move in the same or opposite direction.

For a new artificial lake, understanding the processes driving the key equilibrium conditions may allow many of the common causes of poor water quality to be avoided through implementing appropriate design. That understanding will also allow the newly established lake and other existing lakes to be managed for best water quality. Where an existing lake has degraded, understanding the processes that have led to that degraded condition will enable action plans to be developed and management strategies to be implemented for the restoration of the lake and to assess the level of water quality improvement that each strategy achieves.

# 4 Designing an artificial lake

Whereas many existing artificial and natural lakes have water quality problems, constructing a new artificial lake provides an opportunity to avoid common pitfalls that cause these problems and “get it right”. When designing an artificial lake, it is important to have a clear understanding of how the proposed lake will fit into the landscape and how it will affect that landscape and the environment when it is complete. To achieve this, a number of questions need to be answered prior to construction.

## 4.1 Pre-development

The following questions are designed for developers to help with the pre-development stage of designing and building an artificial lake. They are also a preliminary guide to planners for considering aspects of the development to decide whether a resource consent is required and if so, what the resource consent conditions should be.

### Assumptions for the questions in this section:

1) It is assumed that the construction of an artificial lake is not specifically prohibited under the Regional Plan covering the proposed development site and that it is a Discretionary Activity under the RMA 1991. The answers to these questions will determine whether it is a permitted/discretionary/prohibited activity in the Regional Plan covering the location.

2) It is also assumed that the developer has the legal right to construct the artificial lake, and has adequately consulted with neighbours and local Iwi.

The answers to these questions define:

- the purpose for the artificial lake
- whether it requires a resource consent
- whether the proposed artificial lake will be of high water quality and what measures are required during construction achieve the highest water quality
- whether it will adversely impact the downstream environment, and
- whether it poses a risk to the public and what level of risk.

### Part 1: Reasons for development

**1.1 What is the primary purpose(s) for the artificial lake?**
*[Aesthetic (ornamental) / water supply (irrigation, fire fighting, drinking) / hydro-power generation / contact recreation (swimming, rowing, power boating – jet sprint, water-skiing, jet ski)/ fish-out / water fowl refuge / shooting / other].*

**1.2 What is the expected maximum depth of water to be maintained in the lake?**
*[< 3 m / 3 to 10 m / 10 to 20 m / > 20 m]* If it is deeper than 3 m it is required to comply with the Building Safety Act 2008.

**1.3 How big will the lake be when completed?**
*[length, width, average depth, minimum depth in open water, maximum depth in open water, total volume. Needs a site plan showing shape and fit to natural landscape features.] If the volume is greater than 20,000* $m^3$ *it is required to* comply with the Building Safety Act 2008.

**1.4 What is the expected range of water level to be maintained in the lake?**
*[relative to a nominal upper water level when being used for the primary purpose]*

**1.5 Will it have public access?**
*[no / yes – free, by invitation, paid entry; public amenities]*

**1.6 Will it have boat launching ramps?**
*[road access, traffic levels]*

**1.7 What is the developer's expectation of the water quality in the lake?**
*[clear / water supply quality (stock or human) / turbid / some algae / no algal blooms / no water weeds / weed beds / other]*

**1.8 Does the developer expect to have fish in the lake?**
*[native species (natural access) / exotic fish species (stocked)]*

**1.9 How will the ground around the lake be landscaped?**
*[pasture / native plants / exotic forest – existing / proposed]*

## Part 2: Artificial lake location and dimensions

**2.1 Where will the artificial lake be built?**
*[Developer needs a site map showing location in relation to property boundaries, and natural water courses (flowing and ephemeral) on the property, plus a map showing the location in the wider area in relation to other waterways and water bodies]*

**2.2 Does the site have any known underlying fault lines?**
*[Developer may need to provide a seismic report for artificial lakes to be built in known earthquake risk areas]*

**2.3 Has the site been evaluated for suitability by a qualified / registered engineer?**
*[Developer may need to provide an engineering report on the soil type, structural integrity, permeability, and hydraulic conductivity of the soil to be flooded and the soil and rock structure beneath where the dam wall is to be built]*

**2.4 Has the design of any bund wall been passed by a structural engineer?**
*[The engineering drawings will need to be provided with the engineers report]*

**2.5 Has the spillway design been passed by a structural engineer?**
*[The spillway design needs to prevent bed scour at the toe of the dam*] Low level dams are known to generate "hydraulics" which can trap anyone falling in and drown them – this also includes kayakers.

**2.6 Has an environmental impact report been produced to assess potential effects on the downstream environment and adjacent properties?**
*[Does the location of the artificial lake affect a ground water supply to the lower catchment, or recharge a downstream groundwater supply]*

**2.7 Will construction of the artificial lake alter a natural watercourse?**
*[dam, stream diversion, culvert]*

**2.8 What is the estimated volume of the artificial lake?**
*[cubic metres]*

**2.9 What is the maximum height of any dam wall?**

*[metres]*

**2.10 Where will the water come from to fill the lake?**
*[Initial stream take (is permit required?) / pumped groundwater (is permit required?) / natural rainfall / other]*

**2.11 Where will the water come from to maintain the water level in the lake?**
*[Stream take (is permit required?) / pumped groundwater (is permit required?) / natural rainfall / other]*

**2.12 What provision has been made for minimum compensation flow in any source water stream?**

**2.13 What provisions have been made to handle storm flows / flood events?**

**2.14 What type of discharge structure will be used on the outlet?**
*[Weir, spillway, power station, irrigation canal, etc.,]*

**2.15 What flow regime will be used when the lake is in operation?**
*[natural, constant, peak demand, minimum compensation water only, etc.,]*

## Part 3: Additional considerations

**3.1 Provisions for reducing environmental impacts during construction.**
*[silt traps required to prevent sediment entering any natural waters – stream or lake]*

**3.2 Sealing of the lake bed in areas with porous soils.**
[*to stop water loss by leakage i.e., recharge of high quality groundwater with contaminated water from the lake]*

**3.3 Dealing with groundwater inflows where the artificial lake intercepts a groundwater aquifer under pressure.**
*[site specific – needs test bores to be drilled to the expected maximum depth of the lake to check for artesian head or percolation. Several bores may be needed depending on the size of the lake and the topography where the lake will be constructed]*

**3.4 Potential downstream effects on groundwater.**
*[quality, quantity, de-watering, recharge]*

**3.5 Potential downstream effects on surface waters.**
*[temperature, nutrients, dissolved oxygen, phytoplankton, macrophytes]*

**3.6 Removal of vegetation and top soil from within the bed area of the artificial lake.**
*[This is to reduce the amount organic matter (carbon) that will drive sediment oxygen demand and thus the potential for poor water quality]*

**3.7 Provisions for water quality remediation.**
*[Flushing / sluice valves / overflow skimmers / marginal buffer zone plantings / inflow / outflow screens / etc.,]*

**3.8 Provision of fish passes.**
*(To accommodate native fish migration)*

**3.9 Long-term management plan to address and pre-empt most common water quality issues.**
*[includes nutrients, suspended solids and temperature – especially in the discharge from the lake into any natural waterways]*

**3.10 Provisions for decommissioning the lake when it is no longer required.**
*[This may include converting a lake from a recreational facility to something else, such as an aquatic habitat / wetland / wildlife sanctuary, or complete removal]*

### 4.1.1 Discussion

In **Part 1**, questions 1.1 to 1.3 give a general overview of the project and define whether the lake will be for single or multiple use. For example, a deep lake with a primary purpose as an irrigation supply might also be used for hydro-power generation. Such a lake might also be used for contact recreation (boating/fishing). The water quality (Q 1.7) might not meet the developer's expectations of clean clear water because the operation of the lake to meet the dual purpose may result in lake bed suspension and shoreline erosion due to changing water levels associated with the water draw off for irrigation in summer and peak power generation in winter. Being a deep lake, it is likely to thermally stratify and water quality may rapidly decline within a few years of filling. This becomes a flag for design considerations.

In questions 1.2 and 1.3, the expected depth range and storage capacity has important implications for regulation and compliance under the Building Act 2004 because, if a dam is not a large dam, i.e., is less than 3 m high and has a storage capacity of <20,000 $m^3$ then it:

1. Does not require building consent (being exempt under Clause (da) of Schedule 1).
2. Does not require the owner to submit an audited Dam Classification Certificate with PIC to the Regional Council or Unitary Authority.
3. Does not require the owner to submit an audited Dam Safety Assurance Programme to the Regional Council or Unitary Authority.
4. Does not require the owner to submit an Annual Dam Compliance Certificate to the Regional Council or Unitary Authority.
5. Is not subject to the dangerous, earthquake-prone or flood-prone dams provisions of the Act (with the exception of the provisions of Section 157 in relation to immediate danger).

It does, however, require a Code of Compliance Certificate for the building work.

### 4.1.2 Proliferation of artificial lakes

Floodwaters are often stored in reservoirs to supply irrigation and stock water during dry times. There is extensive water harvesting throughout New Zealand (McKerchar et al. 2005) with a large number (>2000) of off-stream storage reservoirs which range in size from small ponds to large artificial lakes (Figure 4-1), and from shallow (<2 m) to deep (>50 m). Most of these are listed on resource consents but there are probably a similar number that were permitted activities and did not require building permits or resource consents. The Ministry of Commerce's New Zealand dam inventory, which was prepared to help identify hazards posed by large dams, lists details of 483 dams in that class (Ministry of Commerce 1997).

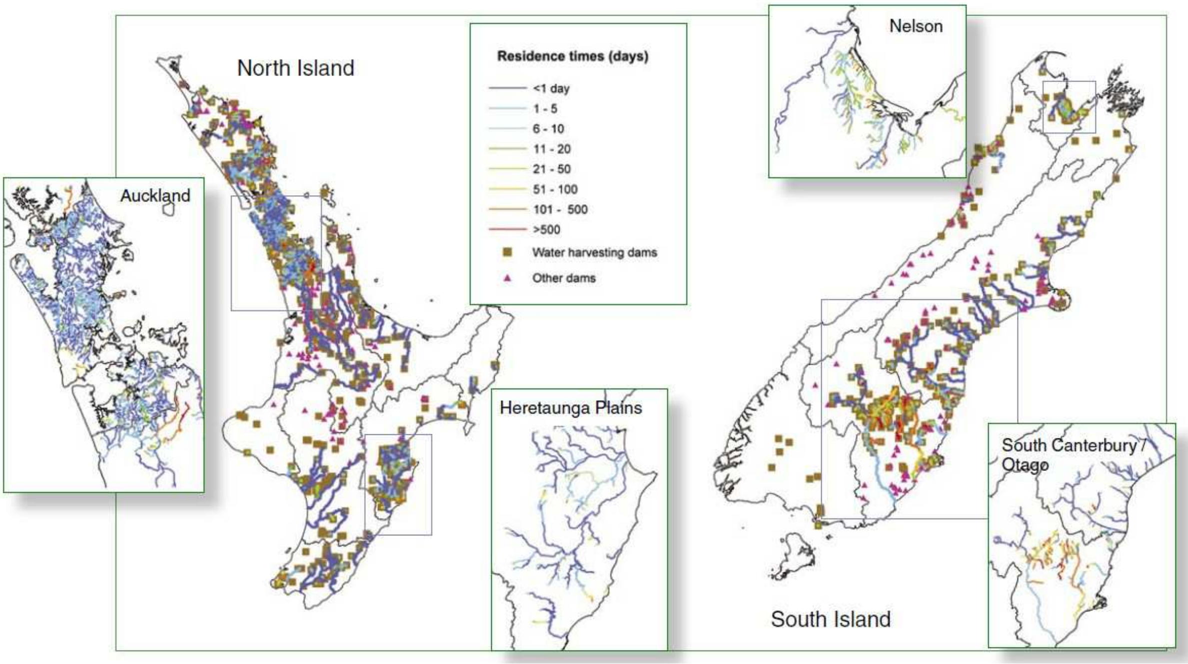


**Figure 4-1: Maps of the water-harvesting index by stream segment around New Zealand.** (Figure from McKerchar et al. 2005).

## 4.2 Design considerations

The design of relatively small artificial lakes will be predetermined by the landscape, topography and the reasons for constructing the lake. Much of the information required is contained in the Guidelines although advice from a resource management consultant at the start of the design could pre-empt costly mistakes. Where the artificial lake receives a groundwater input, land management in the catchment may affect the water quality in the lake (See section 5.2: Special considerations).

For large artificial lakes, a consultant is essential. An additional tool also essential for designing large artificial lakes is a lake simulation model which has the ability to predict the water quality that is likely to occur in the proposed artificial lake based on climate data and water quality data from the source water. While the use of a lake simulation model is an additional cost on the project, which may not be justified for a small artificial lake, by using such a model it is possible to test a range of scenarios to assess the effects of different designs on the water quality of the lake (See section 4.3 Use of Predictive Models).

### 4.2.1 Vegetation and soil

Because the artificial lake will have residual soil and plants on the bed from when the lake is filled, decomposition of that carbon will cause oxygen depletion of the lake water for several years until that carbon has been consumed or buried. Removal of excessive vegetation before the lake is filled will reduce the extent of oxygen depletion and the time it takes for the lake to develop a stable equilibrium.

It may not be practical to remove all vegetation within the footprint of the dam. In this case felling and removal of trees that would otherwise be near the surface of the artificial lake when full would be prudent to eliminate hazards to recreational water users including swimming, boating and fishing.

Where areas of soil have been removed exposing bare subsoil or clay, there may be suspension of fine particles that cause elevated turbidity in the lake for a period until the sediment stabilises.

### 4.2.2 Shallow lakes

#### Off-stream storage reservoirs for irrigation

Off-stream storage reservoirs, which are often large shallow artificial lakes, are numerous on the Canterbury plains and elsewhere throughout New Zealand. For each off-stream storage reservoir there may also be a structure such as a low weir across the river or stream to provide a take point for the water to fill the reservoir. Because of the height of the weir and the volume of water behind it, a low weir may not require a building permit (section 2.6 Large Dams) but will require a resource consent under section 13(1)(b) of the RMA, for disturbance of the river or stream bed, and section 14(1)(b) for diverting and taking water. The amount of water that can be taken should also be specified in the resource consent. Construction of the weir may be a discretionary activity under the Regional Plan but it should require an engineering design certification (see Section 4.1, **Part 2**, sub-section 2.5) and a building code of compliance certificate for the structure.

The take point will usually include a diversion canal to direct the river water to the off-stream storage facility. To meet the requirements of the resource consent for a water take, there will need to be a sluice gate to close off the take point. Sluice gates present a hazard to the public who are likely to the use the deeper water in the canal behind the weir as a place to swim. When the sluice gate is open, water is drawn through a small gap across the bottom of the gate structure. The flow through this gap creates a hydraulic pressure which is sufficient to hold a person against the gap and drown them e.g., NZ Herald 2012 article (Appendix E). The sluice gate requires a screen to prevent this happening – the screen will also prevent debris from entering the diversion channel.

The storage reservoir for the irrigation water will need to be designed by an engineer. Ideally, to assist in subsequent water quality management, the reservoir should be divided into two separate reservoirs. To reduce water loss through the bed of the reservoir, the bed should be sealed – clay or impermeable synthetic liner with a riprap protective cover. The sealing of the reservoir bed prevents the contamination of the reservoir with nutrient rich groundwater. The riprap material used to line the reservoir will affect the growth of nuisance plants and algae.

The water quality in the storage reservoir will be dependent on the residence time of water in the reservoir and the quality of the source water from the river. A short residence time would keep the water in high quality. A perimeter fence close to the edge of the reservoir would provide a safety barrier for the public and would prevent the reservoir from becoming a roosting place for water fowl, especially geese. Geese feed on land and defecate in the water. If there is no land for them to roost on around the lake they will not enter the lake.

Surface runoff should be excluded from the reservoir by using mounded / raised banks around the reservoir and providing stormwater drains to divert that water elsewhere.

The reservoir will act as a settling chamber for silt from the river allowing the water to become clear. As clarity improves, the bed of the reservoir is likely to become coated with periphyton. The filamentous algae growing in the river will seed the reservoir. The resultant growth in the relatively still waters of the reservoir will be greater than in the river where the current flow and the occasional flood or “fresh” will slough off the periphyton. Long streamers of periphyton may develop in the reservoir and these could block pumps. The periphyton can be managed by lowering the water level in the reservoir to allow drying in the sun or freezing in frosts. A dual reservoir system would allow this management strategy without stopping the irrigation system by drawing one side down for treatment and using the other side as the supply while the treated side is being treated and refilled.

### Ornamental lakes and water features

Recently, in the Auckland region, there has been an increasing trend in the construction of dams for ornamental or aesthetic reasons, or for the creation of wildlife habitat. Ornamental lakes and water features are often found in an urban development landscape or on farms. This type of artificial lake is often formed by placing a weir or dam across a small stream as an on-stream lake but could also be formed by diverting part of a stream flow though a constructed off-stream impoundment which then drains back into the stream below the artificial lake. These lakes have irregular shapes and variable depth of water reflecting the topography of the land that was inundated. Because of the height of the weir or dam built to hold the water and the volume of water behind it, a low weir or dam may not require a building permit (section 2.6 Large Dams) but will require a resource consent under section 13(1)(b) of the RMA for disturbance of the river or stream bed, section 14(1)(b) for diverting and taking water, and section 15(1)(a) for discharging contaminants to water. Construction of the weir may be a discretionary activity under the Regional Plan but it should require an engineering design certification (see Section 4.1, **Part 2**, sub-section 2.5) and a building code of compliance certificate for the structure.

If water is being diverted from a stream to flow into the artificial lake as an off-stream impoundment, the resource consent should specify the amount of water that can be taken under different circumstances and reference the take to the minimum flow in the river. Where the whole flow of the stream is being captured in the on-stream artificial lake, the resource consent should specify the quality of the water that will be discharged from the artificial lake back into the stream below the lake. For both on-stream and off-stream artificial lakes, the resource consent should specify the restrictions placed on the discharge water with reference to the likely impact on the ecology of the receiving water, the distance downstream before the effect is negated, and tolerance thresholds for and duration of events.

From a Regional Planning perspective, artificial lakes that are not correctly designed and maintained can provide a source of contamination of the downstream aquatic environment (Maxted et al. 2005)[1]. The main contaminants are high temperatures and low dissolved oxygen concentrations which are key stressors in summer and can persist for several hundreds of metres downstream of the discharge (Lessard & Hayes, 2003). Unlike nutrients or suspended solids, which have long-term cumulative effects that become visible over time, high temperatures and low DO concentrations have acute effects that reduce the biodiversity and abundance of organisms in the stream. The sensitivity of an organism to high temperatures and low DO concentrations both in the lake and in the stream will be different for each species and will depend on the exposure period. The adverse effects can range from slight to severe (Figure 4-2). The design of the shallow artificial lake needs to address these issues.

---

[1] http://www.rsnz.org/publish/nzjmfr/2005/087.php

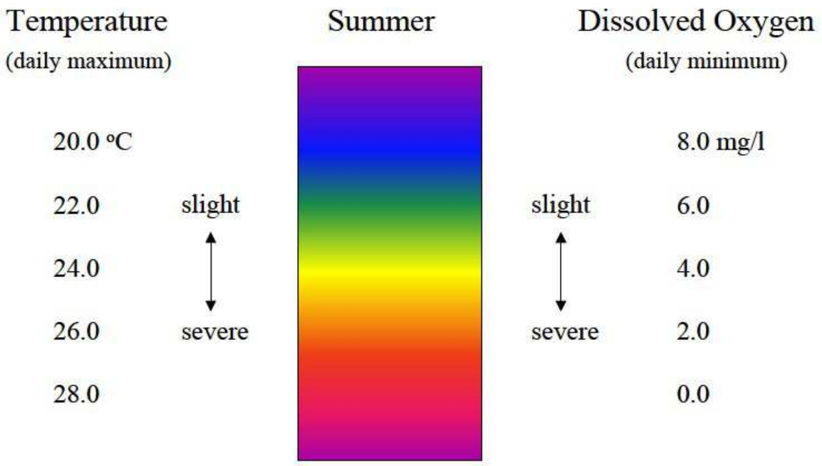


**Figure 4-2: Effects of high temperature and low dissolved oxygen can range from slight to severe.** Above **slight** - no adverse effects; below **slight** - beginning of adverse effects, generally reduced growth and reproduction; between **slight** and severe - variable effects depending on the species sensitivity, exposure history and presence of other stressors; below **severe** - mortality of sensitive species and some tolerant species. (Figure derived from Maxted et al. 2005).

## Key points to consider in the design of a shallow lake:

1. **Temperature and Dissolved Oxygen:**

   Shallow lakes typically have a large surface area to volume ratio which allows them to warm quickly in summer and cool quickly in winter (Figure 4-3).

   Excessive heating can be mitigated to some extent by the use of shade. Trees that shade parts of the lake in early afternoon will reduce the maximum temperature reached in the lake. The choice of shade tree is important. While deciduous broadleaf trees from the northern hemisphere are aesthetically pleasing in a landscape, their large flat leaves can smother the bed of a lake causing sediment anoxia as they block oxygen diffusion into the sediments and decomposition of the leaf carbon consumes oxygen from the water. In shallow artificial lakes that thermally stratify in summer (e.g., Virginia Lake, Wanganui), this source of carbon and nutrients can cause degradation of the lake water quality. Evergreen native tree species with small leaves (e.g., kahikatia, kauri, maire) will tolerate growing in wet areas and are likely to have less adverse impacts on the lake water quality than broadleaf deciduous trees.

   Planting alignment of the shade trees can be used to funnel the prevailing summer winds across the lake to promote evaporative cooling and water column mixing. They should not be used to produce shelter from the wind as that would enhance leaf fall into the lake and water column stability which could favour some algal species.

   Shade over the outlet stream joining into the downstream river can lower the temperature of that water and reduce the thermal stress on the downstream environment. Shading the inflow stream will produce cooler inflow water which is likely to underflow to the deeper parts keeping them oxygenated (Figure 4-3). In-lake shading of shallow areas (<1 m deep) using plants such as water lilies can reduce water temperatures locally and provide shelter for aquatic biota including zooplankton, which graze phytoplankton.

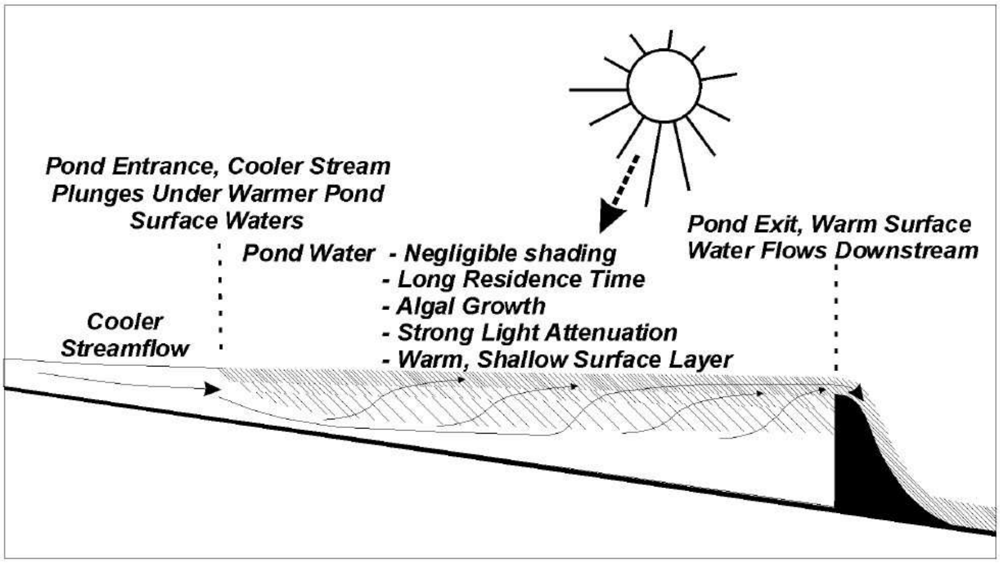


**Figure 4-3: Conceptual model of heating in a shallow lake.** (Figure derived from Maxted et al. 2005).

Providing deeper areas in the lake will provide habitats that can support aquatic species with different requirements for temperature. Deeper water will generally be cooler than the shallower areas and thus may be cool refugia for fish species (Figure 4-4).

The design of the outflow from the lake is important. A surface overflow across a weir skims of the warmest water from the lake (Figure 4-3). It will also skim off phytoplankton, especially cyanobacteria which would float as a surface scum. Although that may be good for the artificial lake, it enhances the impact of the artificial lake on the downstream environment.

To manage the water quality in the lake and reduce the severity of or prevent anoxic events, the outflow from the lake could be in the form of a bottom water siphon, commonly known as a hypolimnetic siphon (Figure 4-4). The greater the depth, the better the hypolimnetic siphon works (see section 3.10.4; Selective draw). The proviso is that the inflow to and outflow from the lake via the hypolimnetic siphon must be essentially the same and the residence time is short enough to prevent anoxia and nutrient release from the lake bed. Allowing water to be taken from the ornamental lake for irrigation could extend the residence time allowing the bottom water to become anoxic, nutrient enriched, and generally unsuitable for discharge into the downstream environment. This scenario requires surface water discharge and remedial action in the artificial lake to improve the discharge water quality to meet the resource consent conditions.

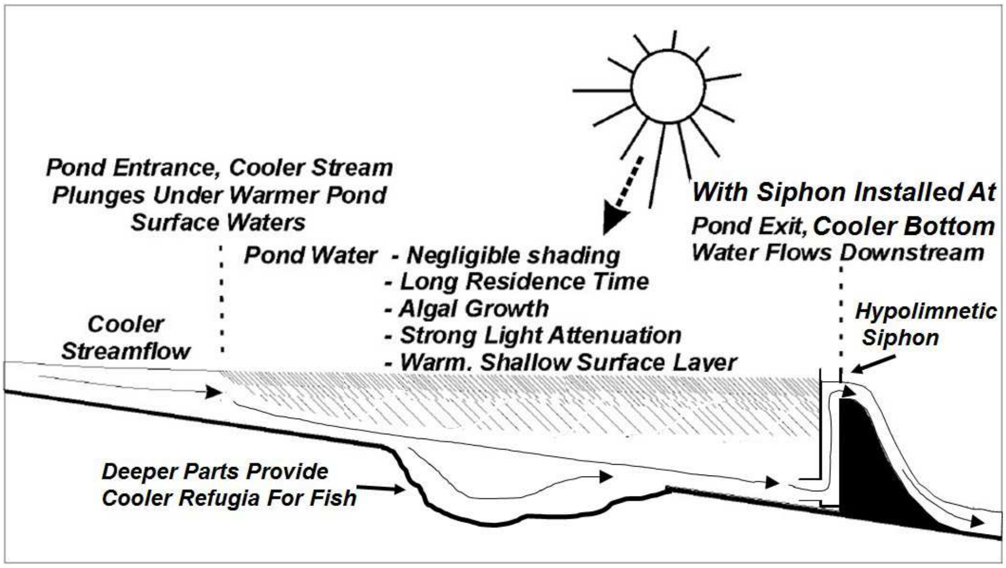


**Figure 4-4: Conceptual model with deep refugia and a hypolimnetic siphon.**

The residence time of water in the lake will also influence the temperature of the water in the lake and the discharge water. A short residence time may prevent the development of excessively high temperatures and low DO concentrations. A short circuit from inflow to outflow will warm less than if the inflow water meanders and mixes through the whole lake.

For off-stream artificial lakes, a management strategy to comply with resource consent restrictions around the discharge of high temperature water into a stream is to have no discharge when the temperature exceeds the consent criteria.

2. **Light:**

A shallow depth allows light to reach the lake bed, supporting the growth of aquatic macrophytes (lake weeds) and periphyton, especially filamentous algae, on the vascular plants and near-shore lake bed. Periphyton species will grow rapidly where there is a nutrient supply and are likely to proliferate around inflow drains and groundwater seeps in sheltered areas of the lake. Wave action can prevent macrophytes from becoming established and can slough off periphyton from the lake bed.

Shade can reduce the growth of macrophytes and periphyton. Shade can be from shoreline vegetation or small particles (sediment and phytoplankton) suspended in the water column.

3. **Sediment suspension:**

While wave action against the shoreline can cause erosion which produces suspended sediments, the shallow depth allows currents from wind-waves to impact on the lake bed, stirring up sediment across the whole lake and making the lake turbid.

Planted buffer zones along the lake edge will provide a buffer against wave action erosion. Exclusion of direct access by stock to the lake edge will eliminate bank collapse due to trampling. Where waterfowl such as geese and swans are expected, the planted buffer zone should be extended onto dry land to prevent them grazing the near-shore plants and leaving a strip of open water between the bank and the emergent plants.

The introduction of exotic fish to ornamental lakes and ponds is common practice. While native species have little effect on vegetation or sediment, exotic species such as Koi carp destabilise the sediment by their feeding habits exacerbating turbidity issues. Other exotic species such as rudd and tench damage the buffer zone plants that protect the shoreline sediments.

**Exotic fish species should not be released into the shallow artificial lake**.

4. **Nutrients:**

Shallow lakes often receive water of poor quality as surface runoff from farms, urban parks and roads. Reticulated stormwater systems from urban and industrial areas may also discharge into the lake. The resultant nutrient and organic nutrient-rich sediments are likely to accumulate in the artificial lake and cause long-term degradation of the lake water quality.

To protect the water quality of the artificial lake, all known nutrient sources to the lake should be managed and minimised. Surface water flows, other than the source water stream or river inflows, should be diverted away from the lake using by-pass drains. Where this is not possible (e.g., stormwater and road runoff), retention ponds should be installed to reduce the suspended solids and nutrient input from these sources. Wetland areas, through which the inflow water must meander before it enters the artificial lake, will reduce the nutrient input and the dispersion of sediment across the lake. Planted buffer zones along the lake edge will intercept groundwater nutrients.

5. **Floods:**

In-line shallow lakes need to cope with flood events whereas off-stream shallow lakes need to be able to restrict the amount of water drawn during a flood event. A critical design feature that requires an engineer’s advice is the size of the spillway:

Is the spillway large enough to cope with a flood event without the dam failing?

In shallow lakes, the design of the internal channels (either natural drowned valleys or depressions put in during earthworks) should have the ability to allow larger than normal flows to move rapidly to the spillway. Alternatively, the stop-bank bunds that define the perimeter of the lake should allow the flood surge to disperse and fill that area without spilling into neighbouring properties.

6. **Fish passes:**

Most shallow artificial lakes will be situated beside or on natural stream systems. Consequently, native fish species such as whitebait, smelt, bullies, kokopu, eels, etc., are likely to be affected by the barrier formed by the dam across the stream, or will enter the off-stream lake on their downstream migration phase. In either case, a fish pass should be included in the design of the dam to facilitate easy passage in and out of the lake.

The design of the fish pass is a specialised field and will be different for each lake. A specialist consultant would provide advice on a design suitable for each lake.

In summary, the construction of a shallow artificial lake will result in a body of water that is likely to have high water temperatures in summer, be relatively turbid especially in winter, and it is likely to support lake weed and/or phytoplankton growth. If the filling water and subsequent top-up water contains high concentrations of P and N, the lake is likely to develop phytoplankton blooms which could shade out the lake weeds. Dissolved oxygen levels are likely to fall when the biomass of plant and phytoplankton settle to the lake bed and decompose. The temperature, dissolved oxygen, turbidity, phytoplankton and fragments of lake weed are all potential problems for the downstream environment.

Mitigation of these potential problems requires a balance between different and often opposing design options prior to constructing the lake. A compromise might include allowing macrophyte weed beds to develop so that particulate matter can settle out of the water column producing clear water, but periodically harvesting the macrophytes to maintain an open water phase. The use of a predictive model could assist with designing and managing the lake (see section 4.3: Use of Predictive Models).

Lake Otamangakau in the Tongariro Power Development Scheme is an example of a shallow artificial lake formed by damming a small stream. Short residence times and the macrophyte weed beds keep the water clear, and the lake is a trophy trout fishery.

### 4.2.3 Deep lakes

#### Legislative considerations

The difference between deep artificial lakes and shallow artificial lakes is the potential for deep lakes to develop a stable thermal stratification for part of the year. The other difference is that, because of the height of the dam built to hold the water and the volume of water behind it, a building permit is required (section 2.6 Large Dams) together with a resource consent under section 13(1)(b) of the RMA for disturbance of the river or stream bed, section 14(1)(b) for diverting and taking water, and section 15(1)(a) for discharging contaminants to water.

Construction of the dam is controlled under the Building Act 2004 and subsequent amendments including the Dam Safety Scheme 2008, which are presently (2012) being updated (See section 2.6). When completed, the dam will also require a building code of compliance certificate for the structure. In light of the recent large earthquakes in parts of New Zealand, the site for the dam needs to have a geotechnical report on the underlying rock structure and the position of any fault lines that might pass beneath the dam structure and the lake behind the dam. It will also need an Assessment of Environmental Effects (AEE) report covering all aspects of the dam construction including, but not limited to, the construction of access roads required to get to the site to build the dam, site clearance, earthworks, diversion of water courses, and a site development plan for rehabilitation of the environment once the dam is complete.

Part of the AEE should include the likely quality of water to be discharged from the lake into natural open waters. As the proposed lake doesn't exist, this assessment requires a prediction by a qualified consultant. Because the predicted water quality will affect the downstream environment over many years in the future, it is recommended that a computer simulation or model of the proposed lake be considered as part of this assessment based on the environmental factors that will affect water quality in the lake at various stages in its life. These factors include the climate and local weather patterns, rainfall, rate of filling, flushing rate or residence time, the catchment land use, the amount and type of vegetation to be left in the dam where it will be inundated, the quality of the source water to fill the dam, and the seasonal effect on the water quality in the dam of thermal stratification in summer or ice cover in winter for alpine lakes. Because the water quality in the new lake will change over the first few years as submerged vegetation decomposes and the associated water is replaced with new water, the model should be run for a minimum simulation period of 5 years and preferably 10 years.

The advantage of having a predictive model available for the proposed lake is that various scenarios of environmental factors and various design and management strategies can be tested before the dam is built. (See section 4.3 Use of Predictive Models).

Once the construction of the dam is approved, the conditions of the resource consent for the dam will be set and should include water quality conditions and the requirements for compliance monitoring of the conditions.

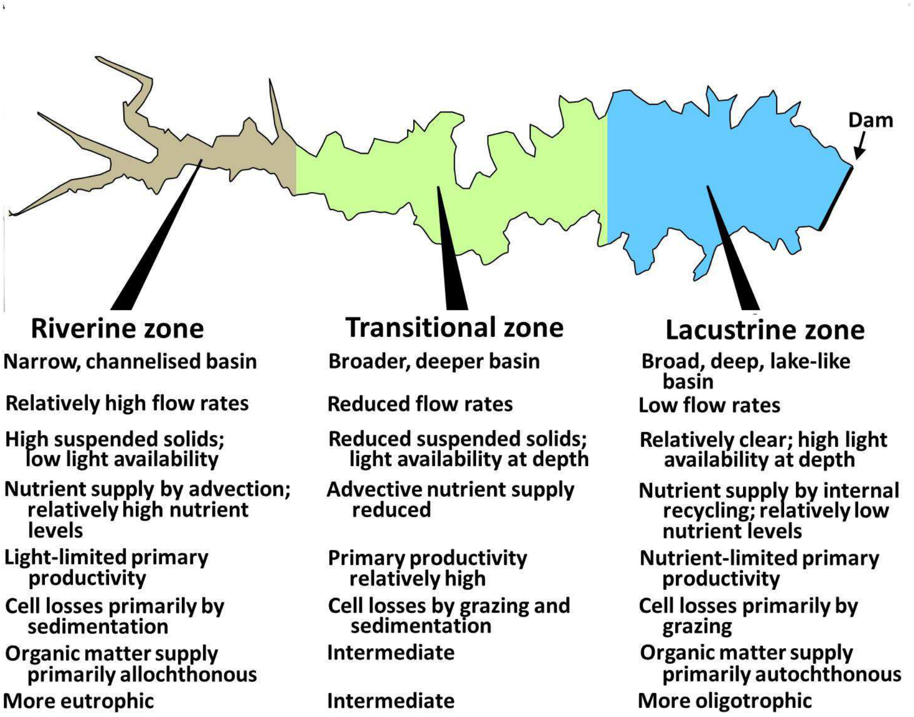
### Basic design considerations

In most cases, deep artificial lakes will be formed by damming a river or flooding a valley, and their main purpose will be as storage facilities for water supplies, irrigation and/or power generation. The overall design of the dam is covered in the guidelines for dams (Foster et al. 2000) and is not repeated here. This section considers features of the dam design that will influence the quality of the water in the artificial lake that forms behind the dam wall when it is full.

The morphological features of the artificial lake are determined by the topography of the valley that was flooded in their formation. In general they will be elongated, dendritic and, in the case of a dammed river, they will have a bed that slopes from the inflow to the dam wall. Where the water in the on-stream dam is stored for irrigation and compensation water to the river below the dam is set at a minimum flow, the downstream recharge of groundwater from the river will be reduced.

When a deep artificial lake is first filled, there is typically a period of poor water quality for several years as the organic matter left within the dam footprint decomposes. Weavers Lake near Huntly is an exception (see Figure 4-7). Formerly a coal mine with minimal organic matter when flooded, it had high water quality which is slowly deteriorating. After that initial phase, the water quality will normally improve and be determined by the quality of the source water. Alpine water draining native forest catchments is likely to have a much higher quality than water draining from rural farm land, which means that high altitude lakes with forested catchments are likely to have better water quality than lowland lakes in rural catchments (Verburg et al. 2010). Consequently, location of the artificial lake within a catchment will to some extent, predetermine the likely water quality in lake.

The water quality in the on-stream lake is likely to change along the length of the lake with the inflow end being more riverine than the outlet end, which will be more lacustrine i.e., lake-like (Figure 4-5).



| Riverine zone | Transitional zone | Lacustrine zone |
|---|---|---|
| Narrow, channelised basin | Broader, deeper basin | Broad, deep, lake-like basin |
| Relatively high flow rates | Reduced flow rates | Low flow rates |
| High suspended solids; low light availability | Reduced suspended solids; light availability at depth | Relatively clear; high light availability at depth |
| Nutrient supply by advection; relatively high nutrient levels | Advective nutrient supply reduced | Nutrient supply by internal recycling; relatively low nutrient levels |
| Light-limited primary productivity | Primary productivity relatively high | Nutrient-limited primary productivity |
| Cell losses primarily by sedimentation | Cell losses by grazing and sedimentation | Cell losses primarily by grazing |
| Organic matter supply primarily allochthonous | Intermediate | Organic matter supply primarily autochthonous |
| More eutrophic | Intermediate | More oligotrophic |

**Figure 4-5: Longitudinal zonation of water quality conditions in reservoirs with complex shapes formed by damming rivers.** (Modified from Kimmel and Groeger,1984).

The progression of changing water quality along the length of the on-stream lake is a function of flow velocity through the system. When the river water enters the lake, the velocity rapidly reduces and the coarse sediment (sands and gravel) falls to the lake bed forming a delta. As the water moves through the lake, the velocity slows further and there is more time for fine sediment to settle out of the water column and the water becomes clearer. Water-sorting of the sediments causes the finest organic material to settle in deepest parts of the lake between the middle reaches and the dam wall.

In off-stream deep lakes, the water quality is likely to be more uniform along the length of the lake. The inflow, which could enter the lake anywhere around its shoreline, is likely to be water diverted from a nearby river and will include surface runoff from the catchment in ephemeral or permanent headwater streams. Inundation of once dry land will cause flow into the ground and thus there may be leakage into the groundwater table. This will become a permanent point source recharge of the groundwater table that may influence the groundwater system below the off-stream dam.

With no well-defined current through the off-stream lake, the fine organic sediment can settle across the whole bed of the lake, although wind-induced currents are likely to cause the very fine sediment to gravitate to the deepest parts of the lake (i.e., sediment focussing).

### Sedimentation effects

In both the on-stream and off-stream lakes, the accumulation of fine sediment causes a problem for the operation of the dam. Firstly, the sediment accumulation represents a physical problem of infilling and loss of storage capacity. In many lakes, the design engineers have simply left sufficient depth below the lowest offtake valve for the sediment to accumulate based on the life expectancy of the dam. For example, Opuha Dam near Fairlie in South Canterbury, the maximum depth is 35 m and the single offtake valve is at the 30 m water depth (A. Meredith, Environment Canterbury, pers. com.). That approach can create a new problem (See case study Opuha Dam, section 6.2).

Selective draw (section 3.10.4) from a fixed depth causes the water to stagnate and stratification develops below the draw depth. Because the sediments are typically highly organic, they will have a high oxygen demand and decomposition processes will cause the bottom water to become oxygen depleted or anoxic and nutrient enriched. Hydrogen sulphide will be present, and the bottom water will have an unpleasant odour. These conditions developed in Opuha Dam (Hawes & Spigel 1999).

This problem will be exacerbated in summer when the lake becomes thermally stratified at a depth higher than the offtake valve. The pool of anoxic water at the bottom of the lake will enhance the oxygen depletion in the hypolimnion and the water discharged will be of poor quality. If the lake is broad and exposed to strong winds, mixing events may disperse the nutrients and sulphide through the epilimnion allowing the water quality in the lake to become degraded. The morphometry of the lake basin behind the Opuha Dam was broad and the water was shallow such that lake was polymictic (see section 6; Case studies). Consequently, the water column in the Opuha Dam became highly degraded in summer (Hawes & Spigel 1999; Meredith 1999).

The design and management concepts to overcome these problems include:

- Having more than one offtake valve with the valves spaced at different depths to allow the selection of different waters to be discharged from the lake. Opening multiple valves also allows blending of the different waters to achieve water of the desired quality and reduce the strength of the draw induced stratification.
- Installing an aeration system in the deepest part of the lake near the dam wall to cause mixing and thus prevent the development of a pool of anoxic water in the bottom of the lake.
- Installing a scour valve at the base of the dam that will enable periodic removal of accumulating sediment.

These design features are included in the 10 water supply reservoirs operated by Watercare Services Ltd for Auckland. Those lakes range in depth from 16 m up to 59 m and range in size up to about 1.6 km$^2$ (see section 6.1). In all of these lakes the aerator consists of a simple alkathene pipe anchored to the bed of the lake with chains attached to weights. The alkathene pipe has air nozzles along its upper surface and compressed air is blown into this aeration bar from a shore-based compressor. This design concept is relatively cheap to operate and is widely used for mixing lakes overseas e.g., the El Capitan water supply reservoir on the San Diego River in California with this type of aeration system producing a mixed water column with DO concentrations >5 g m$^{-3}$ (Fast 1968). This type of aerator has been suggested for use in Lake Opuha (Brown 2003) (Figure 4-6).

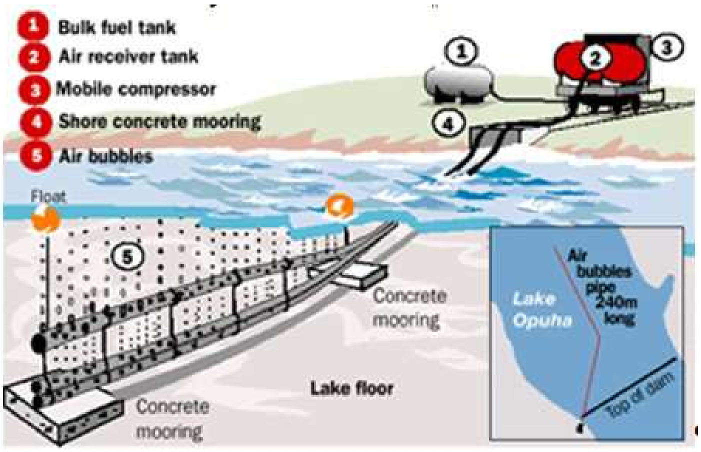


**Figure 4-6: Schematic of a simple aeration bar type aerator system.** (Graph by Gary Roberts, NZ Herald from Brown 2003).

The air-bar aerators are effective mixing tools but have the disadvantage of raising the water temperature throughout the water column. Whether they would be capable of mixing the water column in Opuha Dam, which has two river inflows and an island near the deep basin that could restrict mixing, should be tested with an appropriate predictive model. The alternative approach is to use hypolimnetic aeration (section 3.11.2) which does not mix the lake and would not raise the bottom water temperature. The various designs available should be tested with a predictive model to determine size and efficacy for that specific lake.

### 4.2.4 Quarries

Flooding a quarry does not take water from a stream or discharge it to a stream but it does divert groundwater. Under section 14(9A) of the RMA, this is a permitted activity unless specifically controlled under the regional plan. The flooding of the quarry, however, may require a resource consent for the change of land-use from a quarry to a lake. The terms of that consent should include directives as to the removal of old machinery and rubbish from the quarry before flooding, so as to reduce potential water quality problems in the future. As quarries typically have steep sides and are likely to have substantial water depth when full, the Health and Safety Act 1992 requires it to be fenced or other appropriate safety measures to be implemented according to the intended use.

The water quality in the flooded quarry will depend on the morphometry of the excavated pit i.e., is it a relatively shallow river gravel extraction site with a large surface area to volume ratio, or is it an open-cast coal mine or rock or mineral extraction quarry which has been sunk deep into the ground to follow a specific rock or mineral load, and what is the proposed use of the lake once the quarry has been flooded.

Flooded gravel extraction pits are likely to be alongside a river with hyperheic flow through the gravel banks into the lake. Shallow gravel extraction pit lakes have been used for water sports such as jet boat eventing but are also commonly used as open water sanctuaries beside wetlands for water fowl. Being shallow, the water is likely to be well oxygenated and the biggest threat to the water quality will be nutrient runoff from farmland and the concomitant growth of macrophytes, periphyton and phytoplankton. The flushing rate is likely to be very slow unless a surface water inflow enters the lake.

Flooding of deep quarries, such as the open-cast coal mine that formed Weavers Lake (Figure 4-7) beside Lake Waahi in the Waikato (Balvert 2006), may produce unusual physical and chemical distributions in the water column as the lake stabilises. Weavers Lake has an area of 54 ha, a maximum depth of 64 m and a trophic status classified as mesotrophic. The expectation for this lake, which has a shelving littoral zone and a very deep centre, is that the deep centre may become stratified for extended periods and the lake could become meromictic, only mixing in years where temperature and wind stress combine to allow deep mixing. Again the flushing rate is likely to be very slow unless a surface water inflow enters the lake.

Because these flooded quarries have groundwater as their primary water source and they are likely to be surrounded by pastoral farm land, the water in the lake is likely to be nutrient enriched. The plant material remaining in the quarry when it filled will decompose and the bottom water oxygen levels are likely to be low or zero. The low oxygen in the bottom waters will be exacerbated when the water column thermally stratifies. The decomposition processes associated with residual coal in a flooded coal mine may release chemical contaminants (e.g., boron) which could leak back into the groundwater contaminating the downslope streams and aquifers.

Design considerations to minimize these effects include terracing the littoral zone to provide suitable substrate for growing marginal wetland plants and emergent macrophytes as a buffer zone around the lake edge. Intercept drains could be installed to prevent surface runoff from adjacent land and roads entering the lake. Stock exclusion fences should be erected around the lake.

Within the lake, consideration should be given to installing aerators to keep the water column mixed. In a lake such as Weavers Lake, where the surface area dimensions are nearly uniform, an air-bar aerator would be less efficient that an enclosed rising plume device which draws the bottom water to the surface before dispersing it laterally. These aerators are destratification devices which need to be in operation as soon as the lake begins to stratify in spring (see section 4.4).

**Figure 4-7: Weavers Lake near Huntly is a flooded coal mine.** The dark water is due to its depth and higher clarity relative to the green of the cyanobacterial bloom in Lake Waahi on the left. [Photo: Google Earth: image flown 29/05/2010].

Once stratification has occurred and the quarry lake has developed an anoxic hypolimnion, destratification aeration would bring potentially toxic water to the surface killing all life in the lake. Under special circumstances, a sudden mixing of the lake would be potentially lethal to humans near the lake if the hypolimnion was supersaturated with carbon dioxide e.g., the limnetic eruption Lake Nyos, Cameroon (Stager 1987; Cotel 1999)[2].

Firstly, hypolimnetic oxygenation (Nordin & McKean, 1982) should be used to raise the oxygen concentration in the hypolimnion without destratification. That would keep the nutrients and other chemicals in the bottom waters until biogeochemical processes can reduce their concentrations. Then the lake can be destratified with a less expensive aerator / mixing system.

## 4.3 Use of predictive models

Prediction of the water quality in the proposed artificial lake is difficult and uses the concept of developing a hind-case model based on historical data to predict the likely conditions in the lake in the future, to best scientific practice. This is a skilled task which is best given to an

---

[2] While large limnetic eruptions are rare (only two recorded events), small eruptions are more common and are mostly seen as muddy water on the surface of the lake when the lake turns over. They are caused by something that seeds the formation of a small bubble in a hypolimnion that is supersaturated with carbon dioxide. That initiates a chain reaction which degasses the water and the bubbles rush to the surface, much like the release of bubbles when opening a bottle of Champagne. The upward rush of gas causes a violent upward water current which carries the sediment to the surface of the lake. In calm conditions, the carbon dioxide forms a smothering blanket around the lake before dissipating. The Lake Nyos eruption caused the death of 1700-1800 humans and thousands of animals.

experienced consultant. There are many lake water quality models available (Riecken, 1995). In most lake modelling studies, the model has been adapted specifically for the study lake (e.g., McKellar et al. 2008). The choice of model will depend on the questions to be answered and the consultant. In New Zealand, the model DYRESM-CAEDYM (developed at the Centre for Water Research, The University of Western Australia) is often used. The use of a model allows prediction of water quality in the newly filled lake and the probable changes in that water quality over the next few years as the lake establishes an equilibrium state, and the organic matter left in the lake when it was filled decomposes.

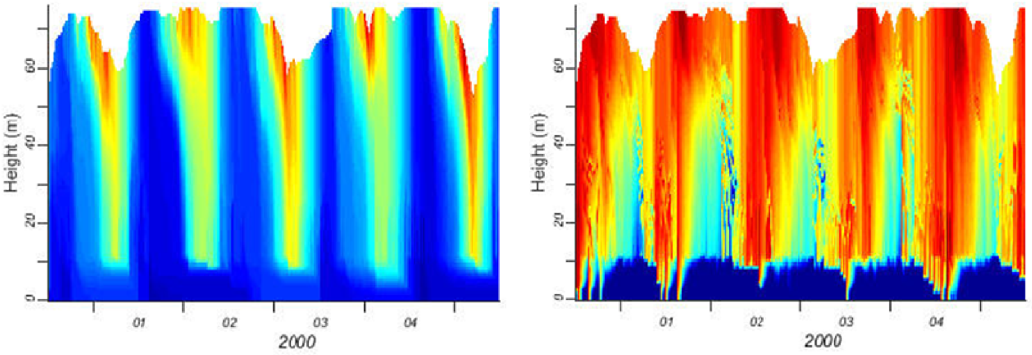
To set-up the model, geomorphic data for the proposed lake is required. These data include the hypsographic contours of the proposed lake, configuration of the dam and outlet structures and proposed operational flow regime for the lake. Using the principle of selective draw to manage the water quality in the lake, one offtake valve should be near the bottom of the lake and other offtake valve(s) should be spaced at intervals higher in the water column. Historical water quality data for the source water together with climate records are also required. Additional meteorological and climate data can be obtained from NIWA’s Virtual Climate Network Stations (VCNS) over the proposed lake site and catchment, as well as from national Meteorological climate stations. If historical water quality data is not available for the specific site, historical data may be available for a nearby river from NIWA’s National Rivers Water Quality Network (NRWQN) which monitors 77 rivers throughout New Zealand and has a 20 year record.

DYRESM-CAEDYM is the one dimensional (1-D) dynamic reservoir model DYRESM coupled with the aquatic ecological model CAEDYM. 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.

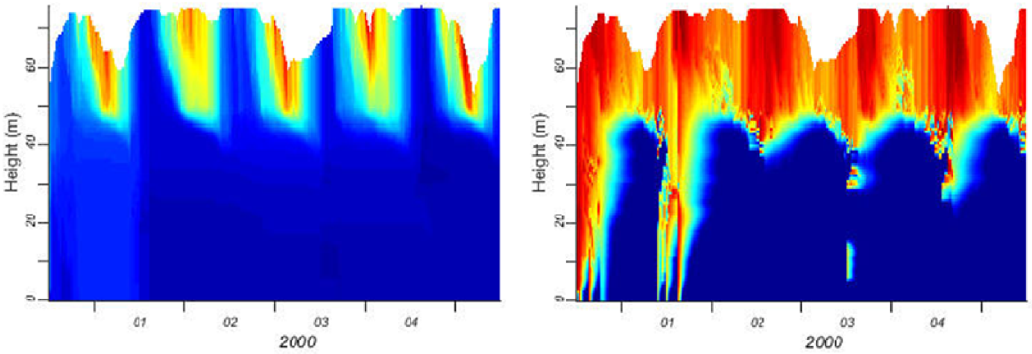
The DYRESM model was developed for geometrically simple reservoirs and lakes where it is reasonable to assume that lateral extrapolation from the 1-D modelling point is valid. However, this model has limitations in long narrow drowned valley lakes with several side arms and constrained bathymetry around the inlets. 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 also affect the validity of the near bottom results towards the inflow end of the lake.

Notwithstanding these limitations, DYRESM-CAEDYM can be used to provide a prediction of likely future condition and water quality in a non-existing reservoir or lake, but 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 is based on a combination of expert knowledge, coefficients from other model applications, and values from literature.

Scenario 1



Scenario 2



Scenario 3

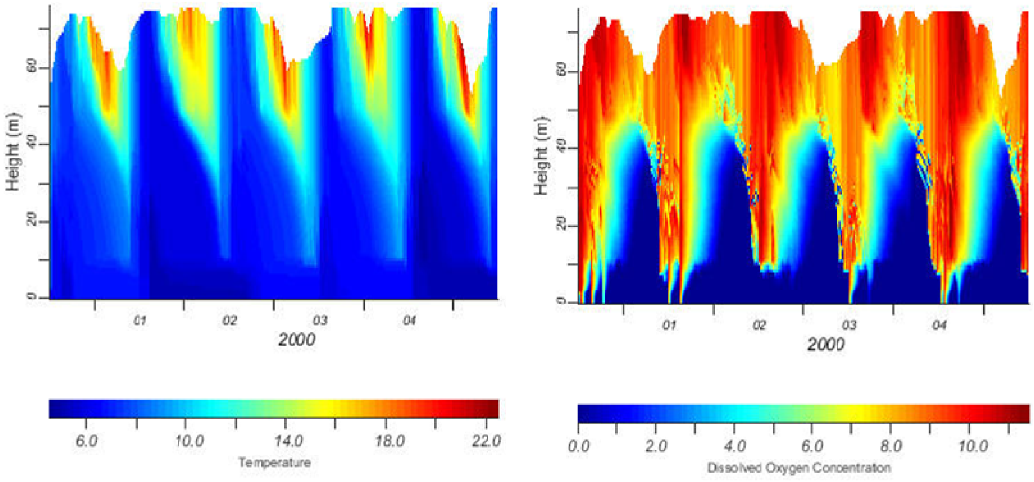


**Figure 4-8: Simulated temperature (left) and dissolved oxygen (right) for three modelling scenarios.** The modelling was used to test the effect of selective draw in a 70 m deep lake where the discharge was equal in volume to the inflow at about 6.3 m$^3$ s$^{-1}$. Scenario 1 has the whole discharge from 5 m above the lake bed. Scenario 2 has the whole discharge from 40 m above the lake bed. Scenario 3 has a flow of 1.2 m$^3$ s$^{-1}$ from 5 m above the lake bed and 5.1 m$^3$ s$^{-1}$ from 40 m above the lake bed. The modelling covers a 5 year period. (Simulation data provided by Limnotrack[3]).

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 from the model are best estimates produced in accordance with

---

[3] Limnotrack, 12 King Street, Cambridge 3434, New Zealand. Email: Limnotrack@gmail.com

best scientific practice and the risk is likely to be low. Notwithstanding these uncertainties, knowing that the model will get the thermal structure 'about right' provides a useful basis for information required to better understand the likely water quality conditions in the future lake.

The advantage of using the predictive model is that a range of scenarios can be run to test out different designs or the effect of changes in the source water quality associated with climate change or catchment management strategies. For example, the DYRESM-CAEDYM model was used to test the effectiveness of selective draw at preventing the development of anoxic conditions in a deep reservoir (Figure 4-8). The model had previously been developed for the reservoir and design variables tested in this example were depth of draw and discharge flow. The model conditions were set for a 5-year period using actual rainfall and a calibrated model of the river flow, which was based on monthly spot.

The model output for scenario 1 indicates that with all water discharged from near the bottom of the lake, the lake water column remained well oxygenated for the whole 5-year period. In scenario 2, taking all the water from 40 m above the lake bed allowed the lake to stratify at that depth and become anoxic below that depth in summer. The model results also indicated that in some years the lake might not mix. In scenario 3, the model output indicated that the lake would mix each year but would develop an anoxic hypolimnion below the high level draw depth in summer.

While predictive modelling is essential for large lakes, it is also useful for smaller lakes in urban developments, e.g., Lake Tewa, a 5 ha artificial lake created in the 2000 house residential and commercial development of Jacks Point on the shores of Lake Wakatipu, Queenstown (Kerr et al. 2009). Modelling can predict what the water quality will be for a range of different management scenarios (Figure 4-9). In this example, the model has predicted the growth of cyanobacteria in the lake for three different scenarios.

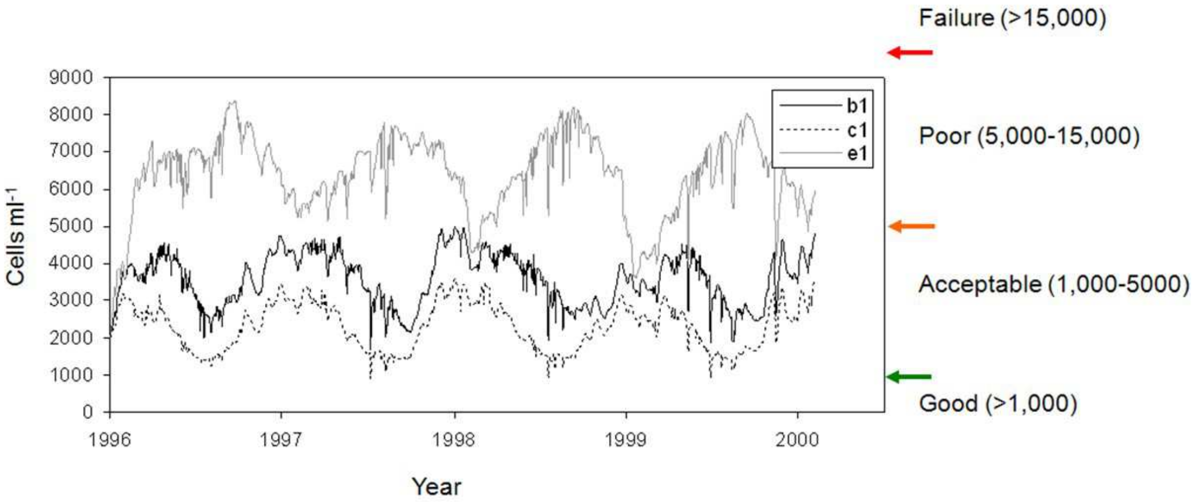


**Figure 4-9: Model predictions of cyanobacteria abundance in Lake Tewa at Jacks Point.** Model condition c1 had an inflow of water from Lake Wakatipu while model conditions b1 and e1 did not. (Figure from Kerr et al. 2009).

The model predictions indicate that the water quality would almost meet drinking water standards (<2000 cells ml$^{-1}$) using scenario c1. Interpreting the data another way, the modelling is suggesting that the lake will always have some level of cyanobacteria present with highest concentrations in summer when the tourist resort would be busiest. Forewarned, management strategies might be implemented to reduce the cyanobacteria biomass.

When a model has been used to predict the condition of a lake, it is essential that there is follow-up monitoring of the lake when it is built. This provides information to improve future modelling and allows adaptive management of the artificial lake to achieve and maintain the highest practical water quality.

## 4.4 Maintenance and management

To maintain a high water quality in the artificial lake requires a management plan (See section 5). Apart from preventing nutrient inflows to the lake from the catchment or surrounding farm land and road runoff, a key element of that plan should be the prevention of bottom water anoxia. This can be achieved in most lakes by using aeration techniques (Nordin & McKean,1982).

### 4.4.1 Aeration protocols

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 3-9B). Consequently, monitoring the temperature and oxygen concentrations through the depth of the water column near the aerator is essential through spring as the artificial lake 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 lake 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 lake 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 lake 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 lake 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 lake or changes in the catchment landuse that have affected the trophic condition of the lake.

### 4.4.2 Scour valve

For large on-stream dams, a scour valve installed in the bottom of the dam wall will allow periodic clearing of accumulating fine sediment and prolong the life of the dam.

Points to consider are:

- The valve needs to be at the lowest point in the dam wall and should have an apron of riprap or concrete to prevent bed scour beneath the dam wall.
- It also needs to be fitted with a screen to prevent logs or other debris jamming the valve open when it is being used.
- Its use needs to be timed to coincide with high flow events which would otherwise cause water to be spilled from the dam over the spillway.

The construction of an on-stream dam deprives the downstream river of the source of gravel and sediment it would otherwise receive if the dam wasn’t there. The sediment released from the scour valve is only the fine component of the upstream bedload entering the lake. Under flood conditions, that fine sediment would normally travel down the length of the river and replenish the food supply for benthic organisms. The dam prevents that replenishment.

Operating the scour valve on a regular basis coinciding with natural flood events returns the fine sediment to the downstream river and reduces the accumulation in the lake. However, because the gravel has been removed, there is less likelihood that the flood flow will tumble the stones in the river bed to keep the fine sediment from accumulating between the stones. Consequently, the frequency of use and the amount of sediment discharged needs to be carefully managed.

# 5 Lake restoration

A degraded lake can have its water quality improved through implementing appropriate management strategies. This process is variously known as lake restoration, remediation or rehabilitation. Before beginning this process, it is important to recognise that the restoration programme will take time and will not return the lake to a once pristine condition that it may have had earlier in its life, but it could improve the water quality to meet a specified water quality goal. The ability to achieve that goal for a specific degraded lake will be determined by the nutrient budget (internal versus external loads), how well the in-lake processes are known, the degree of restoration required to achieve the goal and the funding available to implement the management strategies required to achieve that degree of restoration.

Restoration is expensive. Prevention is cheaper than restoration. That said, other than cost, there are few limits on the size, shape or depth of lake that can be restored. A restoration programme is being developed for Lake Rotorua (area 81 km$^2$) and initial results suggest that it is working with a mean annual Trophic Level Index (TLI) of <4.1 (as at winter 2012). The first part of the restoration of Lake Rotoiti (~30 km$^2$) has been completed (diversion wall) and has markedly reduced the incidence of cyanobacterial blooms in that lake. A restoration programme for Lake Rotoehu (8 km$^2$) includes the installation of two large aeration systems in winter 2012 to be tested during summer stratification. The restoration strategy for Lake Okaro (0.3 km$^2$) a formerly hypertrophic lake, includes a constructed wetland on the inflow streams and dosing the lake with a range of P-inactivation agents. These measures have produced significant improvements in lake water quality although there is still some way to go to sustainably reproduce the mesotrophic water quality achieved in summer 2010. While there might be a perception that artificial lakes are generally small, several are greater than 1 km$^2$ and their degradation was likely to have been due to a flaw in their design at construction (e.g., Lake Opuha, surface area 7.1 km$^2$).

There are also a number of instances in New Zealand and overseas where natural lakes “technically” become artificial lakes because of control structures on their outlets to manage water levels or control the out flow. For example, the weir on Lake Horowhenua was installed in 1956 to hold a minimum water level that would define the legal boundary of land surrounding the lake, the control gates on Lake Rotoiti (North Island) were installed in 1982 to control lake levels in the lake and flood flows downstream, and the control gates on Lake Taupo were installed in 1941 to increase the storage capacity of the lake for hydro power generation and are also used to reduce flooding downstream.

Although the effects of such control structures are likely to be minimal on deep lakes, the resultant change in hydraulic regime on shallow lakes could be substantial. The installation of the weir on the outlet of Lake Horowhenua had ecological consequences which have led to the lake becoming hypertrophic. Extracts from a review of the water quality and restoration prospects (Gibbs 2011) are included in this chapter as specific examples of practical lake restoration considerations.

Lakes provide people with many services: aesthetic enjoyment, recreation, fish, transportation, water for irrigation, drinking and dilution of pollutants. Lake degradation results from excessive nutrient inputs, toxic substances, habitat loss, overfishing, species invasions and extirpations. The goal of management is to balance the uses of lakes with conservation measures to sustain ecosystem services over time (Carpenter & Lathrop 1999).

The scientific basis of lake degradation is generally well understood, although each restoration project requires some level of new site-specific research. **Remediation** may require management actions which are difficult to implement for social or institutional reasons. While there is an implicit expectation that **restoration** will return the lake to its original pristine condition, the reality is that some processes on the way to degradation are irreversible (Carpenter & Lathrop, 1999). Consequently, the expectation of restoration needs to be tempered with the knowledge that the lake may never reach its original pristine state and that the objective of a restoration project will be to **rehabilitate** the lake to improve the water quality and lake conditions to an achievable level. This rehabilitation level then becomes a management goal. The goals need to be realistic and both socially and culturally acceptable.

Restoring a degraded lake to a new desirable condition is an adaptive management process which must include a monitoring programme to assess the success of management strategies employed to reach that goal, and the flexibility to adapt the management strategies based on those monitoring results.

Research studies in the international literature can provide understanding of lakes, their catchments and the mechanisms that sustain ecosystem services; the causes of lake degradation; and methods and technologies for lake restoration. From a lake perspective, the ecosystem is in steady-state with the catchment and changes to any aspect of the lake ecosystem will cause the lake to adjust until a new state is established (Duarte et al. 2009).

Such changes take time and, although a remediation technique may appear to offer a “quick fix”, the resultant new state may not be reached for several years. These lags and delays may appear to be failures but may actually be unforeseen bottlenecks requiring new techniques to be developed (Gulati et al. 2008).

Traditional techniques relying on management of land based nutrient sources to reduce algal biomass in the lake are being augmented with biomanipulation techniques which use natural biological processes to target specific processes in the lake that will culminate in a water quality improvement (Jeppesen et al. 2007). The success of such techniques varies with lake size and climate.

**A key point which is fundamental to the restoration of any degraded lake is to “turn off” the sources of nutrients entering the lake at the same time as the in-lake interventions are being implemented.** This is especially important for shallow lakes which receive a high proportion of their hydraulic load from groundwater. Reducing the nutrient input to the ground and thus the groundwater nutrient load must be part of any rehabilitation strategy used to restore the water quality of these lakes.

Before the lake can be restored, there needs to be adequate baseline information against which to measure any change. “Adequate” would normally imply several years of water quality or biological data, including fish surveys (Baker et al. 2008), to identify seasonal patterns and interannual variability and trends (Figure 5-2) that might otherwise be misinterpreted in the context of the remediation interventions. However, where these data are not available, a snapshot of the water quality to calculate a TLI value may be sufficient to classify the lake by Trophic Level and thereby allow a restoration goal to be set, while that data is being collected. Waiting for the data may allow the lake to deteriorate further and thus be more difficult to restore.

**Lake restoration is a stepwise process:**

1 Measure the present condition of the lake and obtain baseline information against which to measure any change. This requires both monitoring (See section 5.7) and data interpretation (See section 5.1). It is not possible to manage water quality if the water quality is unknown.

2 Set management goals that are realistic (See section 5.2). For natural lakes, these need to be set in consultation with the community and iwi. For artificial lakes the consultation should include the consenting authority. A lake environmental consultant should be included in these discussions to advise what is and isn’t possible within a specified time and budget. As part of setting the goals, the measure indicating success should also be defined.

3 Identify management options (See section 5.3). There are likely to be several different ways to achieve the goals. For example, if the goal was to reduce the TLI to below a specified level, there are four components of the TLI (Section 5.1) that could be manipulated individually or in combination to achieve the target goal, and the manipulations could be implemented in the catchment or in the lake. As a general rule, the first step should be to reduce or eliminate the external load of nutrients and sediments to the lake. If that is not enough then in-lake interventions may be needed. Each option has a cost-benefit that may override the use of the more expensive options and some options may be socially and / or culturally unacceptable.

4 Select the management tools required (See sections 5.4 and 5.5). There are a broad range of tools available for implementing management options. These range from engineering solutions to water treatment, both chemically and with natural biomanipulation solutions. Aquatic organisms living in the lake – macrophytes, fish, snails, mussels, invertebrates – may be the cause of the problems with the lake or they may offer a solution to the problem.

5 Develop a management strategy (See section 5.6). Having decided the goals, the management options and the most appropriate tools to achieve the goals, there needs to be a strategy or plan that sets out the order and timing (e.g., seasonal cycle) for implementing each remedial action.

6 Monitor the effects of implementing the management strategy (See section 5.7). This is mandatory as it provides the information on whether the remedial action has improved the lake or made things worse.

7 Adapt the management strategy including tools if necessary, based on the monitoring results to achieve the goals. It is likely that some remedial actions will require adjustments to improve their efficiency.

8 Implement a maintenance programme to keep the lake at the new water quality condition.

This process has been set out in a simplified flow chart (Figure 5-1). The flow chart can be expanded to contain additional information or additional steps as required. The role of the consultant is to provide expert advice at key points in the restoration process. A consultant may not be required for many artificial lakes but for others, the use of an appropriate consultant could be beneficial and may be essential. Engineers are consultants and must be used wherever changes are contemplated to the physical structure of the dam forming the artificial lake.

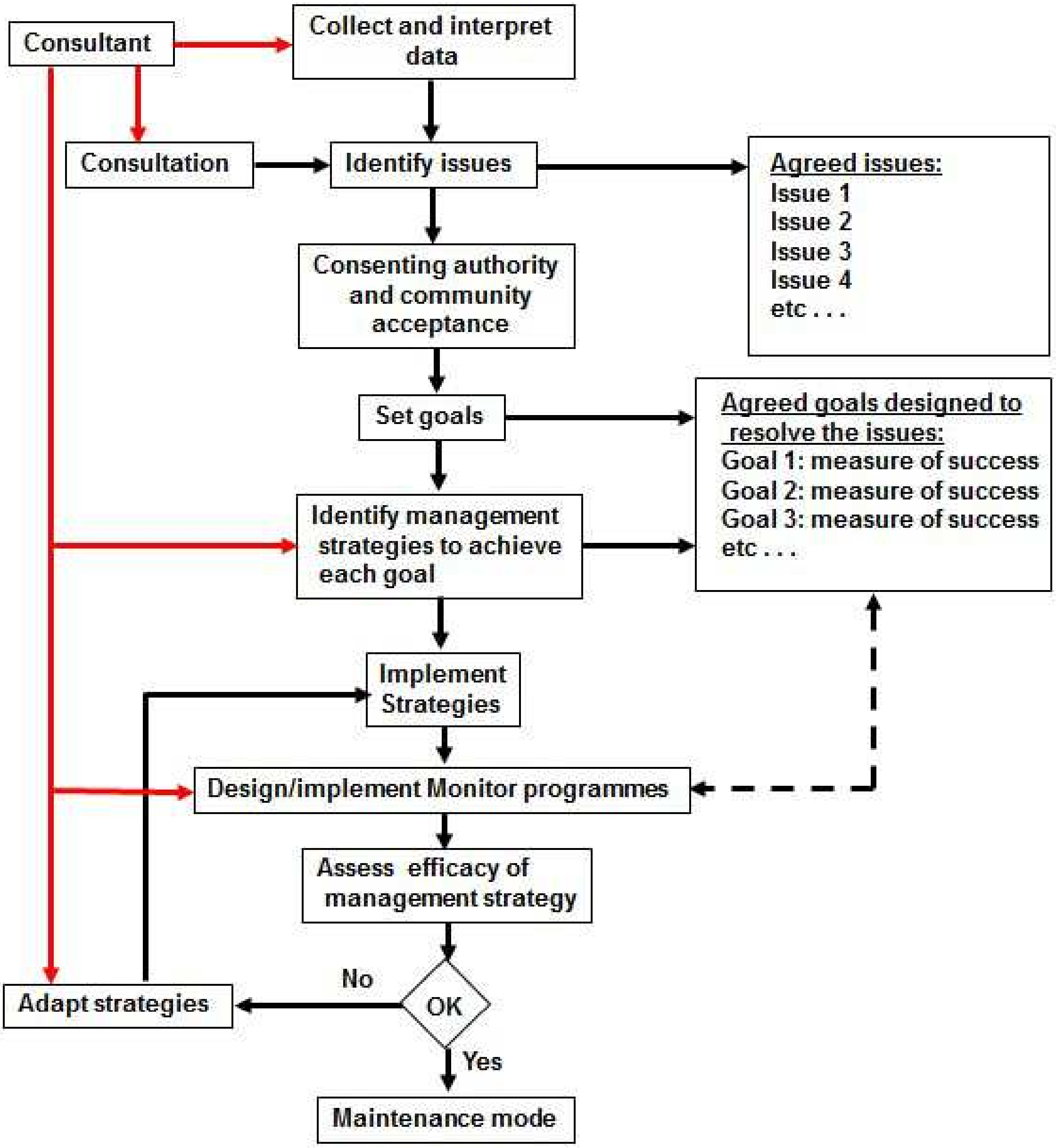


**Figure 5-1: Management flow diagram for the rehabilitation of a lake.** The issues, goals and measures of success can be filled in and additional sections listing the tools to be used can be added. The role of the environmental consultant at key points indicated by red arrows is optional depending on the competence of the lake manager and the size of the lake. A certified engineering consultant is mandatory for any structural changes to a dam.

## 5.1 Water quality and trophic condition

New Zealand lakes can be classified by trophic level based on a combination of 4 key variables: chlorophyll *a*, TN, TP, and Secchi depth (SD) (Table 5-1).

**Table 5-1. Lake classifications, trophic levels and values of the four key variables that define the different lake classifications.** The trophic level has no upper limit. (From Burns et al. 2005).

| Lake classification | Trophic level | Concentration (mg $m^{-3}$) | | | Secchi depth (m) |
|---|---|---|---|---|---|
| | | Chla | TP | TN | |
| Ultra-microtrophic | 0.0 – 1.0 | 0.13 – 0.33 | 0.84 – 1.8 | 16 - 34 | 24 - 31 |
| Microtrophic | 1.0 – 2.0 | 0.33 – 0.82 | 1.8 – 4.1 | 34 - 73 | 15 - 24 |
| Oligotrophic | 2.0 – 3.0 | 0.82 – 2.0 | 4.1 – 9.0 | 73 - 157 | 7.8 - 15 |
| Mesotrophic | 3.0 – 4.0 | 2.0 – 5.0 | 9.0 - 20 | 157 - 337 | 3.6 – 7.8 |
| Eutrophic | 4.0 – 5.0 | 5.0 – 12.0 | 20 - 43 | 337 - 725 | 1.6 – 3.6 |
| Supertrophic | 5.0 – 6.0 | 12.0 – 31.0 | 43 - 96 | 725 - 1558 | 0.7 – 1.6 |
| Hypertrophic | <6 | >31 | >96 | >1558 | < 0.7 |

Logarithmic transformation of the mean annual data[4] for these variables provides a numerical index i.e., TLI as a number to represent the lake classification. The equations used are:

- Nitrogen $TLn = -3.61 + 3.01 \log10 (TN)$
- Phosphorus $TLp = 0.218 + 2.92 \log10 (TP)$
- Chlorophyll *a* $TLc = 2.22 + 2.54 \log10 (Chla)$.
- Secchi depth $TLs = 5.10 + 2.27 \log10 (1/ZSD – 1/40)$

The four resulting numbers are then averaged to form the TLI. This is known as the TLI4 (makes use of four variables). There is also a TLI3, which excludes Secchi depth (Verburg et al. 2010).

Lake Horowhenua is classified as hypertrophic which means that it will have chlorophyll *a* concentrations greater than 31 mg $m^{-3}$, TP and TN concentrations greater than 96 mg $m^{-3}$ and 1500 mg $m^{-3}$ respectively, and Secchi depth values less than 0.7 m. In 2005, the TLI3 value for Lake Horowhenua was 6.27, and the lake was ranked 107 out of the 114 monitored lakes in New Zealand (Verburg et al. 2010).

Comparison of historic and present data for Lake Horowhenua (Table 5-2) shows the changes that have occurred between 1988 and 2000 and over the period of continuous monitoring from 2000 to 2009. In 1987 a treated sewage discharge into the lake was removed with a subsequent reduction in the amount of P in the sediments. This is the likely driver of the observed change between 1988 and 2000. Notwithstanding this, almost all of the data fall within the range of hypertrophic (Table 5-1). The exceptions were the Secchi depth data which were greater than expected.

---

[4] Refer to Burns et al. 2000 for the protocols for collection and processing data for estimation of TLI values.

**Table 5-2**. Mean annual Chlorophyll *a*, TP, and TN concentrations (mg $m^{-3}$) plus Secchi depth (m) data for 1988 and from 2000 to 2008. These data have been log transformed to produce a TLI value.

| Date | Chla | TP | TN | SD | TLc | TLp | TLn | TLs | TLI |
|---|---|---|---|---|---|---|---|---|---|
| 1988 | 60 | 253 | 2767 | 0.49 | 6.74 | 7.24 | 6.75 | 4.40 | 6.28 |
| 2000 | 26.8 | 131 | 2450 | 0.65 | 5.85 | 6.40 | 6.59 | 4.68 | 5.88 |
| 2001 | 61 | 191 | 1990 | 0.72 | 6.75 | 6.88 | 6.32 | 4.78 | 6.18 |
| 2002 | 27.3 | 144 | 2160 | 0.8 | 5.87 | 6.52 | 6.43 | 4.88 | 5.92 |
| 2003 | 70 | 199 | 2820 | 0.7 | 6.91 | 6.93 | 6.78 | 4.75 | 6.34 |
| 2004 | 117 | 272 | 3780 | 0.73 | 7.47 | 7.33 | 7.16 | 4.79 | 6.69 |
| 2005 | 63 | 113 | 4660 | 0.68 | 6.79 | 6.21 | 7.43 | 4.72 | 6.29 |
| 2006 | 64 | 213 | 2810 | 0.63 | 6.81 | 7.02 | 6.77 | 4.64 | 6.31 |
| 2007 | 110.7 | 299 | 3730 | 0.73 | 7.41 | 7.45 | 7.14 | 4.79 | 6.70 |
| 2008 | 211 | 150 | 3370 | 0.79 | 8.12 | 6.57 | 7.01 | 4.87 | 6.64 |

The mean annual data converted to TLI values (Table 5-2) indicate that the lake may have begun to recover between 1988 and 2000. The TLI value in 1988 was 6.28 and in 2000 it was 5.88. However, after 2000 there is a statistically significant ($p < 0.01$) trend of TLI increase indicating that the water quality in Lake Horowhenua has been declining over the last 10 years (Figure 5-2).

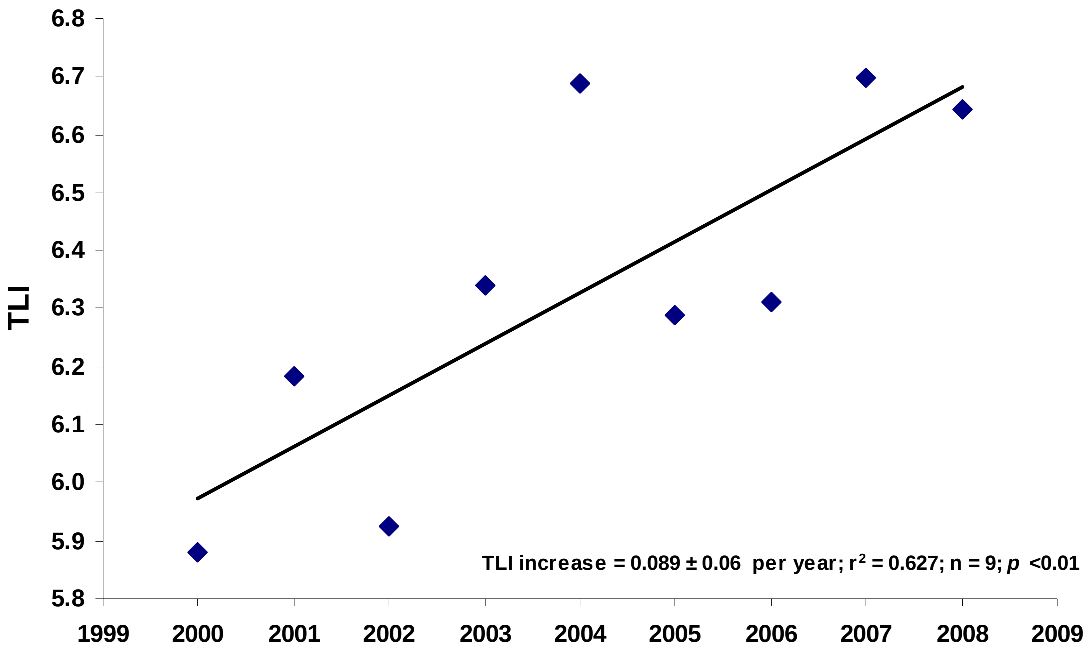


**Figure 5-2: Trend analysis using a linear regression through the annual TLI values.** Although there is interannual variability, data from 2000 to 2008 suggest that the TLI is increasing and thus the water quality is declining. The trend is statistically significant ($p < 0.01$). (Regression details on the figure).

Where there is large variability in the data used to calculate the annual mean TLI, there is likely to be large interannual variability in the TLI value, which result in a high level of uncertainty about any trend observed in the TLI. In the case of Lake Horowhenua (Figure 5-2), the trend is statistically significant ($p < 0.01$) and it explains about 60% of the change that has occurred in the dataset over the specified time period.

## 5.2 Setting management goals

Continuing the use of Lake Horowhenua as a case study example, practical management goals for that lake would include:

1. to reduce or eliminate the occurrence of nuisance cyanobacteria blooms
2. to improve the water quality of the lake from hypertrophic to supertrophic or eutrophic i.e., reduce the TLI for the lake from its current level of 6.7 to <5
3. to reduce the abundance of aquatic macrophytes in the lake to enable unimpeded use of the lake for contact recreation, and
4. to maintain or enhance the fishery in the lake and its tributaries.

These goals are essential to restoring the mauri of the lake. They are closely linked such that changes made to achieve one goal will interact with and affect the other goals. For example, while achieving **goal 1 will be a measure of the success for goal 2**, goal 3 may be negatively impacted by this success as increased light levels through clearer water will allow aquatic macrophytes to grow and spread. The overall effect on the fishery, goal 4, will depend on the new balance between competing aspects of the lake ecology.

It is unlikely that a single action will rehabilitate the lake and any management strategy will need to include the use of several management tools in the lake and in the lake catchment.

**Goal 2: Improving the water quality**

The trend of decreasing water quality indicated by the TLI trend analysis (Figure 5-2) is in contrast to the reducing pool of P in the near surface sediments. Historical data indicates that about 55% of the P input to the lake comes from the release of P from the lake sediment (the internal load) during periods of bottom water anoxia and that stimulates the growth of nuisance cyanobacteria blooms. This implies that to meet the first goal, remedial action should include a focus on stopping the P release from the sediment in summer. This raises a question “What causes the sediment to become anoxic when the maximum water depth is only 1.8 m?”

The natural decline of P in the sediments due to flushing and burial is slow and the release of DRP from the sediment may not reach acceptable levels for more than 100 years. To reduce this time frame significantly, management strategies need to include in-lake interventions as well as stopping the input from the catchment. Stopping the release of P from the lake sediment has the potential to lower the TP concentrations and thus the chlorophyll *a* concentrations in the lake. Applying these criteria to the 2000 to 2008 data, without changing the TN or SD data, suggests mean annual chlorophyll *a* values could reduce to around 9 to 17 mg $m^{-3}$ and mean annual TP values would be around 52 to 83 mg $m^{-3}$. These values translate into a mean TLI of around 5.5, which implies a water quality improvement from hypertrophic to supertrophic.

A TLI value of around 5.5 is above the value of 5 set in goal 2. Reducing the TN would improve the water quality further and would lower the TLI. However, reducing the TN is difficult because of the high N concentrations in the groundwater and surface water inflows to the lake. For example, in 1988/89 the mean TN concentrations in the Arawhata Stream and groundwater, which account for more than 80% of the inflow to Lake Horowhenua, were around 10,500 mg $m^{-3}$ and 8,450 mg $m^{-3}$, respectively. Between 2000 and 2009, the mean TN concentration in the Arawhata Stream was around 13,500 mg $m^{-3}$, which indicates that the external N input has been increasing in recent years, consistent with the TLI trend (Figure 5-2). This increase in the TN loads in the Arawhata Stream coincides with the expansion of market gardening around the Arawhata Stream in recent years. The paucity of data and high seasonal variability in the available TN data in the Arawhata Stream (Figure 5-3) makes such a trend difficult to detect although a step change may have occurred.

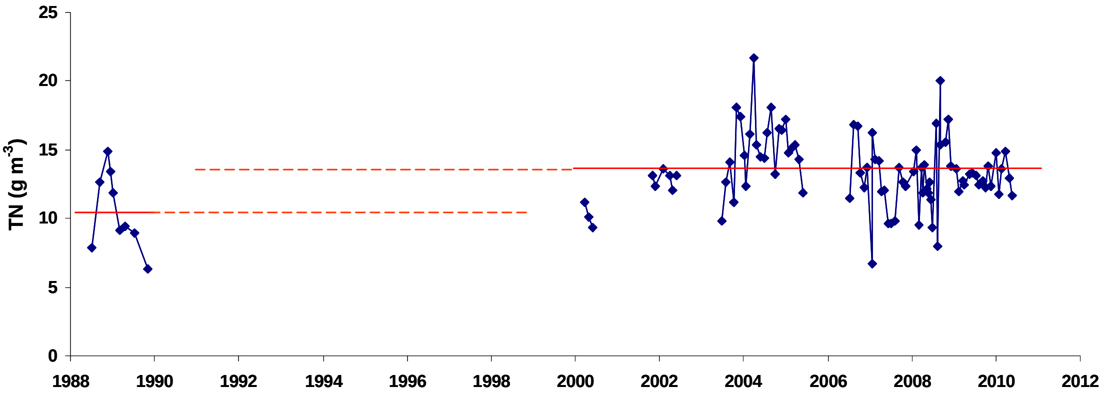


**Figure 5-3: Time-series total nitrogen (TN) concentrations in the Arawhata Stream inflow to Lake Horowhenua.** The dashed lines are means for the two data periods.

Despite the apparent increase in TN, there is no significant trend of increasing TN concentrations in the Arawhata Stream data. Conversely there is also no indication that the TN concentrations are reducing. Consequently, with a mean residence time of around 47 days and the flushing waters having such high TN concentrations, the TN component of the TLI for Lake Horowhenua is likely to remain in the hypertrophic classification without management intervention.

Because most of the N input to the lake comes from the catchment via streams and groundwater, and most of the streams receive groundwater inputs, that management intervention will need to focus mostly on the lake catchment and ways to protect surface waters and reduce contamination of the surface groundwater aquifer. Management strategies will also need to consider buffer zones to intercept the groundwater contaminants before they enter the lake until the catchment strategies become effective.

### Special considerations

The choice of Lake Horowhenua as a case study example is because it has a number of special features which place this lake on the cusp of a significant decline in water quality. It is also in the depth range of many artificial lakes.

Lake Horowhenua water column has high levels of N but no P for much of the year. This is because the groundwater is well oxygenated and flows through iron-rich aquifers which have coated the cobbles with iron oxides. These oxides adsorb the P (section 3.5) and, consequently, the ground water and stream inflows do not inject P into the lake.

The groundwater table is close to the land surface allowing good oxygenation to keep the iron as insoluble oxides. Being close to the surface, however, the groundwater is vulnerable to contamination, especially from organic carbon. Organic carbon comes from animal waste and the land disposal of whey. Elsewhere in New Zealand dairy effluent is spray irrigated onto pasture and whey may be spread by truck. As more effluent and whey is spread on the land the soil becomes overloaded with organic carbon which then begins to decay, consuming oxygen in the decomposition processes. If this were to happen in the Lake Horowhenua catchment, the resultant oxygen demand could cause the groundwater to become anoxic. If the groundwater became anoxic, the iron oxides would dissolve and the P bound to it over the millennia would be released to flow freely into the lake. That would cause the lake to become an algal "soup" all year round.

In this type of catchment with shallow groundwater, dairy intensification or the disposal of whey are primary concerns for lake managers trying to restore lake water quality.

### Goal 3: Reducing aquatic macrophytes

The aquatic macrophytes or "lake weeds" of concern in Lake Horowhenua are *Potamogeton crispus* and *Egeria densa* (Figure 5-4). Both are rooted plants with the ability to grow to the surface where the *Potamogeton* emerges to flower. While *Potamogeton* is well established in the lake, it is uncertain whether or to what extent *Egeria* has become established.

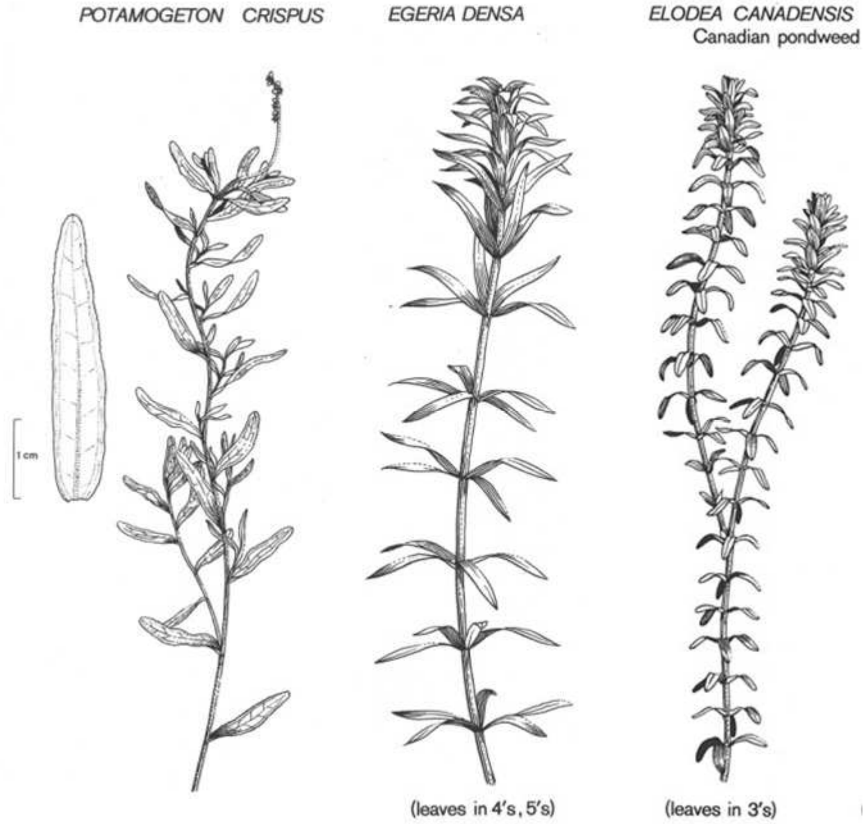


**Figure 5-4. *Potamogeton crispus* (left), *Egeria densa* (middle) and *Elodea canadensis* (right) (drawings from Mason & West 1973).**

The spread of *Potamogeton* is by seed, which can rest in the sediment for several years until conditions are right for germination, but more commonly from pieces of plant broken off the main weed bed by wave action or the grazing of swans and other water fowl or during weed harvesting. Fragments of lake weed can survive considerable periods out of water and are often transferred between lakes on boat trailers and leisure activity equipment such as fishing gear. Eel traps moved from one lake to another could spread the weed, as will the misguided aquarium keeper who discards fragments in open drains or even empties a goldfish bowl into the lake. This is also often how pest fish are spread.

Management of the spread of lake weed is one of public education and making people aware of the consequences of their actions.

*Potamogeton crispus* has been in Lake Horowhenua for many years. The annual cycle is for growth in spring when it rises to the surface to flower. This growth pattern appears to be a rapid spreading of the plant as was noted by Brougham & Currie (1976) (Figure 5-5).

**Figure 5-5.** Time series showing the spread of *Potamogeton crispus* in Lake Horowhenua in summer 1975/76. (From Brougham & Currie 1976).

By mid-summer, when the water is warm, *Potamogeton* senesces (dies back) and the growth collapses to the lake bed where decomposition releases both N and P to the water column and decomposition processes contribute to the depletion of oxygen in the bottom waters. *Potamogeton* has a low tolerance to high temperatures and low alkalinity, but a high tolerance to sediment disturbance and to most aquatic herbicides such as Diquat and Endothall (P. Champion, NIWA, pers. comm.). The plant germinates from seed so elimination would be difficult as there would be a large seed bank in the sediment. While it is highly palatable to herbivorous fish such as grass carp, these fish are non-selective in their feeding and would remove all available / accessible plant material. A weed harvester could provide a way to clear areas for recreational purposes, but will not eliminate this lake weed.

*Egeria densa* is a recent invader of Lake Horowhenua and was first noted in the lake in July 2001 (Edwards & Clayton 2002). Edwards & Clayton (2002) commented that the introduction is "likely to have far reaching consequences on the ecology of this lake. One of the features of many shallow lakes that have been invaded by *Egeria* is that after several years of domination by this weed, all of the submerged vegetation rapidly declines. After vegetative decline events, water becomes typically more turbid than before on account of re-suspension of bottom sediments. The ensuing turbid waters are generally too turbid to support submerged plant growth, which has been the case in many of the shallow Waikato lakes*."*

No plants of *Egeria densa* were found in Lake Horowhenua at the 13 sampling sites in August 2002 (Champion et al. 2002). However, the authors commented that where this weed has invaded other shallow Waikato lakes and Lake Omapere, the lakes have lost their diverse submerged vegetation becoming "a monoculture of often surface reaching *E. densa."* They also noted that "dense beds of *E. densa* in Lake Omapere appear to have prevented diffusion of oxygen through the water column to the lake bed and benthic respiration was responsible for benthic anoxia." The consequences of this benthic anoxia appeared to be a decline in *E. densa* health and biomass, and an increase in dissolved N and P as a result of macrophyte decomposition and release from the anoxic sediments both responsible for an increase in planktonic cyanobacterial abundance.

The projected consequences of an invasion of *E. densa* in Lake Horowhenua could be a switch from the annual cycle of summer turbidity and winter clear-water phases to a period of increasing water clarity while the weed beds establish, followed by a collapse of vegetation, benthic anoxia and sustained cyanobacterial blooms for several years.

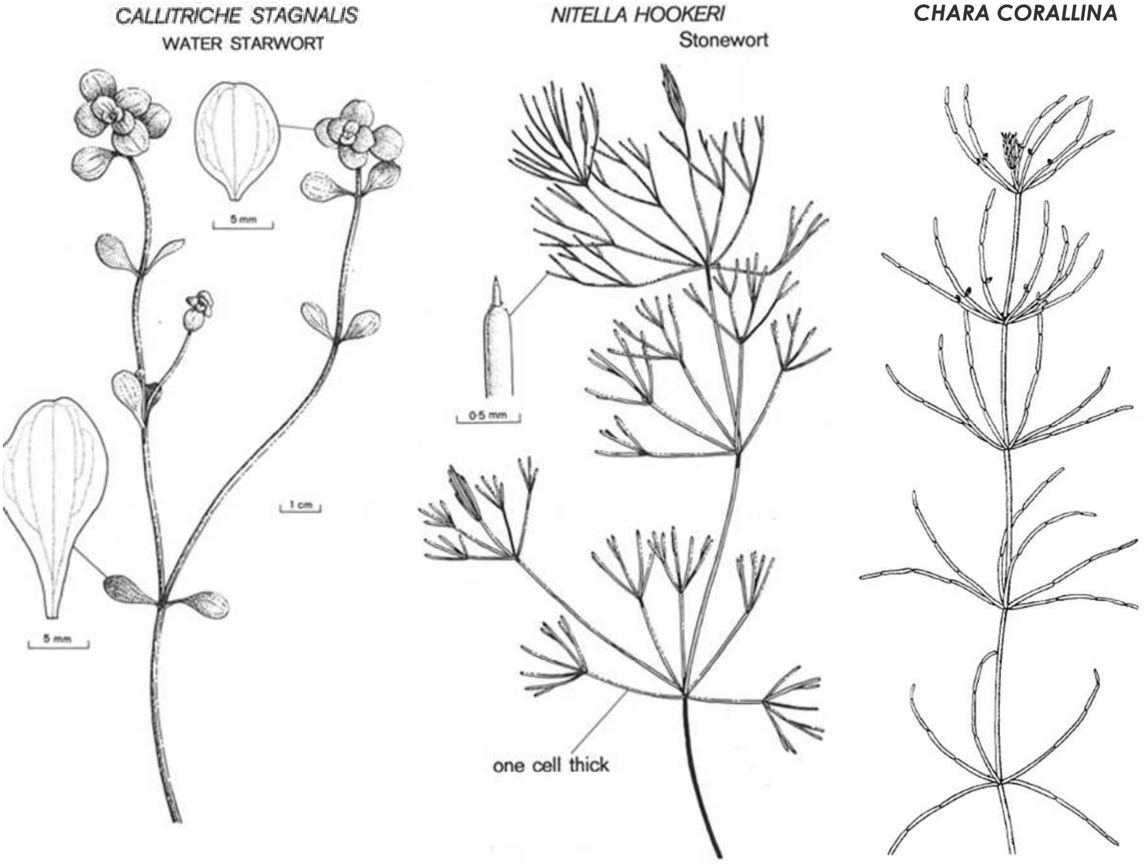


**Figure 5-6: Native pond weeds.** *Callitriche stagnalis* (left), *Nitella hookeri* (middle) and *Chara corallina* (right). (Drawings from Mason & West 1973).

The control of *E. densa* once established is not easy and quarantine prevention is the best approach. However, it can be controlled to some degree using the herbicide Diquat. A resource consent would be required for the use of this herbicide.

Other aquatic macrophyte species in the lake in August 2002 included *Potamogeton pectinatus* and *Nitella hookeri/cristata* (Figure 5-6) at <5% of the plant cover with small patches of *Chara corallina* (Figure 5-6), *Elodea Canadensis* (Figure 5-4), *Elatine gratioloides* and *Callitriche stagnalis* (Figure 5-6) (Champion et al. 2002). Some of these plant species e.g., *Chara corallina*, are probably remnants of the original flora of the lake which would have covered much of the lake bed.

While macrophytes such as *Potamogeton* are rooted in the sediments, they draw much of their nutrient requirements, especially $NO_3$-N, from the water column. Consequently, when they begin their spring growth, they have the capacity to remove all of the free $NO_3$-N from the lake. After the plant flowers and collapses to the lake bed, decomposition releases the N and P from the plant material back into the water column. At the same time, decomposition of the plant material lying on the lake bed, consumes oxygen and cause the sediments beneath the weed to become anoxic. Under these anoxic conditions, P is released from the sediments where it can stimulate algal growth.

**Goal 4: Maintenance or enhancement of the fishery**

In the past, Lake Horowhenua has been renowned for its abundant food resources. Fish and other aquatic species (D Rowe, NIWA, pers. com.) that are likely to have been in the lake in the past include:

- eel (tuna) both short-finned (*Anguilla australis*) and long-finned (*A. dieffenbachia*)
- flounder (patiki)
- mullet (*Mugil cephalus*)
- inanga (whitebait, *Galaxias maculatus*) and the other Galaxids, the banded Kokopu and giant Kokopu
- smelt (*Retopinna retropinna*)
- common bully (*Gobiomorphus cotidianus*)
- koura (freshwater crayfish), and
- kākahi (freshwater mussel, *Hydridella menziesii*).

Of these, eel, flounder, inanga and kākahi were important fisheries. More recently, gold fish (*Carassius auratus*), perch (*Perca fluviatilis*) and to a lesser extent, trout have been additional components of the lake fishery.

Enhancement of the fishery does not mean adding new species but eliminating/controlling population densities of pest fish in favour of native or desired fish. It also means ensuring that there is access to the lake for migratory diadromus species.

Lake Horowhenua does not have koi carp, rudd or tench. These three species can destroy marginal buffer zone plants which protect the shoreline from erosion by wind waves and are a major cause of turbidity in infested lakes. Public education is required to ensure well-meaning people don't empty the unwanted ornamental fish into the lake or deliberately release these species into the lake to provide a fishing resource for future generations, as has happened in many Northland lakes.

Over-fishing is thought to be one cause of the depletion of fish stocks in Lake Horowhenua, especially eels, but more realistically, the decline is probably a response to the degradation of the lake and the installation of the weir to control the lake level. Many of the fish species that were once found in the lake are diadromus and have an essential part of their life cycle in the sea. The weir is a barrier to smelt, flounder and mullet and would affect the natural stocking of the lake with inanga. The return of those species to the lake would require a fish-pass to be constructed. However, providing access to the lake would not guarantee a restoration of the fishery if the water quality issues are not addressed.

Invertebrate species (aquatic insects) that require sand or cobble lake beds are missing from the food web although there is an abundance of larval chironomids (*Paratanytarsus grimmi*) in the silty sediments. Zooplankton grazers such as the cladoceran, *Daphnia carinata*, are super abundant during algal blooms and provide food for juvenile fish, as do water boatmen (*Sigaria arguta*).

The fishery at present is a function of the turbid lake environment. Kākahi (freshwater mussels), which are filter feeders, would have been abundant across the lake bed and their filtering would have controlled the algal biomass in the water column. Elsewhere, kākahi abundance can exceed 100 $m^{-2}$, but in 2002 the highest densities found were 6 $m^{-2}$ (Champion et al. 2002). This decline is a direct response to increasing turbidity with the sediment particles interfering with feeding by reducing the relative proportion of algal food ingested at the kākahi's maximum filtering rate. Periods of benthic anoxia would also adversely affect kākahi survival and it would also affect koura, although koura could avoid anoxic zones.

Perch are carnivorous and apply top-down pressure on the fishery through predation on juvenile kokopu, goldfish and bullies. Adult perch can grow very large and in the 2002 lake survey, a 0.5 m long perch was observed at one site (Champion et al. 2002). As juveniles, perch out compete other species for the zooplankton food supply. The turbid waters provide shelter for perch from predation by shags. The turbidity also allows their juveniles to survive predation by adult perch.

Removal of the perch from Lake Horowhenua would be very difficult and is not a viable management option. Rotenone poisoning is not an option as it would non-selectively kill all species of fish in the lake. However, a reduction in turbidity would allow increased predation of perch by shags and would allow the adult perch to predate juvenile perch. This would reduce the pressure on the zooplankton population which would increase and reduce the algal biomass further reducing the turbidity in a positive feed-back loop. The downside of clearer water is the growth of macrophyte weeds. A management option would be to control which macrophyte species grew by the judicious use of weed harvesting and targeted spray applications.

## 5.3 Management options

Before a management strategy can be developed for the restoration of a lake, it is important to understand what the hydraulic and nutrient budgets are and how that lake works. This allows targeted management strategies which focus on key points in the seasonal cycle of the lake where a small intervention may create the greatest benefit. It will also identify management strategies that are not appropriate and should not be used on that lake.

As a starting point, the review of the limnology of Lake Horowhenua (Gibbs 2011) has identified that the lake has a large internal load of P in the sediment as a legacy from 25 years of sewage effluent input. The review also identified that the summer algal bloom is largely in response to P release from the anoxic lake sediment. From the assessment of the macrophyte component of the lake ecosystem, the weight-of-evidence indicates that the collapse of the lake weed in mid to late summer is the most likely cause of the sediment anoxia which allows the release of P from the sediments in a lake that is otherwise so shallow that it should be fully aerobic all year round. Inflows of anoxic water from the Arawhata stream may augment anoxia in the lake at night and has the potential cause thermal stratification in calm conditions.

A decision support and risk assessment framework has been produced for the management of lake sediment P release (Hickey & Gibbs, 2009). Lake Horowhenua has also been modelled to assess its prospects for restoration (Gibbs & White, 1994). The concept of collapsing weed beds causing the anoxia was not considered in Gibbs & White (1994), only that the sediment experienced anoxia. Notwithstanding this, between these two publications, there are a range of management tools that could be applied to the lake to block or reduce that P release. The decision support and risk framework considers tools for in-lake management of P but Lake Horowhenua also has a major N problem which should be addressed concurrently. Some of the tools used for P management will also serve to reduce N while others will be exclusively targeting P.

## 5.4 Management Tools – Engineering solutions

The following is a range of management tools that have been used for the restoration of degraded lake. The most recent tool “Computer modelling” uses environmental, climate and water quality / biogeochemical monitoring data from the lake to build a simulation of the lake to estimate the likely benefits to the lake of applying one or more of the management tools. These tools, which are described in detail, include:

- Lake weed control.
- Stormwater and groundwater treatment.
- Floating treatment wetlands.
- Marginal buffer zones.
- Storm water diversion.
- Inflow diversion.
- Flushing – external source water.
- Enhanced flushing using fluctuating water levels.
- Dredging.
- Aeration using bubblers.
- Aeration by discing.
- Aeration by nitrate injection.
- Clay flocculation of cyanobacterial blooms.
- Phosphorus inactivation with flocculation.
- Phosphorus inactivation with sediment capping.
- Computer modelling.

While a combination of these tools can address the internal problems in the lake, there is also an overriding requirement to address the sources of nutrients from the catchment.

### 5.4.1 Lake weed control

The weight of evidence indicates that the key to restoring the water quality of Lake Horowhenua and its fishery is the management of the lake weed. There are four approaches to this issue: (1) Mechanical weed harvesting; (2) Spraying; (3) Biomanipulation and (4) changing water levels. Before undertaking any strategy to control lake weed, there needs to be a clear understanding of the goal and the consequences of each action.

The weight of evidence of the importance of lake weed includes the fact that the tall weeds remove all the $NO_3$-N from the lake water during spring when there are high inflows of $NO_3$-N enriched stream water. This evidence also suggests that under low flows the weeds become N-limited and, being unable to sustain the amount of biomass with the nutrients available, they senesce releasing the nutrients in the plants back into the water. In all management strategies, an important question to be answered is ‘What happens to the nutrients?”

1 **Mechanical weed harvesting** is a direct method for managing lake weed. It is used in many lakes in New Zealand and around the world. It is a good way to keep waterways open such as access around boat launching ramps and swimming beaches. However, it does not stop the weed re-growing in the same season or the next. Consequently, weed harvesting is an on-going management option with on-going costs. The operational costs associated with weed harvesting depend on whether the weed is truly harvested, i.e., cut and removed from the lake, or simply cut and allowed to fall to the lake bed and rot. This latter action could initiate a release of the P from the lake sediment earlier in the seasonal cycle while there are still high levels of N in the water column.

The advantages of weed harvesting are that it has the potential to remove significant amounts of nutrients from the lake in a short space of time. The harvested weed can be composted to off-set harvesting costs. Done in summer when the weed is just reaching maturity would not change the nutrient status of the lake water at that time but would prevent the weed from falling on the lake bed and releasing P from the sediments and the subsequent development of substantial cyanobacteria blooms.

The disadvantages are that removal of the weed too early would also reduce the removal of $NO_3$-N from the lake water shifting the lake from nutrient limited in summer to nutrient replete. It is uncertain what algal species would become abundant, but it is likely that there would be a major increase in algal biomass. This, in turn, could cause light limitation to the weed beds which could completely disappear.

This effect is known as “flipping”. Flipping has occurred in several prominent New Zealand lakes, most notably, Lake Omapere. Lake flipping can be a natural process typically associated with the collapse of extensive weed beds. The reference to the potential dangers of allowing *Egeria densa* into Lake Horowhenua refer to this effect. When a lake flips, most often it is from macrophyte dominance to phytoplankton dominance. The lake is then difficult to manage as the option for an intermediate stage of reduced macrophytes and reduced algal biomass has been essentially eliminated, and may only be achieved at great cost.

2 **Spraying** could have a similar effect as the weed harvesting without removal of the cut weed management option unless the timing is appropriate. The ideal time to spray would be in early spring when the weed seeds have only recently germinated and the plants are only just starting to reduce the $NO_3$-N concentrations in the lake. The use of Diquat on *Potamogeton* sometimes fails because the plant has a coating of periphyton and fine silt to protect it from the herbicide, i.e., the plants are “dirty”. Sprayed when the plants are young, ensures that they are clean, they are vigorously growing and adsorbing the herbicide, and there is plenty of light to sustain grown. At that time, there should only be a minimum of plant biomass to fall to the lake bed and, consequently, only a small amount of P release from the sediment. The $NO_3$-N concentrations would remain high in the lake and the algal species assemblage would tend to be dominated by the non-cyanobacteria species. Algal biomass would be produced with the magnitude of any bloom depending on the amount of P released.

Spraying coupled with P inactivation technology using sediment capping (see later) offers a solution to the problem of P release following spraying. The P inactivation technology binds the P as it is mineralised in the sediment and permanently locks it in the sediment where it is unavailable for algal growth. Under these conditions, the lake water has a high N:P ratio which does not favour cyanobacteria. With extremely low P concentrations the algal biomass is likely to be low due to P limitation.

Another benefit of spraying with Diquat is that the native plants, the charophytes, are not affected by this herbicide and could re-colonise the lake bed, stabilising the sediment.

3 **Biomanipulation** is becoming more popular in European countries. The technique makes use of natural processes of grazing and predation to achieve the final goal. Zooplankton graze algae and herbivorous fish graze macrophytes. However, just introducing some herbivorous fish may do more harm than good as herbivorous fish may decide to consume desirable species, and they could go on consuming other vegetation when all of the weed has been consumed. As they grow larger, they disturb the sediment and increase the lake turbidity.

Grass carp (*Ctenopharyngodon idella*) were introduced into New Zealand in the 1960s to combat the spread of different species of lake weed. Grass carp have been released by Northland Regional Council (NRC) into two lakes: Lake Swan in May 2009, and Lake Heather in June 2010. In Lake Swan, NIWA determined that most of the *Egeria* and about 40% of the *Hornwort* was removed within 12 months of stocking. The cost of releasing 400 grass carp in Lake Heather in 2010 was $17,000. Peter Wiessing, the Council’s Kaitaia Area Manager, said that it was “the most cost-effective and environmentally sustainable option to eradicate these weeds.” (Northland Regional Council News Archive 15 June 2010). On a proportional basis, Lake Horowhenua would require about 8000 grass carp at a cost of about $350,000. The consequence of making such a release is that all other options would be negated as the grass carp destroyed the marginal wetland plants and loosen the sediment.

A follow up on the grass carp management strategy in Lake Swan is that summer 2010/11 the lake developed a phytoplankton bloom. The cause is uncertain but it is likely that removal of all the weed also removed the mechanism for reducing the N concentrations in the lake leaving high nutrient concentrations through the summer period to support phytoplankton growth.

Silver carp for reducing phytoplankton biomass is impractical in a lake the size of Lake Horowhenua (296 ha) due to the extremely large number of fish that would be required and the impact that would have on the fishery. Once silver carp, or grass carp were introduced, the fishery could not be restored to any previous state. At present there is doubt as to their efficacy at reducing algal biomass and, consequently, no compelling reason to use silver carp.

A key point in this lake is the grazing pressure on the zooplankton which are capable of reducing algal biomass. Juvenile perch predate the zooplankton as noted above. Perch numbers could be reduced by reducing the turbidity in the lake allowing their predation by shags. Carp would increase the turbidity of the lake water. Shag perches constructed in the marginal wetlands near, but not over water, would enhance predation of perch.

The release of grass carp or silver carp into Lake Horowhenua is not recommended and other species of coarse fish such as rudd, tench and koi carp should be prohibited in the lake. It could be prudent to include this prohibition in the regional plan.

4 **Changing water levels** makes use of solar heating to kill the weeds in summer or freezing in frosts to kill the weed in winter. This technique has been used in hydro lakes on the Waikato River with limited success. It has the draw back that the dead weed decomposes and the resultant high oxygen demand can cause severe oxygen depletion. A similar effect can occur when the water level is suddenly raised after a prolonged bed exposure which has allowed terrestrial plants to grow. Severe oxygen depletion can lead to fish kills (Appendix F).

### 5.4.2 Stormwater and groundwater treatment

Waste water treatment uses holding ponds and wetlands for reducing the nutrient load before the water is released into an open waterway.

**Figure 5-7: The constructed wetland at Lake Okaro at the time of construction.** Top: Public access to the wetland is provided by a viewing walkway through the part of the wetland in the lake domain. Bottom: The stream water is forced to follow a convoluted flow path by the use of ridges within the wetland. The broken line indicates the short circuit path for flood events. [Photos and overlay: John Quinn, NIWA].

Advanced pond systems (APS) and high rate algal ponds (HRAP) have been designed for treating dairy shed effluent (Park & Craggs 2010). On a larger scale, a constructed wetland used on two natural streams flowing into Lake Okaro (Tanner et al. 2007) (Figure 5-7) has substantially reduced catchment nutrient loads on the lake.

The main disadvantages of the technique are that, 1) to be efficient they cover a large area to give sufficient contact time for nutrient and sediment stripping, 2) they are less efficient at removing P than N, and 3) they may not cope with flood flows and the stream short circuits directly to the lake with no renovation.

The Okaro wetland was designed to be a publicly accessible attraction and has walkways incorporated to allow easy access for public viewing within the lake domain. Access to the portion of wetland on farm land is restricted. The wetland has a number of ridges which cause the water to follow a convoluted flow path, thus increasing the contact time for plant uptake of nutrients and for the sedimentation of particulate matter (Figure 5-7).

### 5.4.3 Floating treatment wetlands

Floating treatment wetlands (FTW) are a new restoration concept where emergent wetland plants are grown in buoyant rafts which are moored in a lake or stream.

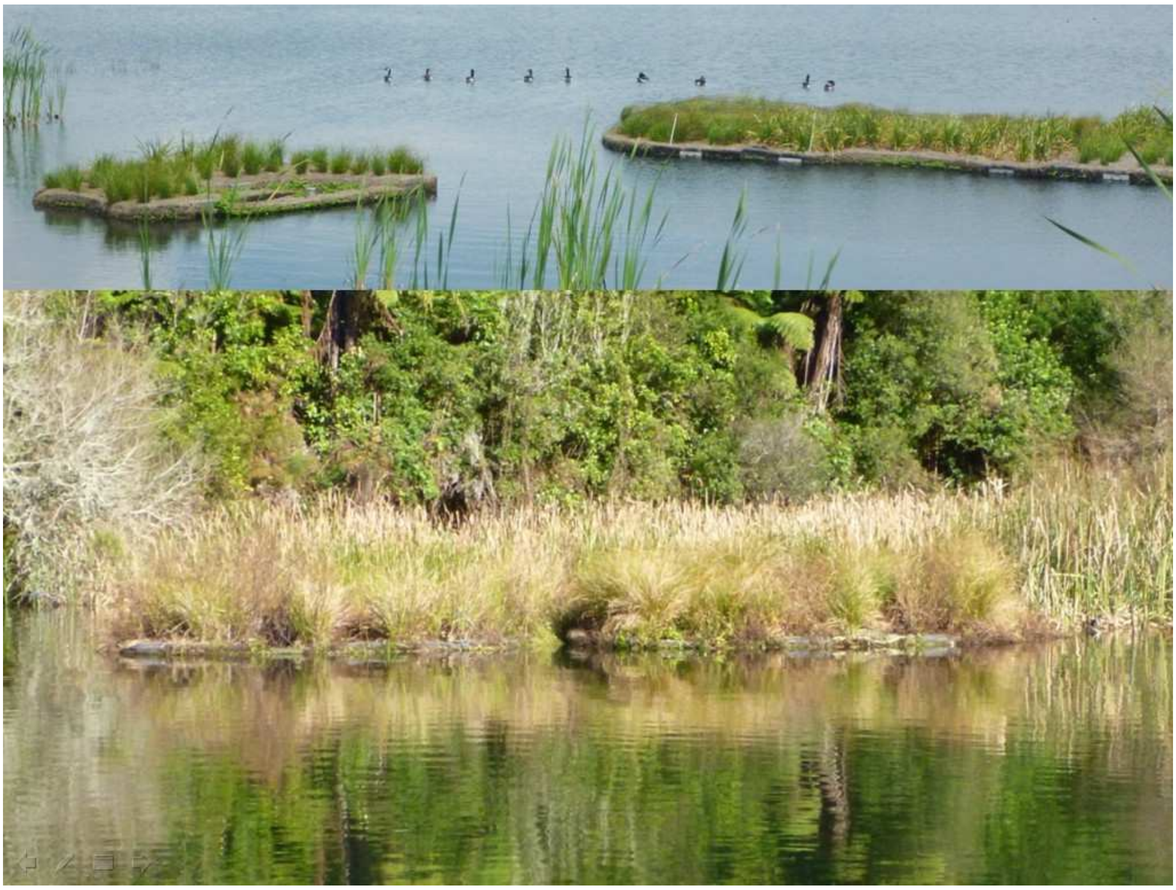


**Figure 5-8: Top: Floating treatment wetlands (FTW)** that have recently been planted and the plants are becoming established. Each of these FTWs comprised several rafts joined together. Bottom: Mature FTWs in Lake Rotoehu blend in with the marginal wetland plants on the lake shore.

These rafts are constructed from recycled plastic (PET drink bottles) in various sized sections that could be 2 m by 3 m for ease of handling and joined together later. The plants are grown in recesses in the raft and their roots extend down into the water where they assimilate the N and P. The FTW concept has been tested near Lake Rotoehu using stream water with promising results (Sukias et al. 2010). An in-lake version with a surface area of 0.3 ha is being tested in Lake Rotoehu at present. The FTWs are aesthetically pleasing and blend in with the natural lake shore environment (Figure 5-8) and provide additional habitat for birds and koura.

### 5.4.4 Marginal buffer zones

Onshore management to reduce nutrient inputs to the lake should look at the sources of those nutrients. However, because the lag time between the contamination of the groundwater and that contaminated groundwater reaching the lake, nutrient stripping of the groundwater at the lake edge is also essential. This is best achieved using marginal wetland buffer zones (Figure 5-9). The surface or unconfined groundwater aquifer is the most vulnerable to contamination in the catchment as it receives the infiltrating rainwater percolating down through the soil. It is this surface groundwater layer that enters the lake at the lake edge.

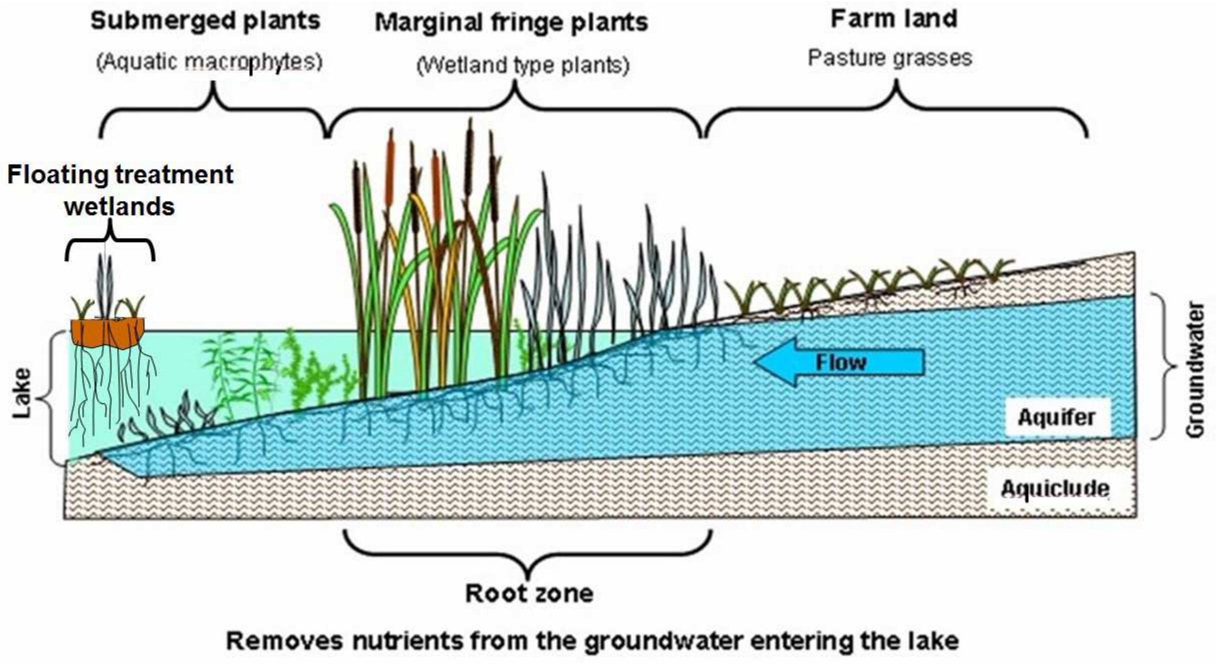


**Figure 5-9: Schematic cross-section of a marginal buffer zone.** A floating treatment wetland (FTW) is included to show the all-important root structure below the raft and where the FTW would be located relative to the marginal buffer zone plants for **Figure 5-8**.

The most effective marginal buffer zone comprises a variety of plants which range in water tolerance from having the tips of their roots in the groundwater (e.g., kikuyu grass) through rushes and flax, to raupo (*Typha orientalis*), and reeds which are almost fully submerged with just the tips of their leaves out of the water (e.g., *Eleocharis*). These plants mostly take up nutrients through their root systems. Further into the lake submerged macrophytes take up nutrients from the water column. In Lake Horowhenua, the lake weed *Potamogeton* takes up the $NO_3$-N from the lake water as it grows in spring, and is capable of removing all of the available $NO_3$-N from the lake in that growth period. The disadvantage of marginal wetland plants is that, unless the biomass from the spring growth is harvested and removed from the lake, the nutrients in that biomass will be returned to the water when these plants senesce in late summer and winter.

The margins around Lake Horowhenua have been planted with flaxes. If these plantings are a monoculture, the nutrient stripping efficiency of the marginal buffer zone could be enhanced by augmenting the flax with a selection of other plants.

Harvesting of marginal buffer zones could be mechanical using weed harvesters in the lake and mowers with catchers (e.g., silage cutters). The alternative to mowers on land is to use short (<1 hour) grazing of the marginal buffer zone by stock. The stock are kept out of the lake with temporary electric fences on the lake edge. Because the grazing period is kept short, faecal material from the stock is mostly deposited inland from the marginal buffer zone after the stock are removed.

### 5.4.5 Stormwater diversion

From the nutrient and water budget on Lake Horowhenua it is apparent that more than 80% of the external P load on the lake comes in the runoff from Levin via the Queen Street drain. The Queen Street inflow is also 45% of the annual internal P load. Diversion of the Queen Street storm water to the Hokio Stream outflow would remove that annual load of P from the lake while reducing the hydraulic load by less than 20%. The Queen Street drain also carries about 14% of the annual N load on the lake as well as faecal bacteria from animal waste on the road i.e., from free roaming dogs and effluent spills from stock trucks passing through the town. Consequently, there would be a benefit to the N load and other contaminants on the lake by diverting the Queen Street storm water flow around the lake.

This option may be more expensive and less culturally sensitive than entraining the Queen Street drain flow through a shore line holding zone behind a wall of floating treatment wetlands (see above). Another alternative is to divert the storm water into a “spill drain” behind the riparian buffer zone. Both of these options dissipate the energy of the storm water inflow so that it does not move out into the body of the lake. Dispersing the flow behind the riparian buffer zone will cause all the sediment to remain on shore and the nutrients in the storm water to be assimilated by the buffer zone plants.

### 5.4.6 Stream diversion

The Arawhata Stream contributes about 50% of the external surface water N load to Lake Horowhenua. Diversion of the this water directly to the Hokio Stream outflow would reduce the TN load on the lake by around 50 t $y^{-1}$ as well as reducing the $NO_3$-N concentration in the lake. Reducing the open water $NO_3$-N concentration would impact on the growth of macrophyte weed beds and potentially the magnitude of their cyclical impact on sediment release of P when the weed beds collapse. With less $NO_3$-N injected into the lake water column, the high proportion of denitrification identified in the nutrient budget would be more effective against the $NO_3$-N seeping through and across the lake bed from groundwater inflows.

Stream diversion has proved effective in the restoration of Lake Rotoiti with the diversion of the Ohau Channel flow from Lake Rotorua through the Okere Falls arm of Lake Rotoiti to the Kaituna River outflow. In that case, the polluted water from Lake Rotorua was adversely impacting on the water quality of Lake Rotoiti causing Lake Rotoiti to become eutrophic with significant algal blooms of cyanobacteria. With the installation of the diversion wall in the outlet arm to Okere Falls, the water quality of Lake Rotoiti has dramatically improved and the algal blooms have largely disappeared.

### 5.4.7 Flushing – external source water

A simple expedient in small lakes overseas is to divert a proportion of a clean stream or river through the lake to reduce the residence time and thus flush the N and P in solution and in particulates, such as algae, down the outlet stream. For Lake Horowhenua, potential external water sources are the Ohau River to the south and the Manawatu River to the north. Without consideration of the water quality of either river or their capacity to deliver water, a continuous flushing volume of 0.5 $m^3$ $s^{-1}$ would reduce the mean annual residence time from 47 days to 30 days. Continuous flushing might not be appropriate in winter when it could increase the risk of downstream flooding. An in-depth analysis of the water quality of the source water would be needed if this option was a serious consideration.

The most appropriate time to introduce flushing would be during the summer low flow period when the natural residence times can be up to 95 days. At this time of year, the lake normally has high DRP from sediment release and thus high cyanobacteria algal biomass. Adding 0.5 $m^3 s^{-1}$ at this time would reduce the residence to around 45 days and help flush the algal biomass out of the lake. Higher flow in Hokio Stream would be beneficial to the fishery as the water would be more likely to be well oxygenated and slightly clearer than the natural condition. The higher through-put has the potential to keep the lake at a higher dissolved oxygen content and thus reduce the P release from the sediment and the concomitant bloom of cyanobacteria.

If a pipeline was installed from the Manawatu River, it would be about 8 km long but the water quality may not be high. Alternatively, an equivalent pipe from the Ohau River would be about 6.5 km long but the volume of water abstracted in summer could adversely affect the downstream ecology of that river.

### 5.4.8 Enhanced flushing using fluctuating water levels

This technique requires manipulation of the weir on the lake to increase and decrease the lake water level at different times of the year to take advantage of specific parts of the lake cycle.

Lowering the water level in winter would enhance the through-put of N from the upstream catchments and would reduce sediment accumulation in the lake. Winter is the time of migratory runs of diadromus fish species such as eels and whitebait which would be moving up the Hokio, and the lower weir would provide better access to the lake. The lower lake level in spring would also provide better access for other management strategies such as spraying weed beds.

Raising the weir in early summer would provide a deeper water column which is more stable and thus would allow suspended solids to settle giving a clearer water column. If the weed beds had been sprayed, this clearer water would not stimulate lake weed growth and the lake would be more suitable for summer contact recreation. The calmer, deeper water column may develop algal blooms if the sediment becomes anoxic and releases P. If such blooms develop, the weir can be operated as a skimmer to remove the floating algal bloom, selectively reducing N and P in the algal biomass. This would be most effective on calmer summer days when the katabatic winds from the east would drive the cyanobacteria blooms to the outlet.

Seasonal changes in water level are potentially good for fisheries with the most productive fisheries having low water levels in summer (J. Boubeé, NIWA, pers. comm.).

### 5.4.9 Dredging

Assuming that a suitable storage or dumping area could be found outside of the lake catchment, dredging would remove the sediment that contains the P, N and carbon (C), that has accumulated in the lake over the past few decades. It would also remove the seed bank for lake weeds. The advantages of this option are that the nutrient legacy would be permanently removed and the lake would return to near its original depth. The disadvantages of this option are the cost to remove the estimated 3 $km^3$ of sediment, the destruction of the existing ecosystem, and the release of nutrients and other toxic chemicals such as sulphides during the process of dredging. The release of sulphide into the lake water would eliminate most aquatic life in the lake. The removal of lake weed seed banks in the sediment would not be selective and desirable species for restoring the lake habitat would be removed along with the undesirable species.

This is an option which is not recommended for the lake. However, given the level of organic sediment accumulation in the Arawhata Stream, dredging of the stream channel may be an option as a measure to reduce the source of nutrients entering the lake in summer. More importantly, catchment management strategies need to focus on soil erosion to prevent the nutrient rich soil being washed off the land (loss of productivity to the farm) and into the lake.

### 5.4.10 Aeration

Aeration (see section 3.11 for details) replaces the oxygen consumed by decomposition processes and prevents the development of anoxic conditions which allow P release from the sediments. This technique is often used in water supply reservoirs to prevent the anoxic release of P, which favours cyanobacteria growth, and the release of minerals such as iron and manganese, which would stain baths, toilets and hand basins in homes and would cause black marks on washing as the water re-oxygenates and these metals precipitate.

The advantages of the technique is that it is relatively cheap, requiring an air compressor, connection hoses and an aeration bar with anchor blocks, and only needs to run in summer when low oxygen concentrations develop. For shallow lakes like Lake Horowhenua the efficiency of an aeration bar would be limited and alternative aerators such as those used in waste water treatment ponds may be more appropriate.

The issue in Lake Horowhenua is not that the lake develops anoxic bottom waters, but the cause of the bottom water anoxia. If it is caused by high sediment oxygen demand, aeration will work. However, if it is caused by the collapsing weed bed preventing oxygen diffusion to the sediments, aeration will not work.

**Hazard warning**: Where aeration with air bars is used in recreational lakes, warning notices should be placed in the launching areas. Because the water in the plume of rising air bubbles has a lower density than normal water, boats will have less freeboard within the bubble plume. Similarly, swimmers entering the bubble plume are likely to sink.

### 5.4.11 Aeration by discing

In shallow lakes, giant discs pulled through the lake sediments open up the sediment allowing deep penetration of oxygen from the water column. The concept behind this tool is that the P will be bound to the iron and manganese oxides in the sediment. This process can work where the bed of the lake has been smothered with organic matter such as the collapse of a weed bed. Modelling of this option (White & Gibbs 1991) indicates that the beneficial effect for P binding is short lived because as soon as the sediments go anoxic once more, the P is released.

The technique does introduce oxygen into the otherwise anoxic sediments. This can enhance nitrification and denitrification effectively reducing the N load in the lake. More importantly it supplies oxygen to the decomposition processes so that organic carbon content and thus the sediment oxygen demand is slowly reduced. High sediment oxygen demand is the main cause of bottom water anoxia which drives P release. However, to achieve a significant reduction in sediment oxygen demand, the discing would need to be repeated frequently.

There are three major disadvantage of discing through weed beds: 1) the organic matter could be driven into the sediment raising the organic carbon content, 2) every leaf node of most aquatic macrophytes can grow so the discing would most likely spread the weed more widely, and 3) the discing would devastate the benthic mussel beds destroying that part of the fishery.

## 5.5 Management Tools – Water treatment solutions

### 5.5.1 Aeration by nitrate injection

In some overseas restoration studies, concentrated nitrate is injected into the sediment with equipment similar to the giant discs to provide an oxygen source for decomposition processes in summer (Hemond & Lin, 2010). The advantages of this technique are that the release of P is reduced and thus the dominant algal species are not cyanobacteria. The release of arsenic (As) is also suppressed. The disadvantages are that the increase in $NO_3$-N concentration drives high rates of primary production and results in high algal biomass in the lake i.e., the lake goes very green. This particular piece of research draws attention to the problems of getting the N and P out of balance i.e., heavy metals such as As and lead (Pb) can be released from the sediments.

This is not a recommended technique for use on Lake Horowhenua or any other degraded lake in New Zealand.

### 5.5.2 Clay flocculation of cyanobacterial blooms

When a cyanobacterial bloom has developed, it is too late to use many of the restoration techniques and it is more appropriate to treat the bloom directly to get immediate results. To that end, much research has focused on the use of clay to floc the bloom so that it settles out of the water column (Sengco & Anderson, 2004; Beaulieu et al. 2005; Padilla et al. 2006; Zou et al. 2006; Biyu et al. 2010; Chen & Pan, 2012; Pan et al. 2012). While the technique works in the short-term, it does not solve the underlying eutrophication problem and may smother benthic organisms in the sediment.

### 5.5.3 Phosphorus inactivation with flocculation

The phosphorus released from the lake sediments is in the form of phosphate which is readily usable by plants, especially algae, for growth. While all plants use N and P in the ratio of 16 N to 1 P (Redfield 1958), the symbiotic bacteria inside blue-green algae, hence the name ‘cyanobacteria’, can convert $N_2$ gas in the atmosphere to $NO_3$-N which the algal host can use for growth. This gives cyanobacteria a competitive advantage over all other algal species when there is a surplus of P and a deficit of nutrient N in the lake water, and they dominate the algal species assemblage. Consequently, an excess of P in the water column is said to favour the growth of cyanobacteria and the formation of nuisance blooms.

Phosphorus inactivation is used to make that P unavailable for algal growth by binding it to a metal. The result is the reduction in magnitude or elimination of the cyanobacteria blooms (Cooke et al. 2005). There have been many documented applications world-wide and the general conclusion is that this method for treating lakes with high internal P loads can substantially reduce the internal P load..

Phosphorus inactivation is a naturally occurring phenomenon where, under aerobic (oxidising) conditions the P can be sequestered onto the surface of metal oxides such as iron and manganese in the sediments. Unfortunately, the process is reversible. Under anoxic (reducing) conditions the iron and manganese dissolve and release the previously bound P back into the water column.

Research has found that if the P is bound to aluminium or lanthanum, the process is irreversible under normal lake conditions and the P is not released under reducing conditions. The consequence of this is that there is very little P available for algal growth and any that appears from dying algal cells is rapidly assimilated by all algae i.e., cyanobacteria no longer have a competitive advantage and are less likely to become the dominant species.

The most commonly used P inactivation agent is aluminium sulphate, commercially know as alum. This is a flocculent in everyday use for the treatment of domestic drinking water supplies to remove sediment. It is also used in swimming pools to clarify the water. In lakes it performs the double function of binding any phosphate in the water column as well as reducing suspended solids. When the alum floc settles to the lake bed, any unused P binding capacity remains active and will bind any P released from the sediments.

**Figure 5-10: Spraying alum onto the surface of Lake Okaro**. The air boat was fitted with GPS navigation to control where the spray was applied.

Alum was sprayed on Lake Okaro (Figure 5-10) in an attempt to reduce the cyanobacteria blooms on that lake (Paul et al. 2008). The water column became clearer after an initial increase in algal biomass and the algal species switched from cyanobacteria to green algae. However, at the low dose rate used there was insufficient aluminium to sequester all of the P in the lake and the cyanobacteria blooms returned in following years.

There are specific requirements for the use of alum in natural waters. Because alum is acidic (the 47% solution has a pH of 2.1) it requires to be buffered to a pH of 6.5 to 7 where the waters have low alkalinity (e.g., <30). Lake Horowhenua has an alkalinity of around 65 measured as g $CaCO_3$ $m^{-3}$, which is approaching the nominal value of 80 above which little or no buffer is required for normal dosing. If alum were to be used on the lake, it is recommended that sodium carbonate buffer is included with the alum to ensure the formation of a floc. Without the buffer there is a risk that the pH would fall below 6, no floc would form and toxic trivalent aluminium ions ($Al^{3+}$) could be released into the water column. This does not happen if the alum is correctly buffered to produce the floc.

A side effect noticed with the use of alum is that some zooplankton can be caught in the floc and then be carried to the lake bed. This effect alters the microbial loop (Figure 3-6), reduces grazing pressure on algae and, left unchecked, the algae may grow rapidly for a few days before the zooplankton populations become re-established. This may explain the increase in algal biomass after alum treatment in Lake Okaro (Paul et al. 2008).

NIWA studies on the P binding capacity of alum found that it can sequester up to 85 g P $kg^{-1}$ alum (Gibbs et al. 2011a) and that it will sequester P from the sediment as well as the water column (Gibbs et al. 2008, 2011b).

Treatment rates for the application of alum are calculated based on the areal load of TP in the top 4 cm of sediment plus the areal load of DRP in the overlying water. For Lake Horowhenua, in summer when the DRP concentrations in the 1.5 m deep water column are around 0.5 g $m^{-3}$ and the top 4 cm of sediment hold ~2.56 g P $m^{-2}$, the total areal load would be around 3.3 g P $m^{-2}$. The estimated dose rate for alum would be around 38.8 g pure alum $m^{-2}$. Alum is supplied in a 46% liquid form which would require a dose rate of about 85 g $m^{-2}$. To treat the whole lake would require about 250 tonnes of liquid alum. The buffer requirement would be soda ash, which is also used in water treatment plants. The amount of buffer required is normally about twice the amount of alum, i.e., about 500 tonnes, but should be checked using the lake water before treating the lake.

The preferred time for treatment would be mid-summer when DRP concentrations in the lake water were maximal.

### 5.5.4 Phosphorus inactivation with sediment capping

The alternative to alum is to use a granular P inactivation agent. These products are designed to inactivate P either in the water column or at the sediment surface before settling on the lake bed as a thin (1–2 mm thick) layer. This is the layer referred to as the sediment cap (Figure 5-11).

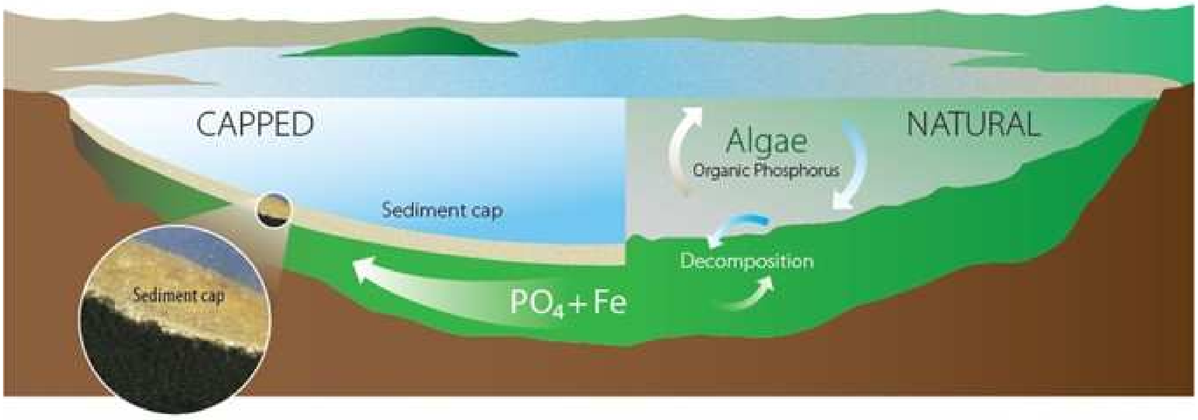


**Figure 5-11. Schematic diagram of sediment capping. The sediment capping is only required in the zone below the thermocline to block P release when the hypolimnion goes anoxic.**

The two sediment capping products currently available on the market are: Phoslock™ developed in Australia by Phoslock Water Solutions Ltd, and Aqual P™ developed in New Zealand by Scion and marketed by Blue Pacific Minerals. Other future potential products include allophane which is a natural volcanic ash currently being investigated by Landcare Research Ltd, but not yet available in commercial quantities, and another product being developed by Fertco Ltd, but not yet available.

**Phoslock™** is a bentonite-based product with a lanthanum salt as the active P binding agent. Phoslock™ has a maximum P binding capacity of around 12 g P $kg^{-1}$ product and does not require a buffer. It disperses rapidly in water and has a long contact time. Because its main action is in the water column, it should be applied in summer when the DRP concentrations in the lake water are maximal. Under these conditions, Phoslock™ has the capability of binding up to 95% of the DRP in the water column (Gibbs et al. 2011a). Once it settles to the lake bed, any unused binding capacity remains available to sequester any P released from the sediment under anoxic conditions. The P is permanently bound to the lanthanum and is not available to algae for growth. Phoslock™ is beginning to be widely used overseas (European countries) and has been used in one lake trial in New Zealand, Lake Okareka.

There are three potential disadvantages of using Phoslock™: 1) Being a bentonite clay based product it is very slow to settle and may take more than a month before the water clears. However, where the lake has high turbidity, this may not be an issue; 2) if the lake has large weed beds, the Phoslock™ can settle on the leaves and not reach the sediment; 3) There are questions about the potential toxicity of Phoslock™ to zooplankton and fish in low alkalinity waters (Gibbs et al. 2011b).

**Aqual P™** is a zeolite-based product with an aluminium salt as the active ingredient. Aqual P™ has a maximum P binding capacity of around 23 g P $kg^{-1}$ product and does not require a buffer. Zeolite has a natural affinity for $NH_4$-N meaning that an application of Aqual P™ has the capacity to adsorb both DRP and $NH_4$-N. Applied as a fine grain powder in a slurry, the product settles relatively quickly to the lake bed where it can form a cohesive capping layer. Because of the short water column contact time (<1 day), the product has a limited effect on any DRP in the water column, binding up to 25% of the free phosphate (Gibbs et al. 2011a) which leaves it with a high capacity for binding P released from the sediment (Gibbs et al. 2008, 2011b; Gibbs & Özkundakci, 2011). Consequently, Aqual P™ is designed to work on the sediment as a sediment capping agent and should be applied in winter or early spring before the sediment becomes anoxic and the P begins to release.

Aqual P™ has been used as a sediment capping agent on Lake Okaro where it was applied as a slurry from a barge (**Figure 5-12**) and achieved a substantial reduction in the internal P load from the sediments. It was also used pre-emptively on Okawa Bay where it was applied as a slurry from a helicopter (**Figure 5-13**) and prevented cyanobacteria growth from developing into a bloom.

**Figure 5-12: Application of Aqual P™ as a slurry from a barge on Lake Okaro.** The barge position was controlled using GPS navigation. [Photo: Andy Bruere, Bay of Plenty Regional Council].

**Figure 5-13: Application of Aqual P™ as a slurry from a helicopter on Okawa Bay, Lake Rotoiti.** The helicopter position was controlled using GPS navigation. [Photo: Graham Timpany, NIWA, Rotorua].

## 5.6 Management strategy

To rehabilitate any degraded lake including Lake Horowhenua, more than one management tool will be required. There will be a range of ways to achieve the management goals. The following flow diagram (Figure 5-14) gives a practical example of the process towards rehabilitation of the lake. The management strategies (Figure 5-15) make use of selected tools discussed in section 4 with a brief explanation of the reasoning behind their selection

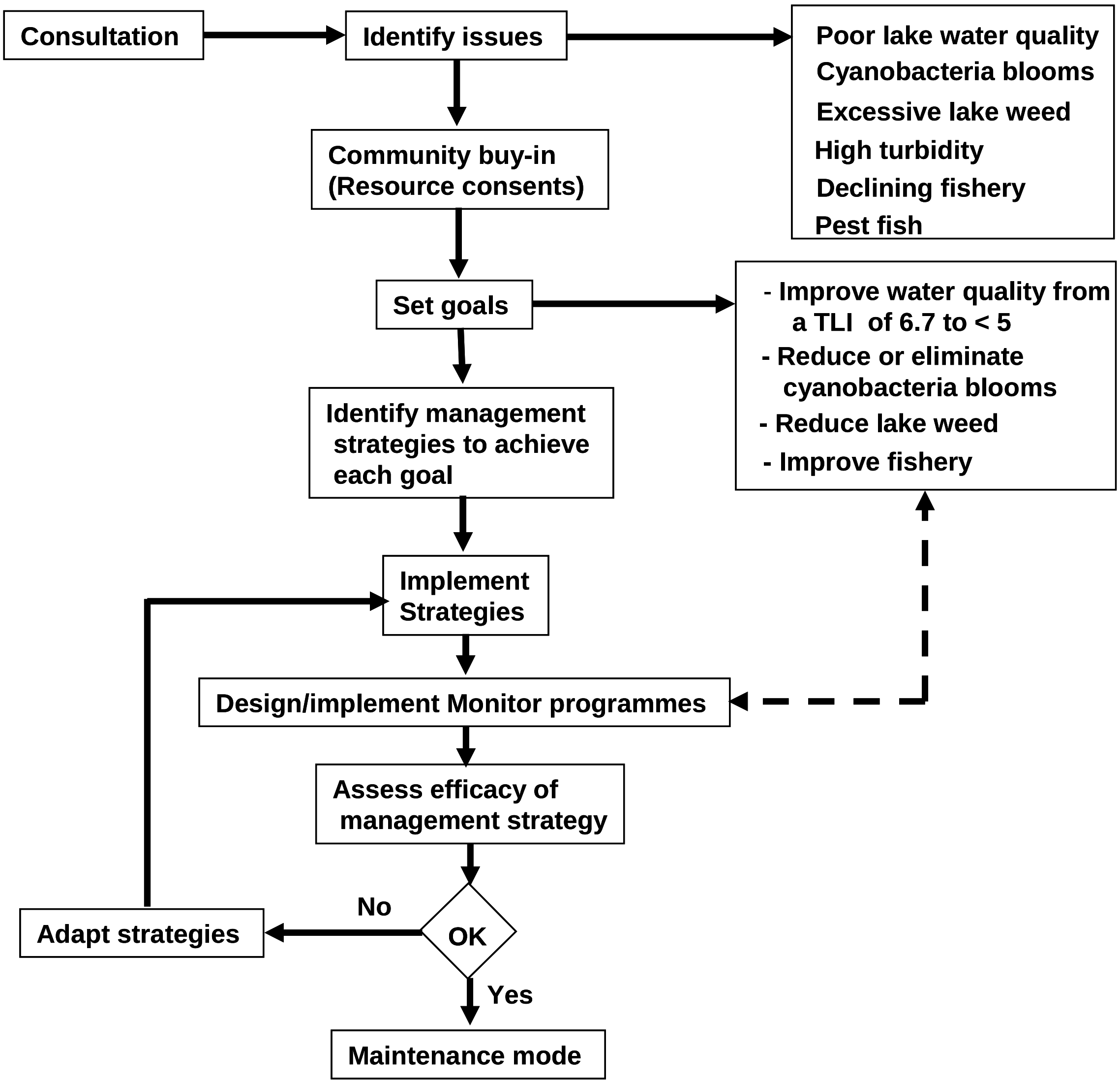


**Figure 5-14: Management flow diagram for the rehabilitation of a lake:** (Expanded from Figure 5-1). The issues and goals shown in the flow diagram are examples for Lake Horowhenua and may be different or include other aspects when management plans are developed for other lakes. (From Gibbs 2011).

The Management flow diagram (Figure 5-14) follows a logical progression starting with Consultation. The consultation process is seeking a mandate from the community to spend their money on the rehabilitation process. In the consultation process, the issues will be identified by all parties including the managers. Some of these issues may be trivial while others may appear insurmountable. The consultation process should find ways to achieve the rehabilitation which are compatible with the framework of regional policy and objectives. The desired outcome of the consultative process is an agreement by all parties on the issues and the remedial actions that are practical and affordable. It is important to the success of the rehabilitation project to obtain the community buy-in so that they accept what is to be done, understand why it is being done and they can follow the rehabilitation progress. Their buy in means that they have an input into the setting of the goals and their expectations of success can be managed. In short the community should “own” the rehabilitation project rather than having it forced on them so that they resent it.

Another critical part of the rehabilitation process is monitoring. Without monitoring it is not possible to determine whether a specific strategy is working in the way it was intended. The measure of success is part of the management strategy and, consequently, the monitoring programme is an integral part of that strategy which allows the management strategy to be adjusted or adapted to improve its performance. The monitoring programme(s) fall inside a feed-back or adaptive management loop. The adaptive management option needs to be stated in the resource consent.

For example, the resource consent for rehabilitation work is often written in a way that is restrictive to the point that it actually prevents the success of the project. It may define the products and materials to be used and the treatment rates. These latter may have been the best estimates from a model but require to be adapted in the “real world” to accommodate environmental variability. Consequently, the resource consent needs to have “room to manoeuvre” but not be a licence to do “whatever it takes”.

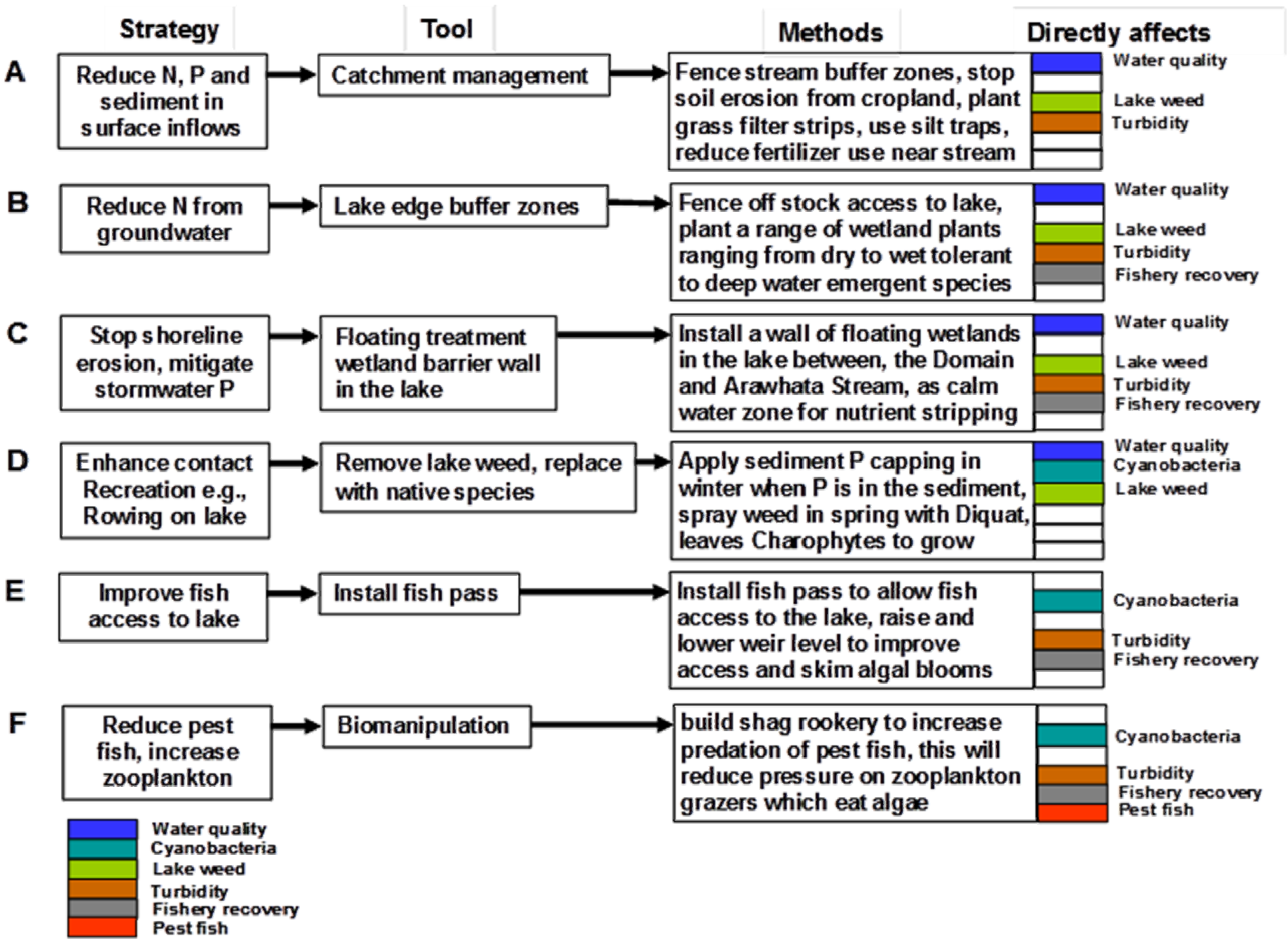


**Figure 5-15:Management strategies required for the rehabilitation of Lake Horowhenua.** These examples cover most issues but there may be others to consider. (From Gibbs 2011).

The management strategies (Figure 5-15) identified from the flow diagram (Figure 5-14) include most issues but there may be other issues which could also be addressed in this way. The reasoning for the use of these specific management strategies is as follows:

A **Reduce N, P and sediment in surface inflows: Why?** Before or concurrent with any in-lake management interventions, the catchment nutrient load on the lake needs to be reduced. Nutrients and sediment in the stream water are dispersed out into the lake where they support weed growth, enhance turbidity and degrade the lake water quality. **How?** On agricultural land, the exclusion of stock from direct access to the streams will reduce bed disturbance and thus sediment, bank erosion and stock defecation directly into the water. These riparian buffer zones need to be wide enough (about 5 m ) to prevent over/under fence grazing destroying the plants and providing sufficient biomass of plants to assimilate nutrients in groundwater and overland flow. On market garden (crop) land, runoff from cultivated land increases sediment in the streams. It also removes arable land from production. To mitigate this soil loss, grass filters will precipitate the soil before it gets into the stream and silt traps will hold fine sediment/soil in detention ponds from which it can later be returned to the cultivated land. The riparian buffer zone will also reduce sediment transport into the stream. An alternative to clearing farm drains by digger is required (possibly spraying). Digging leaves disturbed bare soil exposed to erosion by rainfall with the resultant sediment flowing directly into the lake. Sediment detention ponds should be constructed to reduce road runoff directly entering streams and the lake. A general reduction in the use of fertilizers within the groundwater catchment of the lake by farming, horticulture, cropping and domestic gardening should be encouraged. Special attention should be given to educating home gardeners about the over-use of fertilisers. Although a relatively small industry in the catchment, the growing of vegetables, tomatoes and other crops without soil in nutrient solutions (i.e., hydroponically) has the potential to add high concentrations to the groundwater and streams There should be no permitted discharge of hydroponic fluid directly to a stream or to the groundwater table.

B **Reduce N from groundwater: Why?** The high N concentrations in the groundwater come from land-use in the catchment. Both N and P would have originally reached the groundwater table but the high iron content of the stony subsoil has sequestered the P. Throughout New Zealand there is a tendency for the over-use of fertilisers in urban gardens and the urban area of Levin, which is above the main groundwater flow into the lake, will be augmenting the nutrients added to the groundwater further back in the catchment. **How?** These nutrients can be removed by plants at the lake edge, before the nutrients enter the lake or in the edge water by plants growing in the lake. Unlike stream water, which disperses out into the lake, the cooler groundwater flows along the lake bed and its nutrients are readily assimilated into plants through their root systems. The plants themselves provide habitats for fish and koura and thus support the recovery of the lake fishery. The habitat will be improved if the buffer zone has more than one wetland plant species. The nutrients stored in the plants should be removed by annually harvesting the leafy biomass or periodically having short (1 hour) stock grazing to crop the biomass before taking the stock out of the buffer zone again.

Another simple expedient is public education. Gardeners are notorious for the thought pattern “if one cup of fertilizer is good for the garden, then two will be better”. The second cup is not used by their plants and is leached into the groundwater with rainfall and irrigation. A change to slow release fertilizers and less of them would reduce the nutrient load in the groundwater.

C **Stop shoreline erosion and mitigate storm water P: Why?** Not all nutrients from groundwater will be removed by the buffer zone due to wave action, which will also stir up the sediments and erode the unprotected shoreline on the eastern side of the lake. **How?** The nutrients that move beyond the buffer zone are in the water column where they can be removed via the root mass from Floating Treatment Wetlands. These root masses provide additional habitat for fish and koura. Because the FTWs are formed into a barrier wall, the wave energy that would normally stir up edge water sediment is dissipated into the FTW wall. The calm zone between the shore and the FTW wall becomes a nutrient stripping and sedimentation zone for storm water discharges e.g., the Queen Street drain. Strategies B and C combine to remove >50% and >80% of the N and P external inputs to the lake.

Wave action due to boat wakes is often a major problem causing shoreline erosion and high turbidity in shallow lakes. Prohibiting power boats travelling at more than 5 knots anywhere on the lake will reduce that source of wave action.

D **Enhance contact recreation: Why?** Contact recreation includes rowing which is greatly impeded by the lake weed when it reaches the surface. Just removing the lake weed by harvesting or mulching is not the answer to this issue. For a long-term solution the tall lake weed, *Potamogeton*, needs to be replaced with a shorter macrophyte species – preferably native charophytes. These where once a large part of the flora of the lake. As water clarity declined, the Charophytes would have become light limited allowing the taller *Potamogeton*, which can grow up to the light, to become dominant. To achieve rehabilitation of the flora of the lake, the water clarity needs to improve. Water clarity is affected by sediment and algal biomass. In Lake Horowhenua, the algal biomass in summer is driven by P release from the sediment following the collapse of the weed beds. The P release needs to be reduced which means managing the lake weed problem.

**How?** There are three components that need balancing: **1)** *Potamogeton* is susceptible to the herbicide Diquat when it is young and the plants are clean of periphyton; **2)** Charophytes are tolerant to Diquat and their growth may be enhanced in the presence of this herbicide (J. Clayton, NIWA, pers. comm.); **3)** any plant biomass that decomposes on the sediment will cause anoxia with the concomitant release of P. To expedite the weed species exchange suggested, the P in the sediment needs to be inactivated using a sediment capping agent before the weed is sprayed. The weed needs to be sprayed soon after germination when the plants are small. Having the lake at its lowest water level at this time would reduce the amount of herbicide required and provide a higher light field to allow the charophyte seeds to germinate. The timing of this strategy is important with only one window of opportunity each year - early spring.

The consequences of removing the lake weed in this way are that the $NO_3$-N that was previously removed by the lake weed will be left in the water column. However, the P release from the sediment will not happen resulting in a P limited system and the water quality should resemble the clearer winter conditions. With calm weather in summer, water clarity could increase dramatically as the fine sediment settles out. This would support the growth of the native charophytes, which will take up the $NO_3$-N from the water column and reduce the algal biomass.

E **Improve fish access to the lake: Why?** The construction of the weir blocked access to three key fish species, flounder, mullet and smelt. **How?** These species are known to use fish passes in other lakes. To restore these species to the lake requires a fish pass to be built around the weir. The lake level is controlled by the weir but there is capability for altering the water level by adding or removing planks on top of the weir. The guidelines for altering the lake level should be investigated with a mind to using the weir to skim algal biomass from the lake in summer and to aid the replacement of lake weed with native charophytes (see D above). Lowering the lake level in spring would reduce the flow velocities in the fish pass when the fish are migrating up the Hokio Stream.

In conjunction with the installation of the fish pass, there should be a reduction in the netting and trapping activities in the lower Hokio Stream for one or more seasons the give the fish a chance to reach the lake without being over-fished.

F **Reduce pest fish and increase zooplankton biomass: Why?** Pest fish can disturb the lake bed allowing sediment to be re-suspended more easily. The herbivorous species can browse the plant community and pull out plants. In searching for food, carp and especially Koi carp suck up sediment to sift out the chironomid larvae (blood worms). They then excrete the excess sediment into the water column raising the lake turbidity. Zooplankton eat algae and reduce part of that turbidity. Juvenile perch eat zooplankton preventing zooplankton populations becoming large enough to control the algal biomass. **How?** The long term solution is to use biomanipulation. Providing elevated roosts close to the lake will encourage the development of a shag population. The roosts should be away from urban developments and sited within the buffer zone but over dry land, preferably a small rise, not in a direct flow path for rainfall runoff to the lake. As the shag numbers increase, their search for food will increase predation of the perch and goldfish. The reduction in perch allows the zooplankton populations to increase and reduce the algal biomass. Less algal biomass results in clearer water making it easier for the shags to catch the pest fish. Without the cover of algal biomass driven turbidity, the juvenile perch can be predated by adult perch in a positive feedback loop. This technique will not remove all of the pest fish and a new equilibrium level will be established with a lower pest fish population density. When the food supply dwindles, the shags will search offshore as well as in the lake for fish. However, having established a rookery, they will not move away from the lake.

These six strategies are presented to show what could be done and how. Each strategy is independent but would work better in conjunction with other strategies. For example, there is little point in spending large sums of money on in-lake remedial interventions if no action is taken in the catchment to reduce the sources of the nutrients that stimulate growth. Consequently, strategies A and B should be implemented either before or with the in-lake strategies C and D. Strategy B has already been implemented and a marginal buffer zone surrounds the lake. This may need to be enhanced to gain maximum benefit.

Strategies E and F can be implemented at any time, but sooner rather than later.

The effects of these strategies should be monitored to determine the level of success. This is very important to enable the adaptive management loop in the management flow diagram (Figure 5-14).

## 5.7 Monitoring

There are three types of monitoring programmes: 1) Compliance monitoring for resource consents (not covered in this report), 2) Monitoring programmes designed to assess the success of management interventions, and 3) Strategic or “state of the environment” (SOE) monitoring programmes designed to evaluate the overall water quality of the lake allowing it to be compared with other lakes nation-wide.

### 5.7.1 Sampling frequency

The frequency of sampling should be enough to include the range of variability expected from naturally occurring cycles. For management interventions, sampling frequency will be relatively short interval targeted to assess an expected effect. This monitoring will continue for the duration of the effect but the sampling frequency can be reduced as the effect becomes apparent and the monitoring is only required to confirm a trend.

For strategic monitoring, the sampling frequency should be sufficient to identify seasonal effects and to provide a meaningful annual estimate of the water quality of the lake.

In both types of monitoring, there may be specific conditions for when to sample, or not, so that event or diel driven effects (i.e., day-night cycles) are reduced. For example, sampling Lake Horowhenua during a wind storm or a flood event would put a bias towards high turbidity, when the turbidity in the lake on most other occasions may be trending lower.

### 5.7.2 Monitoring strategy success

Monitoring programmes designed to assess the success of management interventions are usually short-term focussed and designed to measure expected changes as a result of those interventions. Their design is usually part of the management strategy so that managers know whether the intervention has been successful and the degree of success achieved can be reported to the stakeholders. Baseline monitoring before the intervention is important to assess the degree of natural variability in the data to be measured. This information may come from strategic SOE monitoring or a specific monitoring programme that will assess the success of the intervention. Suggested monitoring strategies for the six management strategies (Figure 5-15) include:

**A.** **Reduce N, P and sediment in surface inflows:** The measure of success may be the elimination of the nutrient spikes in the Arawhata Stream and a reduction in overall concentration of all parameters measured. It should include the elimination of any anoxic events or low oxygen (<5 g m$^{-3}$) in summer. **Note the dissolved oxygen is expressed as a concentration, not % saturation**. Chemical transitions occur at specific DO concentrations while % saturation changes with temperature making it difficult to assess the position of the transition zone.

The critical issues are where to sample a stream, what to measure, and what is the measure of success. Where to sample in Arawhata Stream should be at the historical

SOE monitoring site. What to measure includes nutrients, suspended solids, dissolved oxygen.

- Measure dissolved nutrients ($NO_3$-N, $NH_4$-N, DRP), total N, total P, and suspended solids in the major stream inflows affected.
- Measure the temperature and dissolved oxygen concentration, preferably with an in situ recording DO logger over a complete 24 hour cycle.

These parameters should be measured before and every month immediately after the intervention for a period of a year. They should also be measured during at least two high and two low flow events using a flow weighted auto-sampler over 24 hour periods. After a year post intervention, the data should be reviewed and the sampling frequency adjusted based on the results obtained. Sediment reductions and DO effects should be relatively quick to respond, whereas nutrient reductions will induce a slower response.

**B** **Reduce N from groundwater**: The measure of success of the buffer zones may be a reduction in dissolved nutrient concentrations in the lake edge water along the eastern shores of the lake. The measure of success in catchment interventions such as the reduction in garden fertilizer application, banning discharge of high concentration nutrient water into the ground, management of irrigation water, management of groundwater abstraction, etc., may be a reduction in $NO_3$-N and $NH_4$-N concentrations in the surface groundwater aquifer on the landward side of the buffer zone. Shallow bores holes <1 m deep with full depth screen liners would be the sampling points. Confirm the boreholes have high $NO_3$-N concentrations when first installed and that they have good flow characteristics. As groundwater flows are slow, sampling frequency can be every 2 or 3 months. Sampling strategies for the bore holes is to pump the groundwater out for at least 1 minute before collecting the sample.

- Measure $NO_3$-N, $NH_4$-N, DRP, temperature and dissolved oxygen.
- Also assess any changes in buffer zone plant communities annually in summer.

**C** **Stop shoreline erosion and mitigate storm water P**: The measure of success of the use of floating treatment wetlands in this strategy will include a sustained reduction in dissolved nutrient concentrations in the lake edge water along the eastern shores of the lake, a reduction in suspended sediment, and an increase in the numbers of small fish and koura. Numbers of kākahi (freshwater mussels) may increase over time as food quality increases and the numbers of bullies, which are critical to the life cycle of the kākahi, increase. The nutrient and suspended sediment monitoring could be incorporated into the strategy B monitoring, assuming that proceeds. Additional monitoring is required:

- Measure changes in population dynamics of small fish using minnow traps.
- Measure population dynamics of koura using traditional Tau bunches.
- Measure changes in mussel populations using quadrats and photography.
- Measure sediment accumulation or erosion rates using buried sedimentation plates.

Monitoring would be undertaken each summer over a period of several years. Some harvesting of the buffer zone plants may be needed to encourage healthy growth.

D **Enhance contact recreation:** The measures of success of this strategy will include a reduction in the number of complaints about lake weed by rowers/boaties, a reduction in the extent of cyanobacteria blooms which trigger a closure of the lake, a reduction in the area of lake affected by the tall weed and, ultimately, the re-establishment of charophyte meadows across the lake bed in place of the exotic tall lake weeds. The implementation of this strategy involves three parts and each can be assessed to give a measure of the success of that component. For sediment capping/P inactivation, there should be no DRP release from the sediments even if the weed beds collapse and cause anoxic conditions at the sediment surface.

- The DRP concentration in the lake at least monthly, and preferably every 2 weeks over summer, to follow the annual cycle of DRP in the lake.

After weed spraying, there should be no nuisance weed beds over the following summer

- Assess the state of the weed beds through the summer by visual inspection. This could include counting viable stems per unit area of lake bed.
- Measure the $NO_3$-N concentrations in the lake at least monthly, and preferably every 2 weeks during spring and summer.
- Assess the algal species assemblage at weekly intervals over the summer (cell counts and biovolume).
- Measure water clarity with a black disc system.

The charophytes should be increasing in abundance as the light levels improve.

- Survey the lake flora at least once per year by visual inspection (qualitative).
- Longer term, 5 yearly quantitative surveys should show a reduction in the area of lake bed affected by tall *Potamogeton* beds relative to charophytes.

Where the tall lake weed returns, a repeat spraying should be made the next spring.

E **Improve fish access to the lake:** The measure of success will be the presence of any of the three species black flounder, mullet, and smelt in the lake after the installation of the fish pass. The abundance of Inanga and eels could also increase due to the reduction in fishing pressure in the lower Hokio Stream.

- Monitor whitebait catches, including by-catch.
- Survey the fishing people for observations of fish species they have seen.
- Photo-monitor the fish pass at appropriate times of year for migratory fish.

- Get accurate catch records from eel fishery.

**F** **Reduce pest fish and increase zooplankton biomass:** The measure of success will be a reduction in the pest fish populations, an increase in zooplankton biomass and a reduction in algal biomass.

- Measure changes in population dynamics of juvenile perch using baited minnow traps and beach seine net hauls.
- Measure changes in population dynamics of zooplankton population using Schindler-Patalas traps.
- Measure changes in population dynamics algal species and biomass.

These monitoring programmes are intended to measure the success of the management strategy. Clearly there is overlap between success monitoring programmes for each strategy. Where multiple strategies are implemented together, the combined monitoring programme should include the relevant components from the individual monitoring programmes. It should also make use of data from the strategic monitoring programme for the lake.

### 5.7.3 Strategic monitoring

A strategic monitoring programme is designed to assess the overall water quality of the lake. This is very different from the monitoring programme to assess success (or compliance monitoring). The success of the management strategies implemented will, however, become apparent in the strategic monitoring programme data over time.

Strategic monitoring is a long term programme. “The longer the better” as long term data enable the assessment of the natural variability in the lake water quality such as seasonal cycles, the El Niño – La Niña effect, the Southern Oscillation Index (SOI) and Interdecadal Pacific Oscillation Index (IPOI). These cycles affect climate and, consequently, the water balance of the lake via the stream and groundwater inflow volumes.

Strategic monitoring is also used to provide the annual SOE report for the lake. The SOE report typically focuses on use-related factors that would show a trend as the water quality changes. To obtain the annual SOE report value, strategic monitoring samples are collected at least 4 times a year to look at the main seasonal data. A more robust approach for Lake Horowhenua would be to tailor the strategic monitoring programme to follow changes in key elements in the lakes seasonal cycle and this may require sampling 6 times per year as a minimum until a coherent database is established. In contrast, lake weed bed surveys can be every 5 years.

In the Horizons Regional Council monitoring data from Lake Horowhenua (up to 2010), a broad range of parameters were measured but not on a regular basis. Consequently, there are gaps of key parameters in the long term database making trend analysis difficult or impossible. While the key parameters for the SOE report are measured, the monitoring programme included parameters that would assist in understanding how the lake works to enable management strategies for restoration to be developed.

Closer examination of the database shows that there are some issues with sampling time differences that generate data variability due to day-night (diel) effects on some parameters. For example almost any value of DO can be obtained for the Arawhata Stream in summer depending on the time of day the stream is sampled. The DO concentrations fall to near zero overnight due to high respiration of the plants and sediment in the stream. In contrast, the DO concentrations are likely to rise above 150% saturation in sunlight as the same plants photosynthesise. Similar diel cycles will occur for $NO_3$-N concentrations in the lake in spring, with concentrations decreasing in the afternoon due to uptake by lake weed for growth. This variability can be accommodated by taking the spot monitoring sample at the **same time relative to sunrise** on each sampling occasion.

To eliminate these issues, a new strategic monitoring programme was designed for Lake Horowhenua to meet the requirements of the SOE and provide good quality data on which to base decisions about management strategies for the rehabilitation of the lake.

There are three components to consider when designing a strategic monitoring programme: 1) the parameters to be measured; 2) when and how to sample; and 3) the time of day that the sample will be collected.

### 5.7.4 Parameters to be measured

To enable nation-wide comparisons, all lakes should be monitored for the same range of physico-chemical and microbiological water quality parameters. For simplicity these should also be the same as for freshwater rivers and streams. These parameters include onsite measurements such as dissolved oxygen, temperature, pH, conductivity and clarity as SD, as well as laboratory tests for chlorophyll *a*, turbidity, inorganic and organic suspended solids (SS and VSS), total and dissolved nutrients (TP, TN, DRP, $NO_3$-N, $NH_4$-N) and the faecal indicator bacteria, faecal coliform and *E. coli*. Phytoplankton samples should be collected for cyanobacteria identification and counts as well as abundance of other algal species on each occasion. These parameters include the information needed to calculate an annual TLI value using the original method (Burns et al. 1999, 2000) which was based on chlorophyll *a*, SD, TP, TN, volumetric hypolimnetic oxygen depletion rate (VHOD) and phytoplankton species and biomass. More recently only the first four parameters have been used for calculating the TLI value (Burns et al. 2005), and a TLI value can also be estimated where the SD data are missing (Verburg et al. 2010). This may be an appropriate measure of trophic level for Lake Horowhenua where even small breezes can re-suspend the lake sediments, due to wave action on the shore. Sampling will still need to occur over a minimum of a two-year period as the TLI is calculated on the two most recent years of data.

Biochemical oxygen demand (BOD) is often included in the analytical suite but should not be used when the BOD concentrations are consistently below the level of detection of <1 g $m^{-3}$. Because Lake Horowhenua is very shallow, water level should be recorded on every sampling occasion. The time of day the sample was collected should be recorded in New Zealand standard time (NZST) not daylight saving time. Other observations such as wind condition, cloud cover, presence of an algal bloom or shoreline algal scum and the abundance of water fowl should also be recorded.

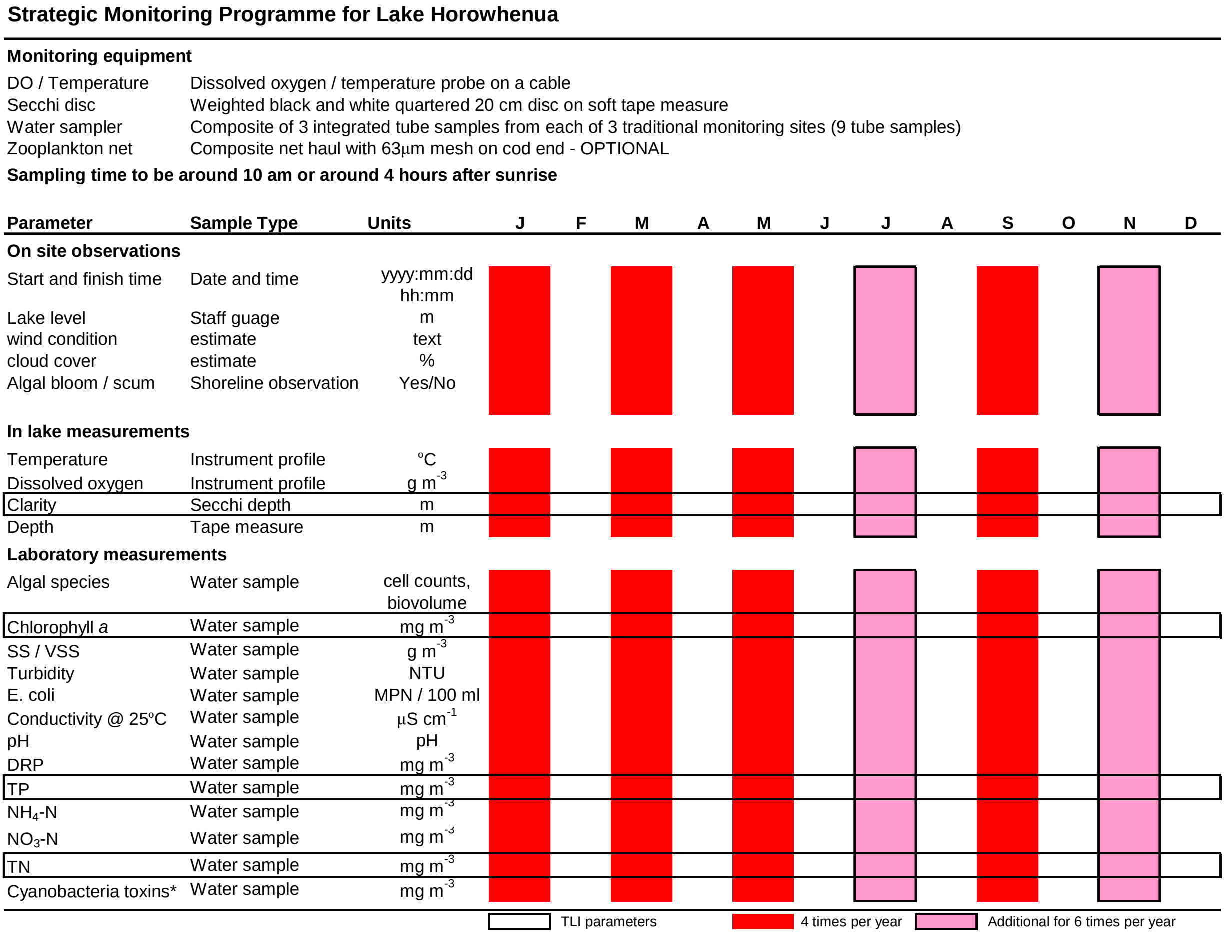
**Note:** The water level staff gauge in Lake Horowhenua should be checked for readability and careful instruction given on how to read and record the level, as the historic database has level fluctuations that range from 0 to 3.2 m; well beyond the depth of the lake.

Analytical methods should provide the lowest detection limits possible to assist with detecting trends in water quality over time. Routine measurements of dissolved oxygen at SOE surface water sampling sites in the lake and streams are recorded as absolute concentration as well as in percentage saturation. Although Secchi depth is used to record vertical clarity in Lake Horowhenua, with a maximum depth of 1.6 m and high turbidity, it may be more appropriate to measure horizontal clarity with a black disc. However, if a trophic level index monitoring programme is implemented as part of the strategic monitoring programme then vertical clarity, i.e., Secchi depth measurements, should also be taken from the mid-lake site.

### 5.7.5 When and how to sample

For strategic monitoring, individual regional councils use different sampling frequencies including 4 times per year, 6 times per year, or monthly. Each sampling strategy has a field cost and an analytical cost which will be part of the consideration when designing the monitoring programme. The recommended minimum sampling regime is 6 times per year at regular 2-monthly intervals (Table 5-3), but monthly sampling is preferred for the first year to establish the seasonality of the data. It is better to have a higher sampling frequency with fewer sites.

**Table 5-3: Strategic monitoring programme design.** Recommended monitoring programme for Lake Horowhenua showing the full range of parameters required to meet the One Plan standards. To match the seasonal cycles of the lake, one sampling date must be in mid-March and that determines the other sampling dates. The programme shows 4 samplings per year (red) as the absolute minimum with the 2 extra sampling dates (pink) to make a total of 6 times per year. Reduced options for just TLI data are also included. Site details and observations should be recorded on every occasion. (*cyanobacteria toxins are only tested for when there are high levels of cyanobacteria in the lake).



**Strategic Monitoring Programme for Lake Horowhenua**

**Monitoring equipment**

| | |
|---|---|
| DO / Temperature | Dissolved oxygen / temperature probe on a cable |
| Secchi disc | Weighted black and white quartered 20 cm disc on soft tape measure |
| Water sampler | Composite of 3 integrated tube samples from each of 3 traditional monitoring sites (9 tube samples) |
| Zooplankton net | Composite net haul with 63µm mesh on cod end - OPTIONAL |

**Sampling time to be around 10 am or around 4 hours after sunrise**

| Parameter | Sample Type | Units | J | F | M | A | M | J | J | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **On site observations** | | | | | | | | | | | | | | |
| Start and finish time | Date and time | yyyy:mm:dd hh:mm | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Lake level | Staff guage | m | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| wind condition | estimate | text | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| cloud cover | estimate | % | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Algal bloom / scum | Shoreline observation | Yes/No | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| **In lake measurements** | | | | | | | | | | | | | | |
| Temperature | Instrument profile | °C | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Dissolved oxygen | Instrument profile | g m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| ☐ Clarity | Secchi depth | m | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Depth | Tape measure | m | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| **Laboratory measurements** | | | | | | | | | | | | | | |
| Algal species | Water sample | cell counts, biovolume | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| ☐ Chlorophyll *a* | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| SS / VSS | Water sample | g m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Turbidity | Water sample | NTU | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| E. coli | Water sample | MPN / 100 ml | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Conductivity @ 25°C | Water sample | µS cm$^{-1}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| pH | Water sample | pH | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| DRP | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| ☐ TP | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| $NH_4$-N | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| $NO_3$-N | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| ☐ TN | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |
| Cyanobacteria toxins* | Water sample | mg m$^{-3}$ | 🟥 | | 🟥 | | 🟥 | | ▨ | | 🟥 | | ▨ | |

☐ TLI parameters 🟥 4 times per year ▨ Additional for 6 times per year

For each parameter there is a protocol of how the sample should be collected.

In Lake Horowhenua, water samples from the mid-lake sites should be combined to provide a single composite sample that is representative of the whole lake. If the TLI monitoring programme is required, it would be appropriate to collect just the 4 parameters required from the mid-lake site on the intervening month (Table 5-3).

The water sample from Lake Horowhenua should be collected using an ‘integrated-tube’ sampler. This consists of a wide bore (~20 mm ID) plastic tube lowered through the full depth of the water column to just above the lake bed (Appendix H). This diameter tube will collect about 450 ml from a 1.5 m deep site. Ideally, water should be collected from each of the three monitoring sites and then combined to produce a single composite sample. This would be more representative than a sample from single site.

The historical database indicates some water quality differences between the three monitoring sites but there is insufficient data to determine whether the differences are ‘real’, as in “being a characteristic of that site”, e.g., consistently different wind stress at each site, or just an artefact of sampling on the day, e.g., differences in the time of day the sample was collected.

To ensure a representative sample is collected from the lake, the composite sample is made up of 3 integrated tube collections from each of the 3 traditional monitoring sites (i.e., a total of 9 integrated tube collections) and these are fully mixed in a 5-litre plastic sample bottle. Mixing is critical before any subsample is taken from the bulk composite sample. Suspended material will settle or float if the sample is not mixed, and this will introduce an error.

Bacteria samples need to be collected separately using protocols for that type of sampling.

Aliquots for algal species enumeration and biomass need to be decanted into a specific bottle for this purpose immediately after fully mixing the bulk composite sample. Normally the algal species sample is preserved with Lugols iodine. This can be done in the field or laboratory.

A missing link in most lakes databases is the estimation of zooplankton biomass and species composition. Zooplankton graze the algae and thus impact on the chlorophyll *a* concentrations. At the beginning of an algal bloom, zooplankton biomass will be low. As the bloom develops, zooplankton biomass increases rapidly until their abundance stops the bloom. Zooplankton biomass would be “nice” but it is a discretionary parameter. If collected, composite net haul samples should be preserved with isopropanol.

### 5.7.6 Time of day effects

Shallow eutrophic lakes like Lake Horowhenua are more susceptible to diel cycles than deeper lakes which have a large hydraulic inertia / dilution capacity. Consequently, the time of day, relative to sunrise, is very important.

- Temperature follows a continuously cycle from low at night to high around 2 hours after midday. Ideally a temperature logger should be used to capture the full diel cycle.
- Dissolved oxygen is continuously consumed by respiration processes in the water 24 hours per day. Photosynthesis replenishes the oxygen during the hours of daylight

proportional to the amount of light and the mass of plant biomass. Photosynthesis compensates for respiration overwhelming it in the morning and can be continuously variable reaching maximum levels around midday before declining again in the late afternoon. On cloudy days the maximum DO levels will be lower than on a bright sunny day. Maximum DO levels are also affected by the presence of weed beds and phytoplankton blooms. Ideally a dissolved oxygen logger should be used to capture the full diel cycle.

- Plant nutrients, especially $NO_3$-N, are consumed by the lake weed for growth. The Lake Horowhenua database indicates that the weed beds can substantially reduce the free $NO_3$-N from the water column. With high $NO_3$-N concentrations in the stream and groundwater inflows, there is a potential to have a time-of-day effect on the $NO_3$-N concentration in the lake sample.
- Sediment in Lake Horowhenua is easily disturbed by wind-induced wave action against the shore. The lake experiences katabatic winds daily during summer starting late morning around 11:00 am and reaching maximum velocities in late afternoon before stopping around 18:00 pm. Sediment resuspension at the time of sampling will also temporally affect nutrient concentrations.
- Sampling during the afternoon has the potential to produce a bias towards high suspended solids, dissolved oxygen, turbidity and nutrients than samples collected in the morning.
- For Lake Horowhenua, it is recommended that water sampling is completed before 10 am or 4 hours after sunrise, whichever is the earlier time.

### 5.7.7 Data integrity

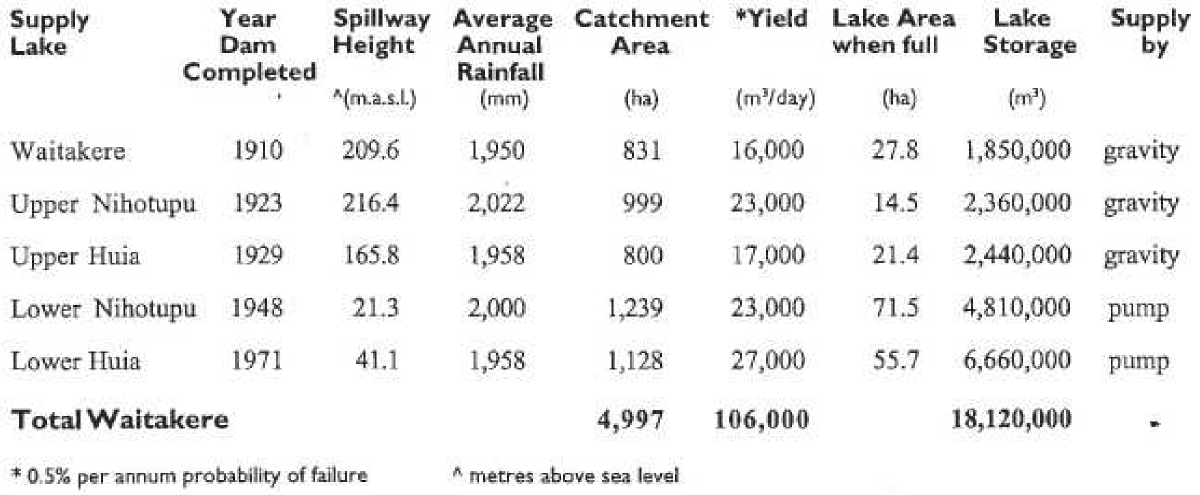
Another important consideration is the maintenance of the database, the checking of data being loaded into the database, and the correction of errors in the database when these are found.

# 6 Case Studies

## 6.1 Auckland Water Supply Reservoirs

There are 10 reservoirs around Auckland that are the water supply lakes for the city. Five of these are in the Waitakere Ranges to the West of the city (Figure 6-1) and the others are in Hunua Ranges to the south-east of the city (Figure 6-2). These lakes are managed as water supplies for the city using simple aeration techniques and the timing protocols for aeration in section 4.4.1. The lakes range in size from 14.5 ha (Table 6-1) up to 169 ha (Table 6-2) with depths ranging from 16 m (Lower Nihotupu) up to 59 m (Mangatangi).

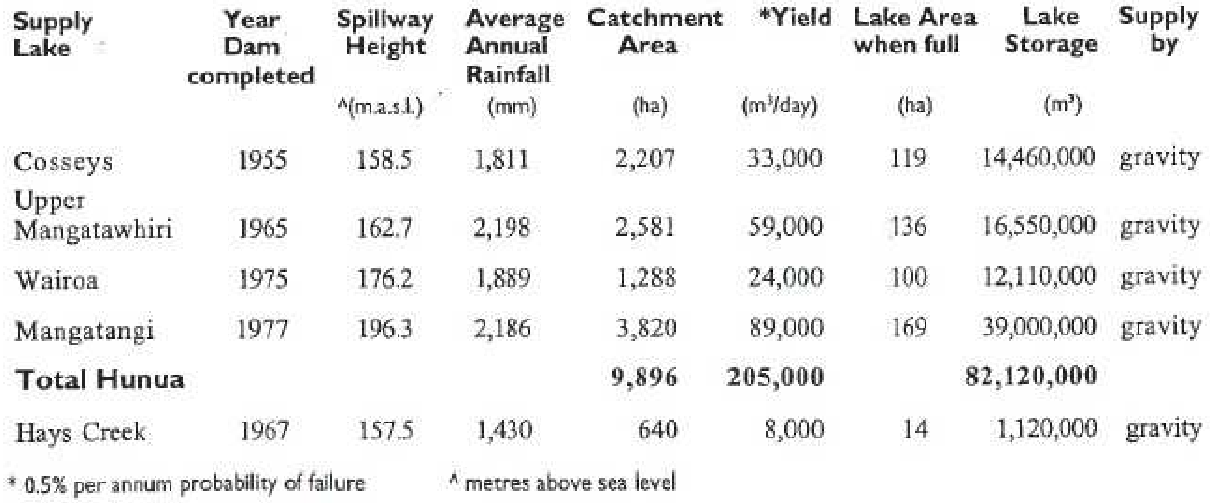
**Table 6-1: Waitakere water supply reservoirs data.**



| Supply Lake | Year Dam Completed | Spillway Height ^(m.a.s.l.) | Average Annual Rainfall (mm) | Catchment Area (ha) | *Yield ($m^3$/day) | Lake Area when full (ha) | Lake Storage ($m^3$) | Supply by |
|---|---|---|---|---|---|---|---|---|
| Waitakere | 1910 | 209.6 | 1,950 | 831 | 16,000 | 27.8 | 1,850,000 | gravity |
| Upper Nihotupu | 1923 | 216.4 | 2,022 | 999 | 23,000 | 14.5 | 2,360,000 | gravity |
| Upper Huia | 1929 | 165.8 | 1,958 | 800 | 17,000 | 21.4 | 2,440,000 | gravity |
| Lower Nihotupu | 1948 | 21.3 | 2,000 | 1,239 | 23,000 | 71.5 | 4,810,000 | pump |
| Lower Huia | 1971 | 41.1 | 1,958 | 1,128 | 27,000 | 55.7 | 6,660,000 | pump |
| **Total Waitakere** | | | | **4,997** | **106,000** | | **18,120,000** | - |

* 0.5% per annum probability of failure ^ metres above sea level

**Table 6-2: Hunua water supply reservoirs data.**



| Supply Lake | Year Dam completed | Spillway Height ^(m.a.s.l.) | Average Annual Rainfall (mm) | Catchment Area (ha) | *Yield ($m^3$/day) | Lake Area when full (ha) | Lake Storage ($m^3$) | Supply by |
|---|---|---|---|---|---|---|---|---|
| Cosseys | 1955 | 158.5 | 1,811 | 2,207 | 33,000 | 119 | 14,460,000 | gravity |
| Upper Mangatawhiri | 1965 | 162.7 | 2,198 | 2,581 | 59,000 | 136 | 16,550,000 | gravity |
| Wairoa | 1975 | 176.2 | 1,889 | 1,288 | 24,000 | 100 | 12,110,000 | gravity |
| Mangatangi | 1977 | 196.3 | 2,186 | 3,820 | 89,000 | 169 | 39,000,000 | gravity |
| **Total Hunua** | | | | **9,896** | **205,000** | | **82,120,000** | |
| Hays Creek | 1967 | 157.5 | 1,430 | 640 | 8,000 | 14 | 1,120,000 | gravity |

* 0.5% per annum probability of failure ^ metres above sea level

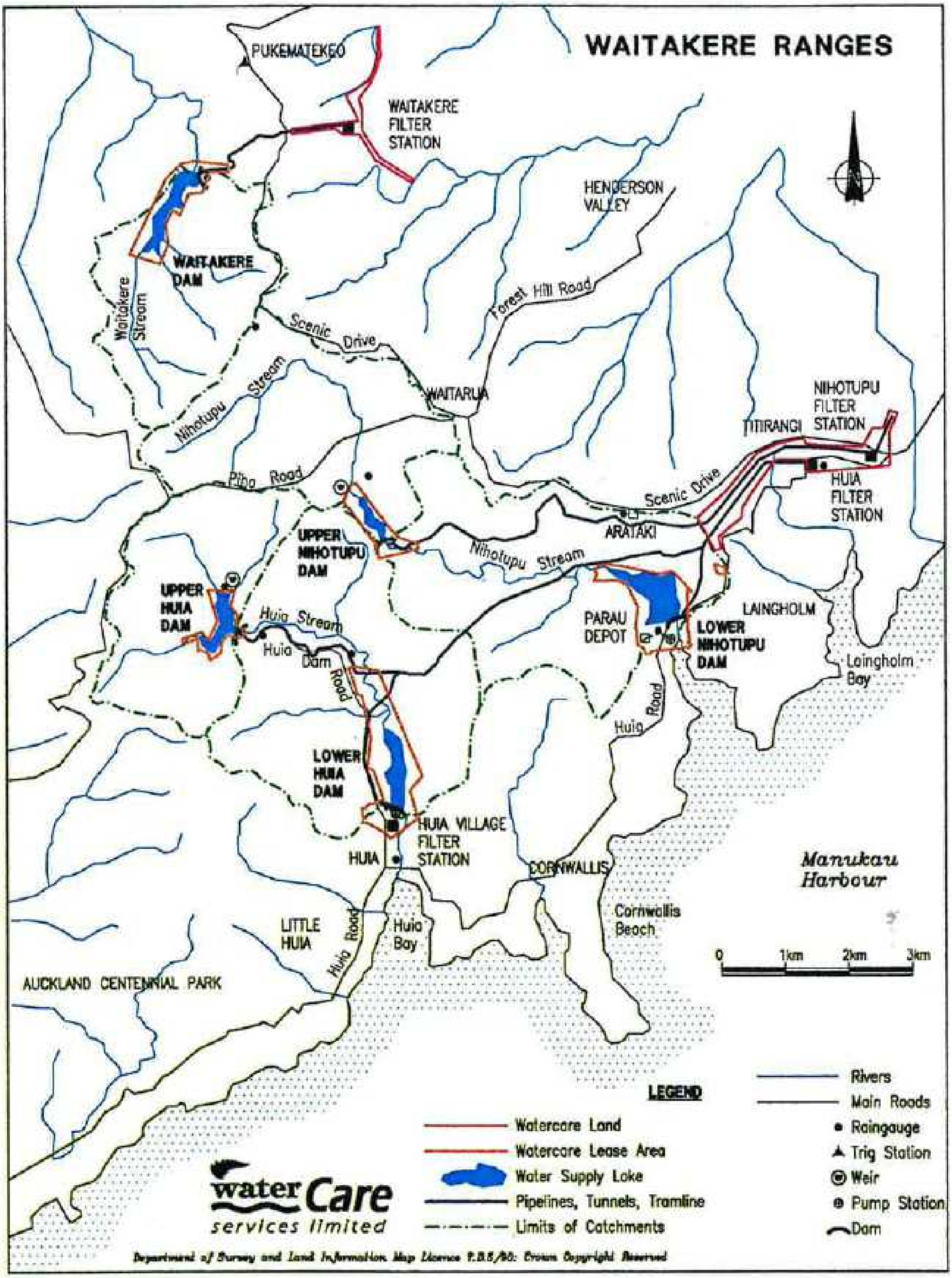


**Figure 6-1: Auckland City water supply reservoirs in the Waitakere Ranges.** (Schematic provided by Watercare Services Ltd).

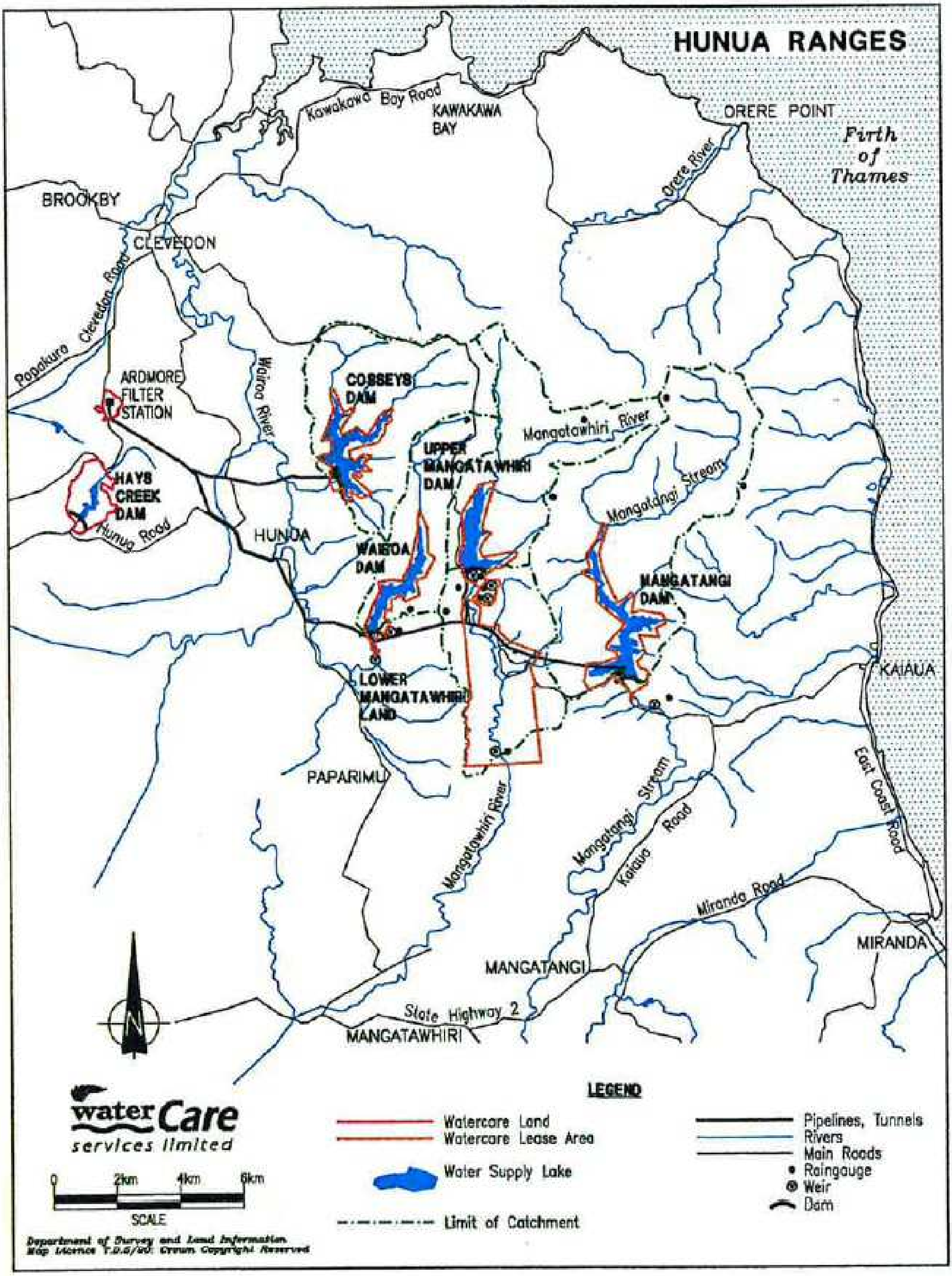


**Figure 6-2: Auckland City water supply reservoirs in the Hunua Ranges.** (Schematic provided by Watercare Services Ltd).

When originally built, these dams had multiple offtake ports at different depths as the only means of managing the quality of the water drawn from the reservoir. In summer the reservoirs would thermally stratify and the bottom water would become oxygen depleted, eventually becoming anoxic with the concomitant release of iron, manganese and phosphorus into the water column. Apart from the off taste and odour of anoxic water, iron and manganese in a water supply cause staining of washing and bathroom fixtures as the water becomes aerobic again. To overcome this requires extra treatment at the water treatment plant and limits the water take the upper water column. Unfortunately, the release of phosphorus can stimulate the growth of algae, especially cyanobacteria, which also impart a taste and odour, and potentially toxins, to the water.

The management strategy of deep draw was developed on the upper Huia reservoir (Spigel & Ogilvie 1985). They examined the effect of prolonged draw from the middle off-take valve in the Upper Huia reservoir (Figure 6-3) over 4 years from 1980 to 1984.

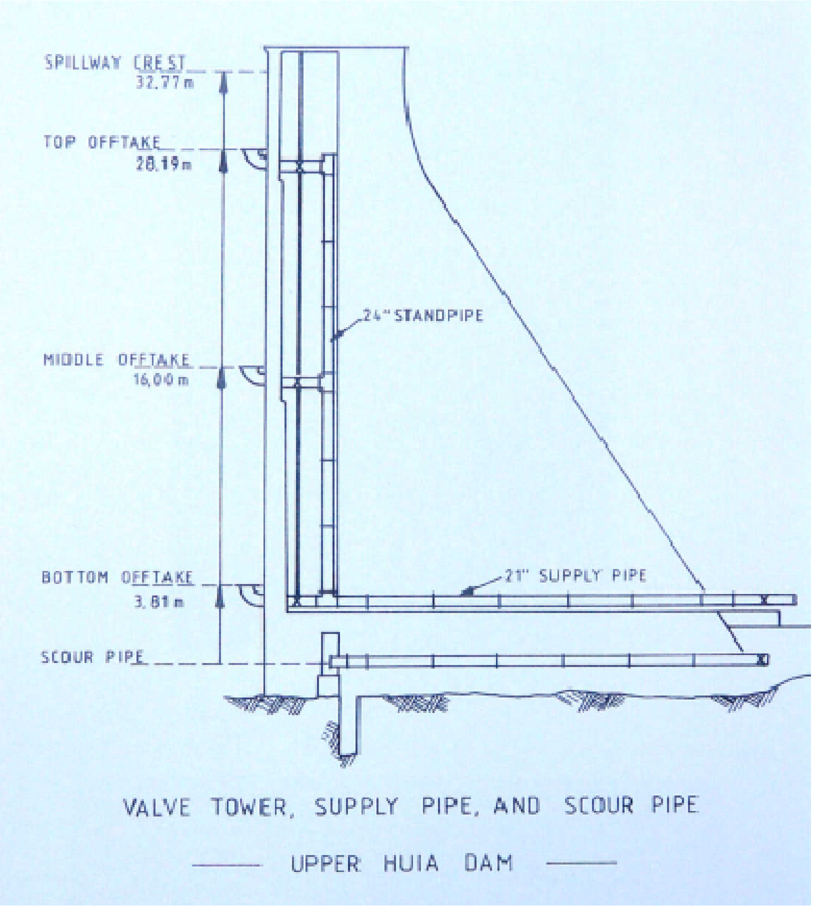


**Figure 6-3: Schematic of the valve tower, off take valves and scour pipe for the Upper Huia Dam.** (From Spigel & Ogilvie 1985, with permission).

They found that continuous selective withdrawal from a fixed depth induced density stratification at that depth. Essentially, water from below that depth was not drawn while the water above that depth was, and became progressively warmer as the lake level fell bringing the warmer surface water closer to the draw depth. The resulting density stratification produced the same geochemical effects as normal thermal stratification, with water below the offtake valve depth becoming anoxic and nutrients and minerals released from the sediments accumulated in high concentrations (Figure 6-4, blue lines).

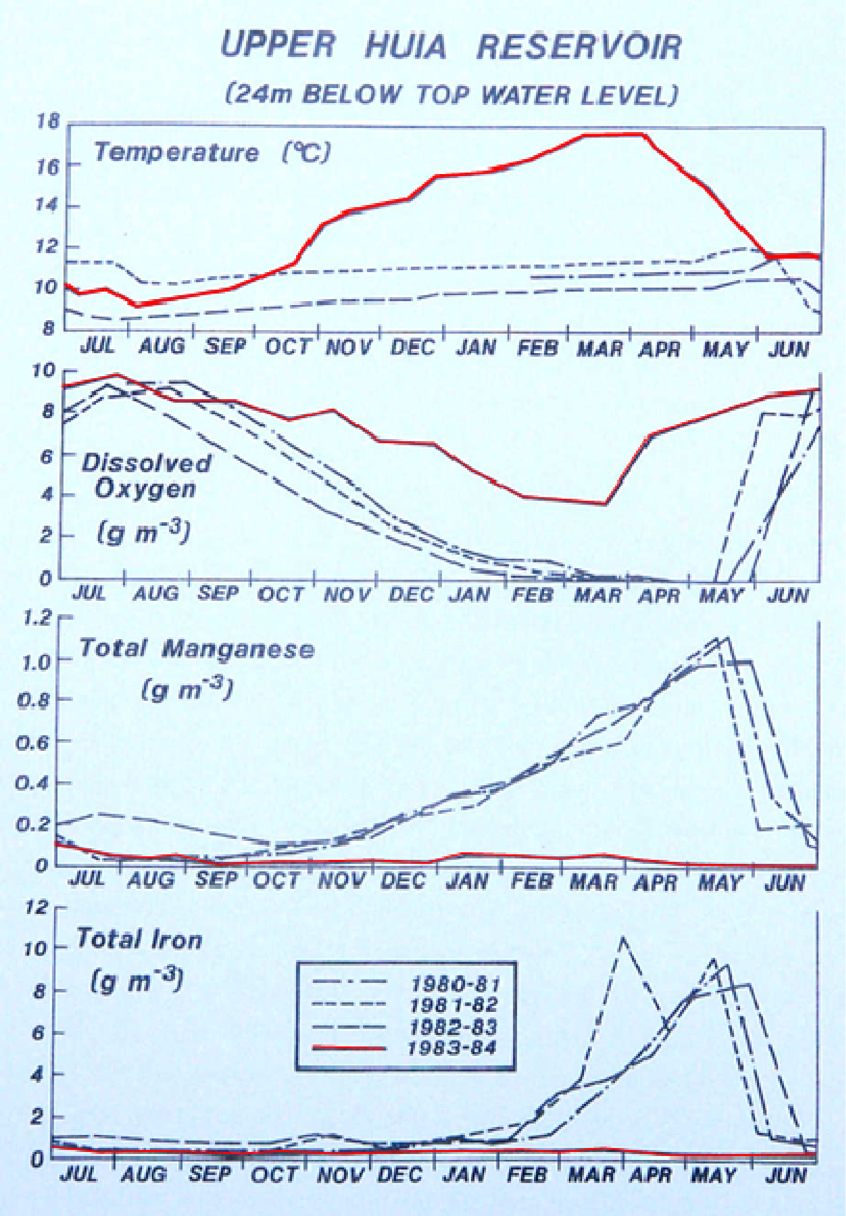


**Figure 6-4: Time series results of temperature, dissolved oxygen, total manganese (Mn), and total iron (Fe) in the Upper Huia reservoir from 1980 to 1984.** In 1980 to 1983, the draw depth was the middle off-take valve. The 1983-84 data show the effect of selective draw from the bottom off-take valve. (Graph from Spigel & Ogilvie 1985, with permission).

Further experiments with shifting the draw depth to the bottom off-take valve caused the water column above the draw depth to remain oxygenated and eliminated the mineral release from the sediments (Figure 6-4, red lines).

This technique was used until summer 2000 when aerators were installed in the reservoirs. At that time cyanobacteria proliferations were noticed for the first time in these reservoirs. The coincidence of a cyanobacteria event following the start of aeration soon became apparent in Lower Nihotupu (Figure 6-5) with early starting of aeration having no significant cyanobacteria abundance whereas late starting after stratification had established coincided with substantial cyanobacteria growths (Figure 6-5).

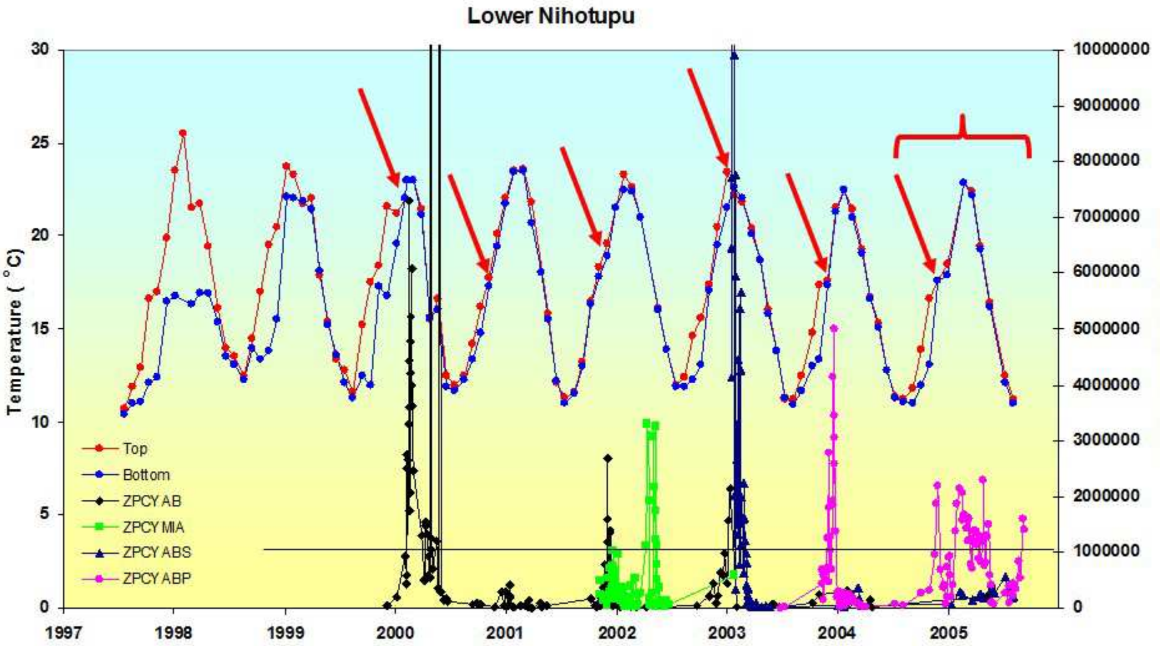


**Figure 6-5: Time series temperature and cyanobacteria cell counts in Lower Nihotupu reservoir.** Red (top) and blue (bottom) temperature lines show the degree of thermal stratification. Red arrows show when aeration was turned on each year. Aeration was kept on from 2005 to 2006 (red bracket). Different colours for the cell counts indicate different cyanobacteria species. Horizontal line is the threshold of cyanobacteria in drinking water. (Data from Watercare, with permission).

From 2006, the timing of turning on aeration was set by the dissolved oxygen regime (section 4.4.1) and the cyanobacteria events were effectively eliminated (Figure 3-10).

Of interest are the changes in cyanobacteria species in this reservoir over time. Most are the nitrogen-fixing *Anabaena* species, although *Microcystis* (a non-nitrogen fixing species) also appeared and became dominant but apparently not in association with aeration.

Although most attention is placed on cyanobacteria blooms, other algal species may also reach nuisance or bloom proportions in lakes. The dinoflagellate, *Ceratium hirundinella*, reaches nuisance proportions in Lake Hayes in summer and has caused problems of filter clogging in a large irrigation water supply in Northland. Green algae such as *Chlorella* and *Botryococcus braunii* can also reach bloom proportions in summer. Diatoms typically reach their peak biomass in the winter-spring bloom when there are sufficient nutrients from winter mixing and enough turbulence to lift them up into the photic zone for rapid growth.

## 6.2 Opuha Dam

The Opuha Dam (Figure 6-6) was originally conceived of as an irrigation scheme for water short areas of South Canterbury, and as an additional urban water supply for Timaru. However, Alpine Energy Limited contended that the economics of the scheme as a stand-alone urban water supply/irrigation proposal were marginal. To ensure a more viable scheme, a power station was added, to utilise the energy available in the head of water held by the dam to provide revenue from electricity sales.

**Figure 6-6: Opuha Dam showing the dam wall and spillway with the lake behind.** The deepest part of the lake lies between the island and the dam wall. The monitoring tower is visible in the lake near the middle of the dam wall. [Internet media photo].

### 6.2.1 Background

The Opuha dam is an earth dam constructed at the confluence of the north and south branches of the Opuha River (approximately 20 kilometres from Fairlie in South Canterbury), and has a power station consisting of generating plant equipment and associated development together with all ancillary and other contracts pertaining to the dam. Water can only be passed through the dam by the 16 cubic metre per second hydro-electric turbine. A secondary weir and control gate a kilometre below the dam are used as a balancing pond and allow the turbine to discharge at peak power requirement times, but water that is stored for irrigation and environmental flow can be released throughout the day from the lower weir.

Approximately 20 kilometres downstream of the dam the Opuha River flows into the Opihi River (Figure 6-7). Another tributary of the Opihi River is the Te Ngawai River. The Opihi

River system provides water from the foothills of the Southern Alps to South Canterbury's closely settled coastal areas.

The lake behind the dam is 330 m long, has an area of 710 ha, a maximum depth of about 35 m and a storage capacity of 91 million cubic metres. The watershed for the dam is 16,000 ha. The offtake is at a depth of 30 m.

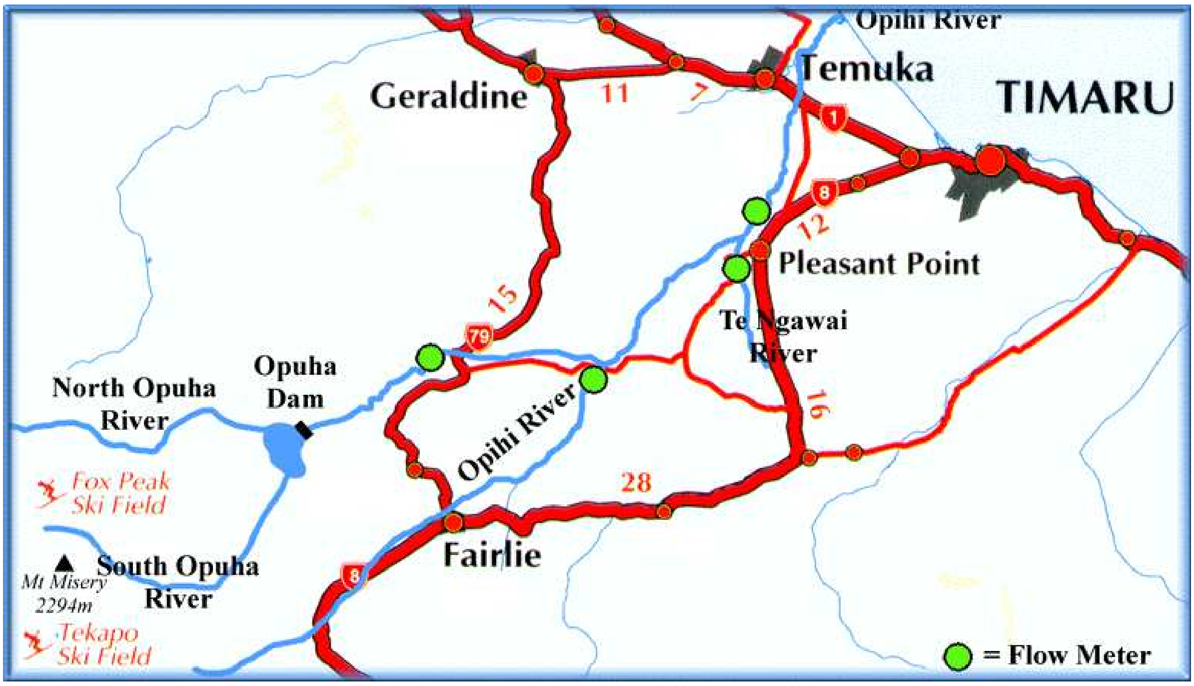


**Figure 6-7: Location map of Opuha Dam.** Base map modified from Automobile Association road map.

The water flows in the Opihi River system are unreliable in summer. Local interests have, therefore, combined to construct the Opuha water supply scheme to provide water for urban consumption in Timaru and for farm irrigation. The scheme relies on the fact that the largest water flows into the Opuha River catchment occur during winter and early spring. This water, which previously flowed into the sea, is now able to be captured by the dam and stored in the associated reservoir. Stored water is therefore released to achieve more reliable monthly environmental flows, and to satisfy the high water demand for irrigation in late spring and summer.

The scheme is subject to constraints, in respect of minimum water flows down the Opuha and Opihi Rivers and the use of water stored behind the dam, by conditions applying to the granting of consents under the RMA 1991. The RMA consents[5] require that the Opuha scheme must be managed to ensure (in the following order of priority[6]):

- a minimum water flow downstream of the dam weir of 1.5 $m^3 s^{-1}$ (to ensure satisfactory conditions for fish life in the Opuha River)
- a minimum specified environmental flow in the Opihi River at Pleasant Point (varying from 3.5 to 8.5 $m^3 s^{-1}$ specified for particular months) which may

---

[5] All relevant RMA consents have been granted by the Canterbury Regional Council or the Mackenzie District Council in the name of Opuha Dam Limited.

[6] As specified in Canterbury Regional Council Resource Consent Documents CRC950577 and CRC950578.

require the release of water from the dam, and which requires the continuous calculation of a river system flow balance for the Te Ngawai, Opihi and Opuha Rivers matched with off-takes for irrigation both upstream and downstream of Pleasant Point and urban water supply for Timaru, and

- the rate of filling of the dam is maximised by restricting winter electricity generation to achieving only the minimum flows above, to ensure that it is full at 1 October each year, the start of the drought season.

Only after meeting the consent requirements can Opuha Dam Limited manage water flows to generate additional electricity to obtain a further cash flow and return on capital from the power station.

Construction on the $32 million Opuha earth dam commenced in 1995 and was completed in 1998. The 700ha Lake Opuha flooded the land east of the Clayton Road on Sherwood Downs, Opuha Gorge Road and "Corra Lynn". Land was purchased from seven farmers for the project. The Opuha dam and lake was officially opened 7 November, 1998, by the Mackenzie Mayor Neil Anderson and the irrigation scheme and power plant has been operating for some time.

In 2008, the dam won the supreme award at the Environment Canterbury (ECan) Resource Management Awards.

### 6.2.2 Dam failure and emergency release

The dam construction was not without incident. Disaster struck in February 1997 when, during a cyclonic storm event, the partially completed dam overtopped and collapsed due to scouring of the dam structure as a result of the absence of emergency bypass channels. The dam water surged down the Opuha River, wiped out the approach to the Skipton Bridge, and tore chunks out of land before roaring into the Opihi River system. It ruined vast tracts of farm land, killed stock, and turned fertile paddocks into instant riverbed and flooded the house at "Blueview" Raincliff Road.

Both the completed dam and the downstream weir have a fusable-plug safety release system designed to burst and release water in a “controlled” manner rather than have the dam / weir collapse during high water levels. On 17 May 2009 rain hit the region again, with the deluge blowing out the fusible plug in the downstream weir, closing bridges and roads and stopping trains. The fusible plug in the downstream weir has blown on two other occasions and is being redesigned. The fusible plug in the Opuha Dam has never blown and has never looked like blowing. Although the Opuha Dam is full at 390 m, the dam has been fitted with an inflatable skirt on the spillway to enable it to store an additional 2 m, which is how it briefly reached a level of 393.2 m above sea level.

### 6.2.3 Other problems

The water quality in the lake initially deteriorated with high dissolved colour, high nutrient concentrations and no oxygen in the bottom waters in summer (Hawes & Spigel 1999; Meredith 1999). Consequently, the water released from the lake in summer was adversely impacting on the downstream environment. Subsequent formal review of dam consent conditions required installation of continuous monitoring of stratification, deoxygenation, and operation of an in lake aeration system. These were operational by 2001 and the degraded water quality conditions have been avoided and effectively managed since.

Excessive nuisance growths of algal mats in the Opuha River below the downstream weir have been a reoccurring problem since the dam was commissioned. These have included prolific growths of toxic cyanobacteria mats and later the introduced algae ‘Didymo’. These growths have also proliferated in reaches of the Opihi River below the confluence with the Opuha River. These have been investigated by NIWA staff (Lessard et al. in prep) and result from excessive flow regulation, a lack of ‘flushing flows’, and an armoured or embedded river bed material. There is on-going examination of mechanisms to address these issues, including elements of redesign of the downstream weir.

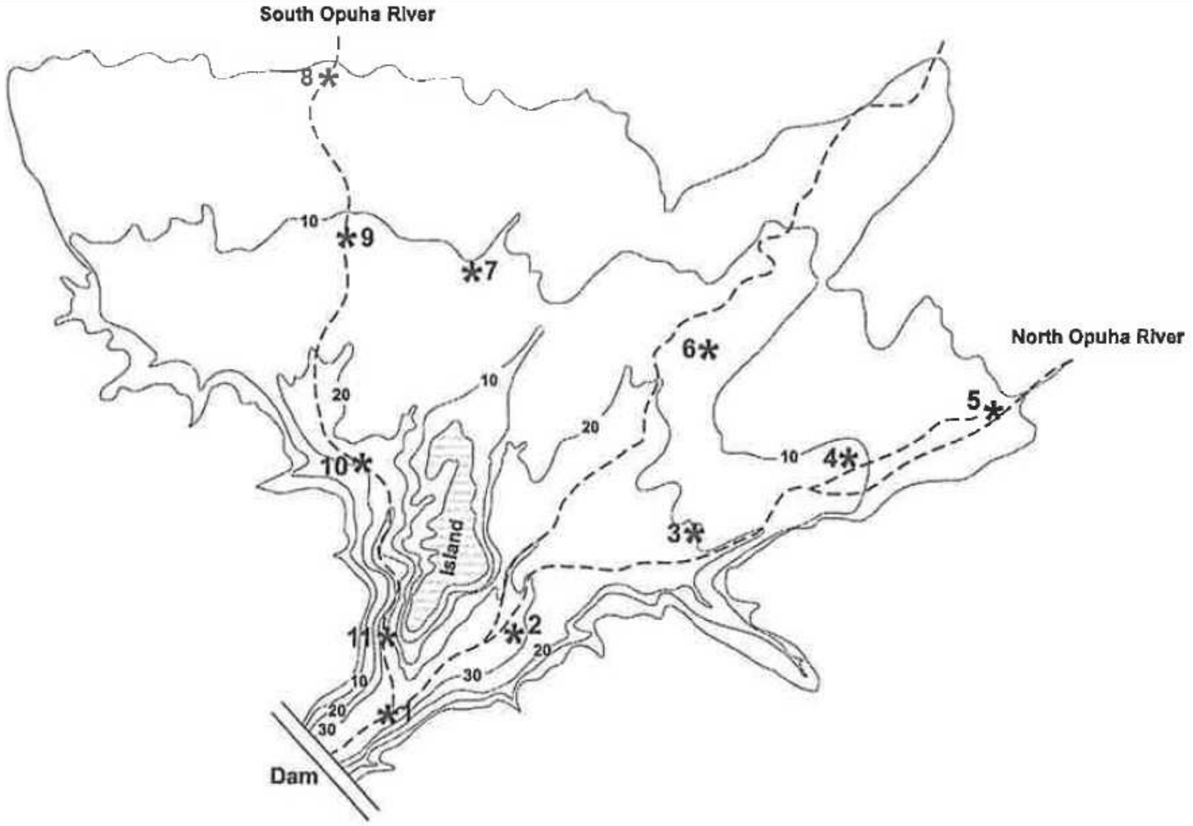


**Figure 6-8: Bathymetry of Lake Opuha .** This chart shows the relative inflow channels of the North and South Opuha Rivers and the formation of the deep basin between the island and the dam wall. Numbers refer to sampling sites used in the 1999 study of the lake (Hawes & Spigel 1999).

### 6.2.4 Design issues

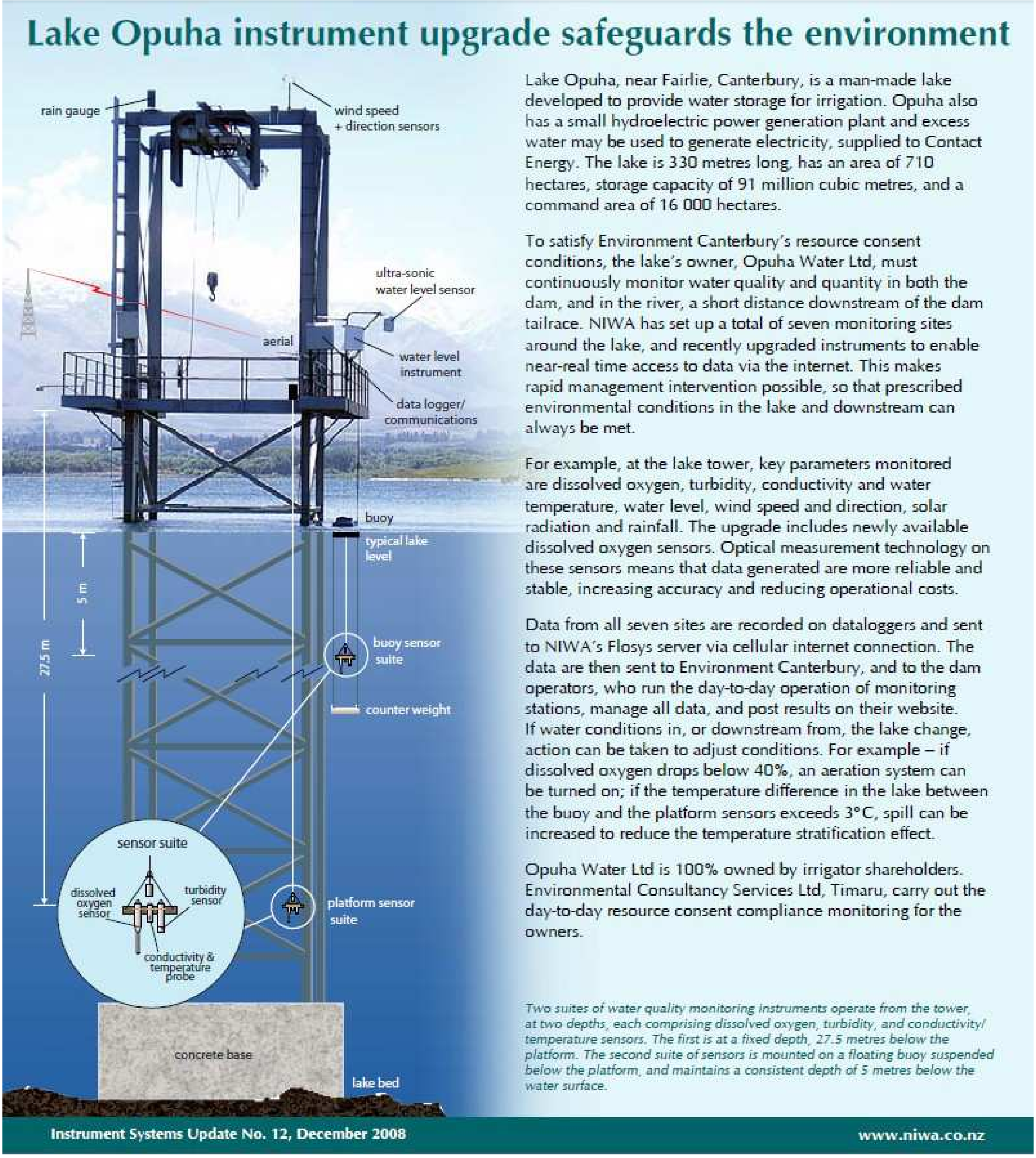
There are four major design issues with the Opuha Dam:

1) Having a single offtake valve near the bottom of the lake. This restricts the quality of the water being discharged to worst possible quality in the hypolimnion when the lake is stratified without the option of discharging cleaner oxygenated water from the upper water column.

2) It is primarily an irrigation dam, not a hydroelectric reservoir. This means that, although the outlet valve always discharges at 16 $m^3 s^{-1}$ cubic metres per second (because it flows through the turbine), it only operates for brief periods of time. Consequently, while the deep offtake was designed to act as a deep draw system to entrain the oxygenated surface waters with that flow (see section 4.3 Use of predictive models), this management strategy is only effective where there is continuous flow. With an area of 710 ha, the short duration flow of 16 $m^3 s^{-1}$ is unlikely to have a substantial effect on the oxygen levels in the deep water basin near the dam wall (Figure 6-8).

3) Large deep irrigation reservoirs will stratify and deoxygenate such that active lake water quality management systems will need to be built into the design. Primary consideration should be given to installing an aeration system to keep the water column mixed during summer and thus prevent bottom water anoxia developing. An aeration system has been installed in Opuha Dam (Appendix G). The offtake system should have multiple valves at different depths to allow management of the water quality being discharged to the downstream environment. This requires a water quality monitoring programme to provide the information needed to allow adaptive management of the discharge water quality. The Tower used to raise and lower the control plug on the offtake valve has been fitted with monitoring instruments (Figure 6-9), and a multi-valve offtake system is being fitted in place of the single control plug.

4) There is no requirement for the periodic discharge of a flushing flow from the dam. Allowing only regulated low flows from the downstream weir eliminates flushing flows and will generate the problems of regulated flow downstream (nuisance algae, armoured bed etc.). Flushing flows “rumble” the river bed stones, sloughing off periphyton and redistributing fine sediment rather than letting it consolidate and smother benthic invertebrate habitats between and beneath stones.



# Lake Opuha instrument upgrade safeguards the environment

Lake Opuha, near Fairlie, Canterbury, is a man-made lake developed to provide water storage for irrigation. Opuha also has a small hydroelectric power generation plant and excess water may be used to generate electricity, supplied to Contact Energy. The lake is 330 metres long, has an area of 710 hectares, storage capacity of 91 million cubic metres, and a command area of 16 000 hectares.

To satisfy Environment Canterbury's resource consent conditions, the lake's owner, Opuha Water Ltd, must continuously monitor water quality and quantity in both the dam, and in the river, a short distance downstream of the dam tailrace. NIWA has set up a total of seven monitoring sites around the lake, and recently upgraded instruments to enable near-real time access to data via the internet. This makes rapid management intervention possible, so that prescribed environmental conditions in the lake and downstream can always be met.

For example, at the lake tower, key parameters monitored are dissolved oxygen, turbidity, conductivity and water temperature, water level, wind speed and direction, solar radiation and rainfall. The upgrade includes newly available dissolved oxygen sensors. Optical measurement technology on these sensors means that data generated are more reliable and stable, increasing accuracy and reducing operational costs.

Data from all seven sites are recorded on dataloggers and sent to NIWA's Flosys server via cellular internet connection. The data are then sent to Environment Canterbury, and to the dam operators, who run the day-to-day operation of monitoring stations, manage all data, and post results on their website. If water conditions in, or downstream from, the lake change, action can be taken to adjust conditions. For example – if dissolved oxygen drops below 40%, an aeration system can be turned on; if the temperature difference in the lake between the buoy and the platform sensors exceeds 3°C, spill can be increased to reduce the temperature stratification effect.

Opuha Water Ltd is 100% owned by irrigator shareholders. Environmental Consultancy Services Ltd, Timaru, carry out the day-to-day resource consent compliance monitoring for the owners.

*Two suites of water quality monitoring instruments operate from the tower, at two depths, each comprising dissolved oxygen, turbidity, and conductivity/temperature sensors. The first is at a fixed depth, 27.5 metres below the platform. The second suite of sensors is mounted on a floating buoy suspended below the platform, and maintains a consistent depth of 5 metres below the water surface.*

**Instrument Systems Update No. 12, December 2008** **www.niwa.co.nz**

**Figure 6-9: NIWA Instrument Services monitoring instruments attached to the offtake valve tower in Opuha Dam.** For more information, contact NIWA Instrument Services (03) 348 8987. [With permission from NIWA].

## 6.3 Virginia Lake

Virginia Lake on St Johns Hill in Wanganui, was known to Maori as Roto Kawau and was an important eeling reserve. Kawau, the name of the black shag, refers to the large number of shags that used to frequent the lake. Europeans settled around the lake in the 1850s and the Borough Council bought the lake in 1874 as a water supply reservoir. A dam and offtake structure controlled the water level in the lake, which was a spring-fed with high quality water. It was fashionable to have a house overlooking the lake (Figure 6-10) and the native evergreen vegetation was replaced with deciduous European trees. The gardens developed around the lake form a popular recreational park where visitors can picnic and feed the multitude of ducks, geese and swans.

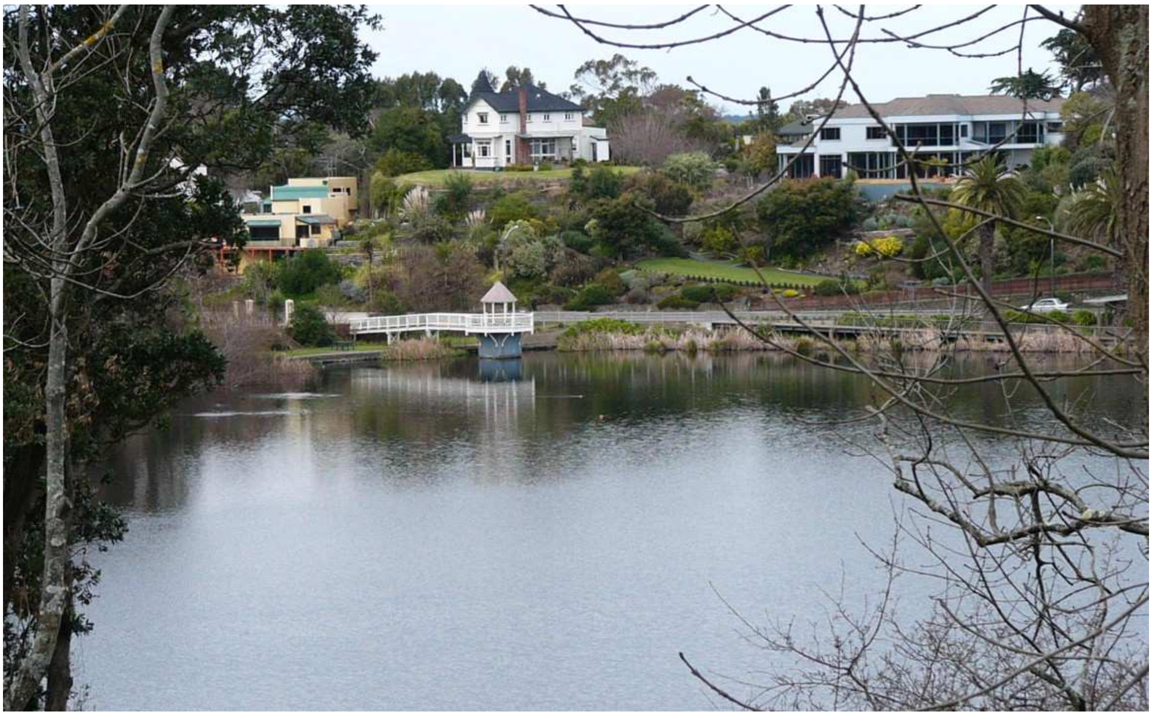


**Figure 6-10:Virginia Lake viewed across the lake from the north to the offtake structure.**

The water quality deteriorated over time and the lake is no longer used as a water supply. Presently it experiences periodic algal blooms of dinoflagellates and cyanobacteria and on occasion there are reports of fish kills and water fowl dying.

Virginia Lake has an area of 4.5 ha, a volume of 540,000 m$^3$, a maximum depth of around 20 m and a residence time of around 1.6.yr. The out flow is via a surface skimmer drop shaft at the offtake structure and this serves to control the lake level. The lake thermally stratifies at a depth of about 6 m and only mixes briefly due to the shelter provided by the tall trees around the lake shore (Figure 6-11). The hypolimnion becomes oxygen depleted to the point of anoxia in spring (Figure 6-12) and phosphate and ammonium released from the sediments drive the algal blooms in spring and summer (Figure 6-13). The intensity of the bloom reduces the nutrient concentrations in the surface waters as photosynthesis causes oxygen super-saturation and high pH as the $CO_2$ is removed from the water. As the pH rises above 9, this results in the formation of toxic ammonia. When the algal bloom is cyanobacteria, it will drift inshore and the ammonia will cause fish kills. As the cyanobacteria senesce they may release toxins that may, together with botulism, be responsible for killing water fowl.

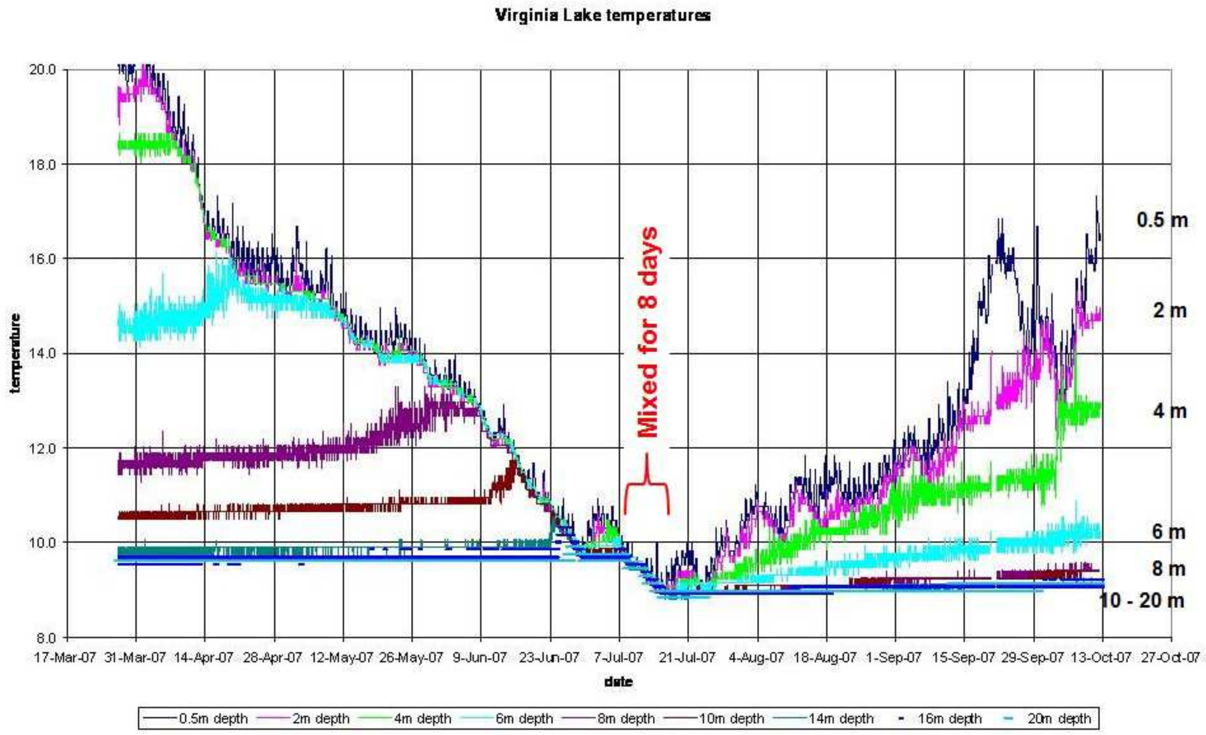


**Figure 6-11:Temperature structure in the water column at the critical winter mixing time.** Each line represents the temperature at a specific depth. The water column is mixed when all the temperature lines merge into one. In this data set the lake was mixed for 8 days. [Data from Colin Hovey, Wanganui District Council]

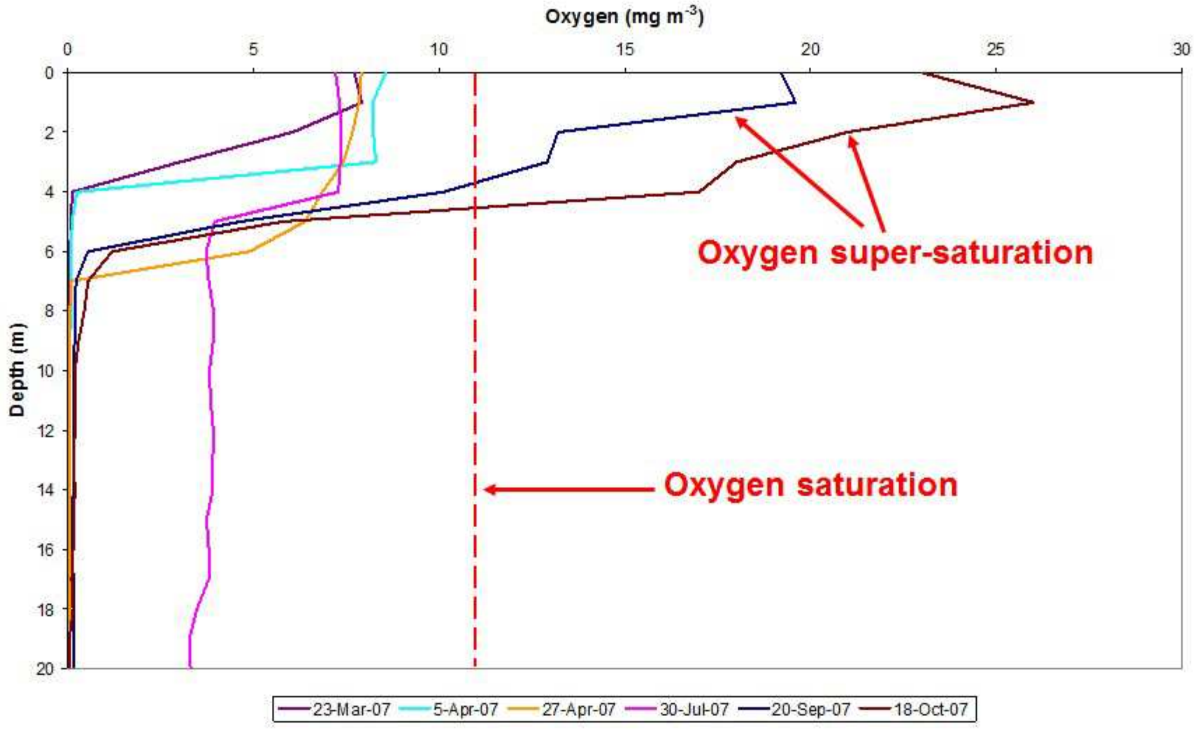


**Figure 6-12:Dissolved oxygen profile sequence in Virginia Lake.** Winter mixing occurred just before the 30 July profile indicating some re-oxygenation of the hypolimnion before it became anoxic again by 20 September. The algal bloom in in September caused DO super-saturation of the surface waters. [Data from Colin Hovey, Wanganui District Council].

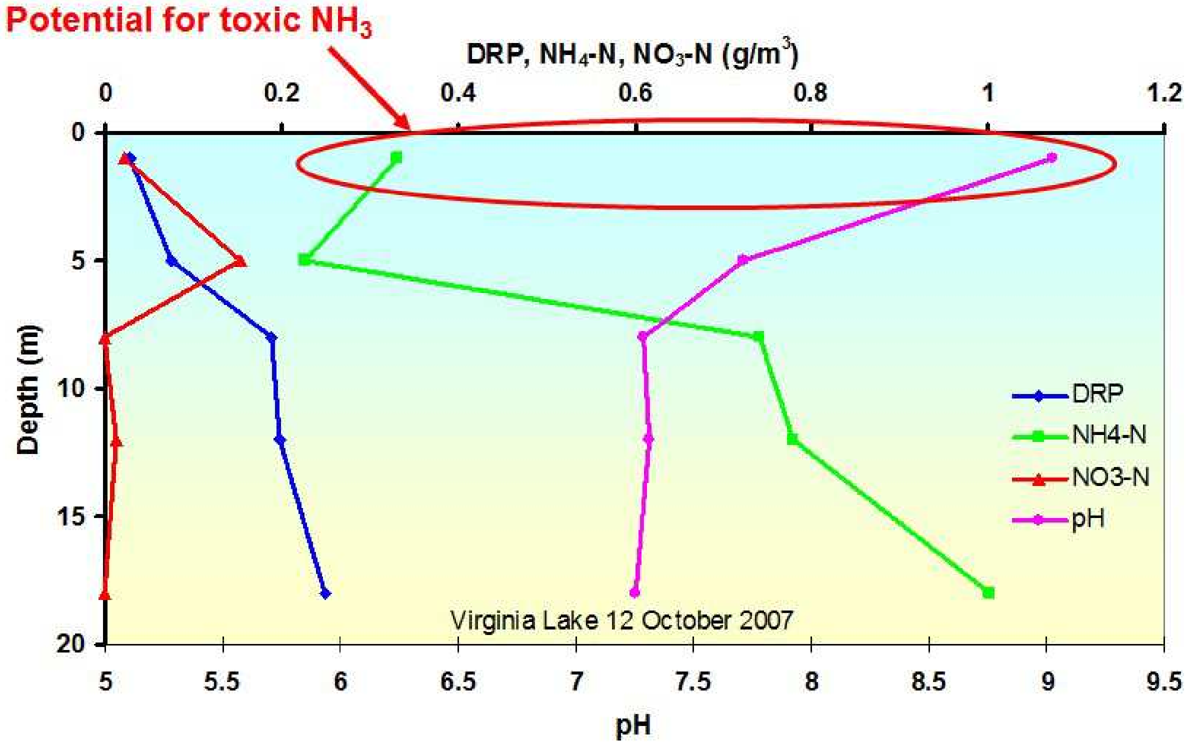


**Figure 6-13:Nutrient concentration and pH profiles in the water column of Virginia Lake during the spring bloom.** The nutrient concentrations are depleted by the algae and the pH rises as the algae consume all the $CO_2$ from the water. Above pH >9, ammonium is present as ammonia, which is toxic to fish. [Data from NIWA].

There are several factors that have combined to cause the water quality problems in Virginia Lake. These include:

- Changing the vegetation from evergreen natives to deciduous exotic species has deposited a large amount of leaf carbon in the lake, which drives the sediment oxygen demand as it decomposes.
- The development of housing serviced by septic tanks in close proximity to lake has contaminated the surface groundwater aquifer with nutrient rich leachate (e.g., Gibbs, 1977a; 1977b) which can enter the lake.
- The introduction of geese and swans to the lake has destroyed the marginal vegetation that would otherwise act as a buffer zone to remove the nutrients from the groundwater. Without the buffer zones shore line erosion is occurring, reducing the clarity of the lake through increased suspended solids.
- The introduction of coarse fish (pest species) will be impacting on the regrowth of these buffer zone plants.
- The feeding of large numbers of ducks introduces large amounts of bread, which settles to the sediments either directly or via faecal material from the water fowl and adds to the sediment oxygen demand.
- Draining stormwater away from the lake and having a surface out flow has reduced the flushing rate.

The lake has a water fountain which is likely to degas the surface water and reduce the super-saturation slightly. A Solar Bee mixer has also been used as a mitigation measure. While this appeared to reduce the extent of the algal bloom, the water column profiles (Figure 6-14) suggest that it may have “hardened” the thermocline reducing the diffusive nutrient flux from the hypolimnion.

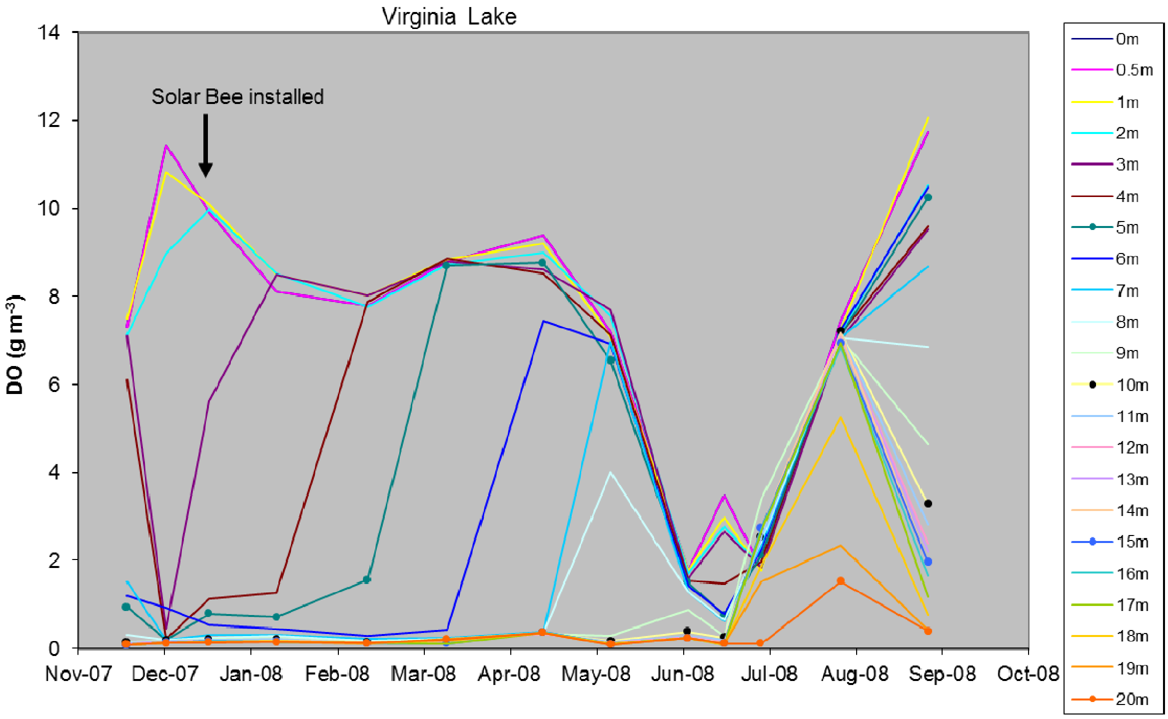


**Figure 6-14:Dissolved oxygen profiles in Virginia Lake associated with the use of a Solar Bee.** The Skirt of the Solar Bee was set at around 6 m. [Data from Colin Hovey, Wanganui District Council].

Restoration action for Virginia Lake could include

- **Aeration to keep the lake fully mixed throughout the year.** Turn on would need to coincide with the brief period of winter mixing to reduce the energy otherwise required to break the thermal stratification. At that time it would be unlikely to alter the magnitude of the spring algal bloom that occurs after mixing. By pumping air through the aeration mixer, the water column would have more $CO_2$ which would tend to reduce the pH below 9, thereby eliminating the production of toxic ammonia. Because the water column would be fully mixed, the cyanobacteria would be less likely to become dominant and the magnitude of algal grow could be reduced to light limitation and critical depth effects.
- **Increase bottom water exchange.** In the absence of an aeration system, the out flow could be engineered to include a hypolimnetic siphon (Figure 6-15) which would discharge the anoxic, nutrient rich bottom water from the lake instead of the nutrient depleted aerated surface water. The out flow water would need to be treated to introduce oxygen and reduce the nutrient concentrations that would otherwise impact the downstream environment. The diversion / piping of additional clean water into the lake as a surface inflow would enhance the flushing. Reducing road runoff would reduce the nutrient load on the lake.

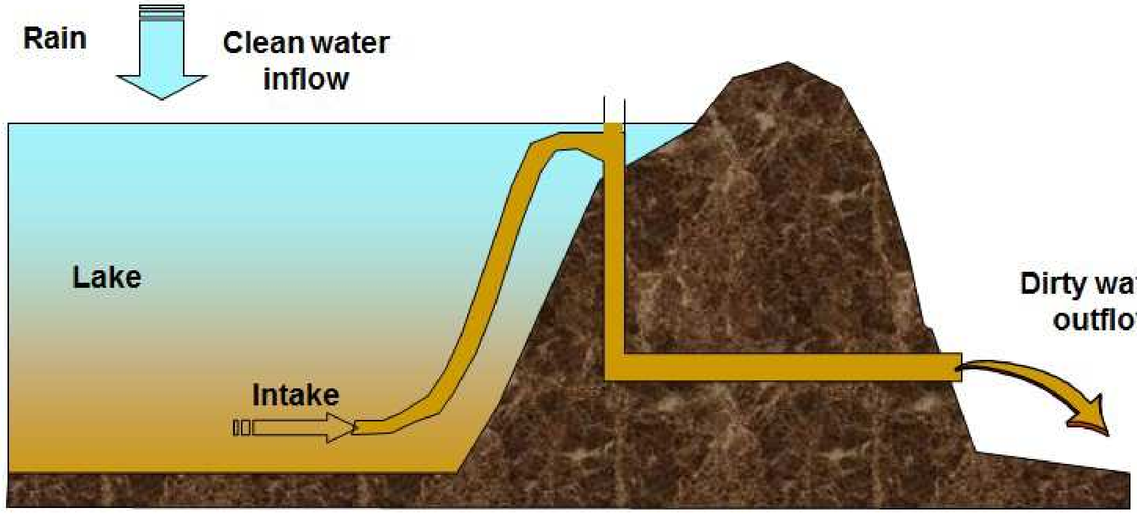


**Figure 6-15:Schematic of a hypolimnetic siphon.** This uses the existing offtake drop shaft out flow pipes but has an intake at the bottom of the lake. The open head tube sets the water level so that bottom water is drawn continuously. The height of the head tube could be set at the maximum lake level under heavy rain events to prevent flooding.

- **Reduce in the numbers of geese and swans on the lake.** This would allow the riparian buffer zones to re-establish and would reduce the nutrient load on the lake. Even though the area now has reticulated waste water, the historical legacy of septic tank effluent will still be travelling in the groundwater to the lake, along with more recent nutrients from lawn and garden fertilisers.
- **The sediments could be treated to reduce nutrient release.** Sediment capping to retain the P in the sediment has the potential to reduce the abundance of algae and dominance of cyanobacteria due to P-limitation.

Virginia Lake is a classic example of how a lake (natural or artificial) can become degraded through small apparently innocuous changes in the lake catchment.

# 7 Acknowledgements

These Guidelines were funded by MBIE through Envirolink tools project contract NIWX0903. Information and data in the report have come from many sources including people in Regional Councils, Research Institutes, Universities and personal experience. Literature sources include peer reviewed scientific paper, reports and information from the internet. The draft document has been reviewed by members of Regional Councils for content and clarity and has been revised accordingly to meet the requirements of the consenting authorities. We would like to thank Dr Adrian Meredith of Environment Canterbury as project champion for guidance and discussions during the preparation of these Guidelines.

# 8 References

Abell, J.; Özkundakci, D.; Hamilton, D.P. (2010). Nitrogen and phosphorus limitation of phytoplankton growth in New Zealand lakes: Implications for eutrophication control. *Ecosystems 13(7)*: 966–977.

Achterberg, E.P.; van den Berg, C.M.G.; Boussemart, M.; Davison, W. (1995). Speciation and cycling of trace metals in Esthwaite Water: A productive English lake with seasonal deep-water anoxia. *Geochimica et Cosmochimica Acta 61*: 5233–5253.

Art, H.W. (1993). Eutrophication. *In:* Art, H.W., (ed.) A dictionary of ecology and environmental science (1st ed.): New York, Henry Holt and Company. 196 p.

Baker, S.; Smith, J.; Davison, B. (2008). Hunua Ranges Dams – Freshwater Fish Survey 2008. Prepared by NIWA for Auckland Regional Council and Watercare Services Ltd. *Auckland Regional Council Technical Report 2008/016.* 50 p.

Balvert, S. (2006). Limnological Characteristics and Zooplankton Dynamics of a Newly Filled Mine Lake. MSc Thesis, University of Waikato.

Beaulieu, S.E.; Sengco, M.R.; Anderson, D.M. (2005). Using clay to control harmful algal blooms: deposition and resuspension of clay/algal flocs. *Harmful Algae 4*: 123–138.

Beutel, M.W.; Leonard, T.M.; Dent, S.R.; Moore, B.C. (2008). Effects of aerobic and anaerobic conditions on P, N, Fe, Mn, and Hg accumulation in waters overlaying profundal sediments of an oligo-mesotrophic lake. *Water Research 42*: 1953–1962.

Biyu, S.; Yi, Y.; Diana, J.S. (2010). Clay Flocculation Counters Microcystin Pollution *In:* China Study. Global Aquaculture Advocate (November/December 2010): 26–27.

Boffa Miskell Ltd (2009). Guidelines for ponds. Greater Wellington Regional Council website file. Available at http://www.gw.govt.nz/so-you-re-thinking-about-a-pond/

Brougham, G.G.; Currie, K.J. (1976). Progress report on water quality investigations: Lake Horowhenua. *Manawatu Catchment Board and Regional Water Board report,* Palmerston North. 60 p.

Brown, J-M. (2003). Air pump urged to help dying lakes. NZ Herald, Oct. 17, 2003.

Burns, N.M. (1995). Using hypolimnetic dissolved oxygen depletion rates for monitoring lakes. *New Zealand Journal or Marine and Freshwater Research 29*: 1–11.

Burns, N.M.; Rutherford, J.C.; Clayton, J.S. (1999). A monitoring and classification system for New Zealand lakes and reservoirs. Lake and Reservoir Management. 15:255-271.

Burns, N.; Bryers, G.; Bowman, E. (2000). Protocol for monitoring trophic levels of New Zealand lakes and reservoirs. Ministry for the Environment

Burns, N.; McIntosh, J.; Scholes, P. (2005). Strategies for Managing the Lakes of the Rotorua District, New Zealand. *Lake and Reservoir Management 21*: 61–72.

Carpenter, S.R.; Lathrop, R.C. (1999). Lake restoration: capabilities and needs. *Hydrobiologia 395/396*: 19–28.

Champion, P.; Dugdale, T.; Matheson, F. (2002). Lake Horowhenua – assessment of the status of *Egeria densa* and implications for lake stability. *NIWA client report No. HAM2002-058* to Horizons Regional Council. 25 p.

Chen, J.; Pan, G. (2012). Harmful algal blooms mitigation using clay/soil/sand modified with xanthan and calcium hydroxide. *Journal of Applied Phycology 24*: 1183–1189.

Cooke, D.G.; Welch, E.B.; Peterson, S.A.; Nichols, S.A. (2005). Restoration and Management of Lakes and Reservoirs. Boca Raton, CRC Press. 616 p.

Cotel, A. (1999). A trigger mechanism for the Lake Nyos disaster, American Physical Society, Division of Fluid Dynamics Meeting, November 21–23, 1999.

De Winton, M.; Champion, P. (2011). Freshwater biosecurity implications from water storage & distributional infrastructure. *NIWA client report number HAM2011-088* to Environment Canterbury. 36 p.

Duarte, C.M.; Conley, D.J.; Carstensen, J.; Sánchez-Camacho, M. (2009). Return to Neverland: shifting baselines affect eutrophication restoration targets. *Estuaries and Coasts 32*: 29–36.

Edwards, T.; Clayton, J. (2002). Aquatic vegetation in Lakes Dudding, Wiritoa, Horowhenua and Pukepuke Lagoon. *NIWA client report No. HMW02201* to Manawatu-Wanganui Regional Council. 24 p.

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 p.

Forsyth, D.J. (1971). Some New Zealand Chironomidae (Diptera*). Journal of the Royal Society of New Zealand 1*: 113–144.

Forsyth, D.J. (1978). Benthic macroinvertebrates in seven New Zealand lakes*. New Zealand Journal of Marine and Freshwater Research 12*: 41–49.

Forsyth, D.J. (1986). Distribution and production of *Chironomus* in eutrophic Lake Ngapouri. *New Zealand Journal of Marine and Freshwater Research 20*: 327–335.

Forsyth, D.J.; James, M.R. (1988). The Lake Okaro ecosystem 2. Production of the chironomid *Polypedilum pavadus* and its role a food for two fish species. *New Zealand Journal of Marine and Freshwater Research 22*: 47–54.

Foster, P.; Morgan, Y.; Amos, P. (2000). Guidelines for resource consents for dams and associated activities. Opus International Consultants report for the Ministry for the Environment under the Sustainable Management Fund. 180 p.

Gibbs, M.M. (1977a). Soil renovation of effluent from a septic tank on a lake shore. *New Zealand Journal of Science 20(3):* 255–263.

Gibbs, M.M. (1977b).  Study of septic tank system on a lake shore: temperature and effluent flow patterns. *New Zealand Journal of Science 20*: 55–61.

Gibbs, M.M.; White, E. (1994). Lake Horowhenua: a computer model of its limnology and restoration prospects.  *Hydrobiologia 275/276*: 467–477. Also reprinted in E. Mortensen, E. Jeppesen, M. Søndergaard, and L. K. Nielsen [eds.] Nutrient dynamics and biological structure in shallow freshwater and brackish lakes. Kluwer Academic Publishers, Dordrecht / Boston / London.

Gibbs, M.; Bremner, D.; van Kooten, M. (2008). Comparison of efficacy of four P-inactivation agents on Lake Rotorua sediments. *NIWA Client Report HAM2008-105* to Environment Bay of Plenty. Project No. BOP08209.

Gibbs, M.; Smith, B.; Budd, R.; Bremner, D.; Edhouse, S.; Greenfield, B. (2011a). Testing sediment capping agents: P equilibrium, P saturation, dispersion and settling velocities. *NIWA Client Report No.HAM2010-117* to Bay of Plenty Regional Council. Project No. BOP11205. 19 p.

Gibbs, M.; Hickey, C.W.; Özkundakci, D. (2011b). Sustainability assessment and comparison of efficacy of four P-inactivation agents for managing internal phosphorus loads in lakes: sediment incubations. *Hydrobiologia 658*: 253–275.

Gibbs, M. (2011). Lake Horowhenua review: Assessment of opportunities to address water quality issues in Lake Horowhenua. *NIWA client report number HAM2011-046* to Horizons Regional Council. 109 p.

Gibbs, M.; Özkundakci, D. (2011). Effects of a modified zeolite on P and N processes and fluxes across the lake sediment–water interface using core incubations. *Hydrobiologia 661*: 21–35.

Gulati, R.D.; Dionisio Pires, L.M.; Van Donk, E. (2008). Lake restoration studies: Failures, bottlenecks and prospects of new ecotechnological measures. *Limnologica 38*: 233–247.

Harding, J.; Mosley, P.; Pearson, C.; Sorrell, B. (Eds). (2004). Freshwaters of New Zealand. New Zealand Hydrological Society and New Zealand Limnological Society publication. 700 p.

Hawes, I.; Spigel, R. (1999). Report on water quality in the Opuha Dam. *NIWA consultants report CHC99/12* to the Opuha Dam Company. March 1999. 27 p.

Hemond, H.F.; Lin, K. (2010). Nitrate suppresses internal phosphorus loading in an eutrophic lake. *Water Research 44*: 3645–3650.

Hickey, C.W.; Gibbs, M.M. (2009). Lake sediment phosphorus release management—Decision support and risk assessment framework. *Journal of Marine and Freshwater Research 43*: 819–856.

Holms, R. (2010). The potential for metal contamination in the Maitai River. Cawthron Institute report No. 1850 to Nelson City Council. *Envirolink 917-NLCC45.* 19 p.

IPENZ (2011). Farm Dairy Effluent Design and Construction, IPENZ Practice Note 21, version 1, September 2011. Wellington. 88 p.

Jeppesen, E.; Meerhoff, M.; Jacobsen, B.A.; Hansen, R.S.; Søndergaard, M.; Jensen, J.P.; Lauridsen, T.L.; Mazzeo, N.; Branco, C.W.C. (2007). Restoration of shallow lakes by nutrient control and biomanipulation—the successful strategy varies with lake size and climate. *Hydrobiologia 581*: 269–285.

Kerr, R.; Hamilton, D.; Kupec, K.; Wagner, C.; Gousmett, K. (2009). Jacks Point lake: predicting water quality in a new urban lake. Proceedings of the South Pacific Stormwater Conference.

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.

Lessard, J.L.; Arscott, D.A.; Booker, D.J; Larned, S.T.; Snelder, T.H.; Suren A.M. (in review): Why Dams must be designed to provide both high and low flows, a case study from the Opuha Dam, South Island New Zealand. Environmental Management.

Lessard, J.L.; Hayes, D.B. (2003). Effects of elevated water temperature on fish and macroinvertebrate communities below small dams. *River Research & Applications 19*: 721–732.

Lewis, W.M.; Wurtsbaugh, W.A. (2008). Control of lacustrine phytoplankton by nutrients: erosion of the phosphorus paradigm. *Internat. Rev. Hydrobiologia, 93(4-5)*: 446–465.

Mason, R.; West, K.R. (1973). Auckland water plants. Botany Division, DSIR, *Information series No. 92*. Government Printer, Wellington. 20 p.

Maxted, J.; McCready, C.H.; Scarsbrook, M.R. (2005). Effects of small ponds on stream water quality and macroinvertebrate communities. *New Zealand Journal of Marine and Freshwater Research 39*: 1069–1084.

McKellar, H.; Bulak, J.; Taylor, B. (2008). A Dynamic Water Quality Model of Lake Greenwood, SC: Development and Application toward Issues of Phosphorus Loading, Algal Dynamics, and Oxygen Depletion. Report to South Carolina Department of Natural Resources, Freshwater Fisheries Research Lab., 1921 Van Boklen Rd, Eastover SC 29044. 76 p.

McKerchar, A.; Shankar, U.; Hicks, M. (2005). Water harvesting: an ideal use of floodwaters? *Water & Atmosphere 13(2)*: 24–25.

Meredith, A.S. (1999). Water Quality of Lake Opuha: Limnological issues in a newly formed lake. Environment Canterbury Unpublished Report. June 1999.

Ministry of Commerce. (1997). New Zealand dam inventory. Ministry of Commerce, Wellington. 36 p.

MfE (2000). Guidelines for Resource Consents for Dams and Associated Structures. Report to MfE Sustainable Management Fund. 180 p.

Mortimer, C.H. (1941). The exchange of dissolved substances between mud and water in lakes 1. *Journal of Ecology 29*: 280–329.

Mortimer, C.H. (1942). The exchange of dissolved substances between mud and water in lakes 2. *Journal of Ecology 30*: 147–201.

Nordin, R.N.; McKean, C.J.P. (1982). A review of lake aeration as a technique for water quality improvement. *APD Bulletin 22*, British Columbia Ministry of Environment. 40 p.

Olsen, D. (2010). Maitai River South Branch Consent Compliance (2009-2010). Cawthron Report prepared for Nelson City Council. No. (not released). 31 p.

Padilla, L.V.; San Diego-McGlone, M.L.; Azanza, R.V. (2006). Preliminary results on the use of clay to control *Pyrodinium* bloom - A mitigation strategy. *Science Diliman 18(1)*: 35–42.

Pan, G.; Dai; L.; Li, L.; He, L.; Li, H.; Bi, L.; Gulati, R.D. (2012). Reducing the recruitment of sedimented algae and nutrient release into the overlying water using modified soil/s and flocculation-capping in eutrophic lakes. *Environmental Science and Technology 46*: 5077−5084.

Park, J.B.K.; Craggs, R.J. (2010). Wastewater treatment and algal production in high rate algal ponds with carbon dioxide addition. *Water science and technology 61(3)*: 633–639.

Paul, W.J.; Hamilton, D.P.; Gibbs, M.M. (2008). Low-dose alum application trialled as a management tool for internal nutrient loads in Lake Okaro, New Zealand. *New Zealand Journal of Marine and Freshwater Research 42*: 207–217.

Pomeroy, L.R.; Williams, P.J.leB.; Azam, F.; Hobie, J.E. (2007). The microbial loop. *Oceanography 20(2):* 28–33.

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

Reyners, M.E. (1988). Reservoir-induced seismicity at Lake Pukaki, New Zealand. *Geophysical Journal of the Royal Astronomical Society 93(1*): 127–135.

Riecken, S. (1995). A compendium of water quality models. Literature survey for the Water Quality Branch, Ministry of Environment, lands and Parks. BC Canada. 133 p.

Schallenberg, M.; Sorrell, B. (2009). Regime shifts between clear and turbid water in New Zealand lakes: environmental correlates and implications for management and restoration. *New Zealand Journal of Marine and Freshwater Research 43*: 701–712.

Schindler, D.W.; Hecky, R.E.; Findlay, D.L.; Stainton, M.P.; Parker, B.R.; Paterson, M.J.; Beaty, K.G.; Lyng, M.; Kasian, S.E.M. (2008). Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. Proceedings of the National Academy of Sciences 105(32): 11254–11258.

Sengco, M.R.; Anderson, D.M. (2004). Controlling harmful algal blooms through clay flocculation. *Journal of Eukaryotic Microbiology 51(2)*:169–172.

Spears, B.M.; Carvalho, L.; Perkins, R.; Kirika, A.; Paterson, D.M. (2007). Sediment phosphorus cycling in a large shallow lake: spatio-temporal variation in phosphorus pools and release. *Hydrobiologia 584*: 37–48.

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.

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, pp. 275–279,The Institution of Engineers, Australia, National Conference Publication No. 85/13.

Stager, J.C. (1987). "Silent Death from Cameroon's Killer Lake", National Geographic, September 1987.

Stumm, W.; Morgan, J.J. (1995). Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters. Third edition, Wiley-Interscience.

Sukias, J.P.S.; Yates, C.R.; Tanner, C.C. (2010). Floating Treatment Wetlands for Remediation of Eutrophic Lake Waters – Maero Stream Trials (Lake Rotoehu). *NIWA client report HAM2010-104* to Environment Bay of Plenty.

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.

Tanner, C.C.; Champion, P.D.; Kloosterman, V. (2006). New Zealand Constructed Wetland Planting Guidelines. National Institute of Water and Atmospheric Research report published in association with the New Zealand Water & Wastes Association available from http://www.nzwwa.org.nz/Constructed_Wetland_Planting_Guidelines.pdf

Tanner, C.C.; Caldwell, K.; Ray, D.; McIntosh, J. (2007). Constructing wetlands to treat nutrient-rich inflows to Lake Okaro, Rotorua. New Zealand Water and Wastes Association 5th Annual South Pacific Stormwater Conference: 17 p.

Tasman District Council (2010). Stormwater Best Practice Guide. Available at: http://www.tasman.govt.nz/environment/water/stormwater-and-the-environment/stormwater-best-practice-guide

Timperley, M.H. (1983). Phosphorus in spring waters of the Taupo volcanic zone, North Island. *New Zealand. Chemical Geology 38*: 287–306.

Vant, W.N. (ed.) (1987). Lake managers handbook, Water and Soil Miscellaneous Publication No 103. Ministry of Works and Development. Wellington. 230 p.

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

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

Viner, A.B. (1987). Inland waters of New Zealand. Edited by A.B. Viner. *Department of Scientific and Industrial Research Bulletin 241*. Wellington. 495 p.

Wetzel, R.G. (1975). Limnology. W.B. Saunders Company. Philadelphia. 743 p.

White, E.; Gibbs, M.M. (1991). The probable impact of discing the sediments of L. Horowhenua. A Taupo Research Laboratory DSIR Marine and Freshwater report to the Regional Conservator, Wellington Region, Department of Conservation, July 1991. 9 p.

White, E.; Payne, G.W. (1977). Chlorophyll production, in response to nutrient additions, of the algae in Lake Taupo water. *New Zealand Journal of Marine and Freshwater Research 11*: 501–507.

Zou, H.; Pan, G.; Chen, H.; Yuan, X. (2006). Removal of cyanobacterial blooms in Taihu Lake using local soils. II. Effective removal of *Microcystis aeruginosa* using local soils and sediments modified by chitosan. *Environmental Pollution 141*: 201–205.

# Appendix A Checklists for Guiding Principles

The following check lists contain a summary of key points that need to be considered during the development of an artificial lake. Their primary purpose is to assist the approval process. They cover:

Pre-development considerations under the Regional Plan or RMA: Is the artificial lake a permitted, controlled, restricted discretionary, discretionary, non-complying or prohibited activity in the region covered by the active plan.

Setting Consent Conditions including getting the appropriate paperwork in order. Check list 2 covers the site development and construction with a clear focus on safety. Check list 3 covers water quality considerations.

Design Guidance summarises the many factors that influence a lake and need to be considered when designing an artificial lake. The design guidance covers the three main types of lake: Shallow, Deep, and Quarries.

Details relative to these check lists will be found in the Guidelines text and prescribed in the local Regional Plan. Where there is no active Regional Plan for a region, the consent considerations default to the appropriate section of the RMA.

Note: Check list Part 1, Question 4 refers to the Building (Dam Safety) Act 2008 proposed amendments which are scheduled to come into effect in July 2014. Until they become law, the definition of a large dam is as defined in Question 3.

The inclusion of the new definitions of what constitutes a large dam in the proposed amendment to the Act is to inform developers and consenting authorities of the impending changes and to highlight critical changes to the wording of the legal definition.

- The present definition uses the word “**depth**” and is referring to the maximum depth of water retained by the dam, not the depth of water at the dam wall.
- The proposed definitions use the word “**height**” and are referring to the height of the dam structure from the toe to the crest.

For example, under the present definition, an off stream reservoir which has a volume of more than 20,000 $m^3$ with a dam wall less than 3 m high must be classified as a large dam if the maximum water depth in any part of the reservoir is greater than 3 m. Under the proposed amendments this would not be a large dam.

## **Artificial Lakes Check List: Part 1** (To assist the approval process)

Applies to all artificial lakes with an area of 1 ha or more

| | **PRE-DEVELOPMENT** | | **Requirements** |
|---|---|---|---|
| 1 | **What is the purpose of the artificial lake?** | | |
| | ☐ Water supply reservoir | | |
| | ☐ Irrigation reservoir | | |
| | ☐ Hydro power | | |
| | ☐ Water feature | | |
| | ☐ Other ________________ | | |
| 2 | **Is the artificial lake to be on stream or off stream** | | |
| | ☐ On stream | Defined as: | Dam across a permanently flowing stream |
| | ☐ Off stream | Defined as: | Dam across an intermittent stream |
| 3 | **Is the artificial lake to be a large dam as defined by the Building Act 2004** | | |
| | (Dam retains 3 or more metres depth and holds 20,000 or more cubic metres volume of water) | | |
| | ☐ Yes | | A building consent |
| | ☐ No | | Go to question No. 5 |
| 4 | **Is the artificial lake a large lake as defined under the Building (Dam Safety) Act 2008, July 2014 amendment** | | |
| | (Proposed 2014 amendment: Dam is 3 m or more high and holds a reservoir of at least 100,000 $m^3$ of water or 8 m or more high and holds a reservoir of at least 50,000 $m^3$ of water) | | |
| | ☐ Yes - Dam Safety Scheme applies | | Audited Dam Classification Certificate (DCC)<br>Potential Impact Classification (PIC) |
| 5 | **Are artificial lakes addressed in the active Regional Plan?** | | |
| | ☐ No - The RMA rules apply | | Continue below - tick one box |
| | ☐ Yes - The Regional Plan rules apply | | Continue below - tick one box |
| | ☐ Is this a permitted activity? | | No consent required |
| | ☐ Is this a controlled activity? | | Consent always approved |
| | ☐ Is this a restricted discretionary activity? | | Consent required |
| | ☐ Is this a discretionary activity? | | Consent required |
| | ☐ Is this a non-complying activity? | | Consent required |
| | ☐ Is this a prohibited activity? | | No consent will be issued |
| 6 | **Have neighbours, Iwi and other potentially affected parties been consulted?** | | |
| | ☐ Yes | | Signed letter(s) of approval |
| 7 | **Has a registered certified civil engineer approved the plan for the dam structure?** | | |
| | ☐ Yes | | Certified copy of plans |
| 8 | **Has the proposed site been checked against the register of land-fills and toxic waste dumps?** | | |
| | ☐ Yes | | Site plan showing nearest relevant dump site |
| 9 | **Has a Geotechnical report been provided for the site showing suitability of soils for dam construction and the location of any and all known local earthquake fault lines?** | | |
| | ☐ Yes | | Certified copy of report |
| 10 | **Is there sufficient legal and physical access to the site of the artificial lake?** | | |
| | ☐ Yes | | Site plan showing access and legal title |
| 11 | **Will the public have access to the artificial lake?** | | |
| | ☐ Yes | | Health & Safety Act 1992 applies. |
| 12 | **Will the use of the artificial lake for the stated purpose generate increased road traffic activity?** | | |
| | ☐ Yes | | Land Transport New Zealand approval |

## Artificial Lakes Check List: Part 2 (To assist the approval process)

Applies to all artificial lakes with an area of 1 ha or more

**SETTING CONSENT CONDITIONS** Consent conditions to consider:

**PLANNING APPROVAL**

13 **Does the project have planning approval for a resource consent?**

☐ Yes — Approved plans to be certified

14 **Has the design and appearance of the the structure been given Planning approval?**

☐ Yes — Approved plans to be certified

15 **Is there a site development plan for rehabilitation of the environment once the dam is complete?**

☐ Yes — Approved plans to be certified

16 **Does the project have approval from Land Transport New Zealand for access from public roads?**

☐ Yes — Written confirmation required

**SITE DEVELOPMENT AND CONSTRUCTION**

17 **Safety**

- ☐ Provide construction site safety instructions and hazard warnings to all site workers
- ☐ Maintain a hazards register for the duration of the site development and dam construction
- ☐ All hazards found on the site shall be recorded and appropriately notified
- ☐ No access for visitors to the construction site without approval and a site guide
- ☐ High visibility clothing and hard hats mandatory for all site workers and visitors
- ☐ All site workers to comply with safe work practice for their occupation and for the site

18 **Construction of access roads required to get to the site to build the dam**

- ☐ Where possible use existing roading - minimize new road cuts
- ☐ Provide sediment retension system for all surface runoff from roads

19 **Site clearance**

- ☐ Safety shall be paramount during all site clearance work
- ☐ No soil or vegetative debris shall be allowed to enter any natural water course from:
  - ☐ the site of the dam construction work
  - ☐ the footprint of the artificial lake

20 **Earthworks**

- ☐ Safety shall be paramount during all earthworks
- ☐ No soil or vegetative debris shall be allowed to enter any natural water course from the site

21 **Diversion of water courses**

- ☐ Safety shall be paramount during work on diverson of water courses
- ☐ Diversion of water courses shall comply with the approved site plan and schedule work

22 **Dam construction**

- ☐ Safety shall be paramount during all work on the dam construction
- ☐ The movement of heavy materials to be scheduled with Transport New Zealand
- ☐ Truck movements for debris removal, fill and concrete may need to be scheduled to avoid interruption of peak traffic flows on public roads
- ☐ Hours of construction may need to be restricted where noise will affect neighbours
- ☐ Hazards noted during dam construction will be mitigated by completion of the dam
- ☐ Hazards associated with sluice gates and hydraulic jumps will be fitted with appropriate signs and, where appropriate, security / safety screens are to be fitted

23 **Site rehabilitation**

- ☐ Safety shall meet the Health & Safety Act 1992 as they relate to open bodies of water
- ☐ The site shall be left free of waste material and debris, holes, pits, sumps and sudden drop-offs that are not readily visible

## Artificial Lakes Check List: Part 3 (To assist the approval process)

Applies to all artificial lakes with an area of 1 ha or more

| **SETTING CONSENT CONDITIONS** | Consent conditions to consider: |
|---|---|

24 What is the life expectancy of the dam in normal use?

| | |
|---|---|
| ☐ Less than 20 years | Decommissioning plan required |
| ☐ 20 years to 100 years | Maintenance schedule required |
| ☐ Greater than 100 years | Engineering reports and maintenance schedule |

**WATER QUALITY**

This assessment will require detailed information from the developer which may include an Assessment of Environmental Effects (AEE) report

25 **Is an AEE required?**

| | |
|---|---|
| ☐ Yes | Large deep lakes on rivers require an AEE<br>Would also benefit from use of predictive modelling |

26 **How will the proposed artificial lake be constructed and filled? (With reference to Q 1 and Q 2)**

| | |
|---|---|
| ☐ Dam across a permanently flowing stream | Minimum flow downstream<br>Periodic high flows to simulate storm events<br>Water quality in lake<br>Water quality of discharge water from lake<br>Provision of a fish pass |
| ☐ Dam across an intermittent stream | Dam affects on local groundwater flow |
| ☐ Raised bund on flat land | Water take limits to fill off-stream lake<br>Diversion structure in river<br>Safety around all control valves and gates |
| ☐ Excavated site in sub-division | Either exclusion of stormwater or for water quality management and litter control if stormwater included |
| ☐ Flooding a quarry | Pre-clean up of quarry to remove metal and rubbish |
| ☐ Other | As appropriate |
| | |

27 **Where will the water come from to fill an off-stream artificial lake?**

| | |
|---|---|
| ☐ Rainwater | |
| ☐ Groundwater | Groundwater take allocation |
| ☐ Permanently flowing stream/ river (Name) | Water take allocation |
| | Peak flow take for storage of flood flows |

28 **Will the artificial lake discharge water into a permanently flowing stream?**

| | |
|---|---|
| ☐ Yes | Discharge water quality including temperature, dissolved oxygen, nutrients (N & P), sediment<br>Algal species in discharge water<br>Fish species in discharge water<br>Macrophyte species in discharge water |

| | |
|---|---|
| 29 **Adverse effects on downstream environment** | Receiving water quality changes in a defined mixing zone below the discharge |
| ☐ Elevated temperatures in discharge water | Limit temperature increase and maximum (e.g. $< 3^{o}$C increase, up to a maximum temperature of $26^{o}$C) |
| ☐ Depleted oxygen concentrations | Limit oxygen depletion to minimum of (e.g., 5 g/m$^{3}$) |
| ☐ Water clarity | Limit water clarity change to maximum of (e.g., 40 NTU) |
| ☐ Water quality | Limits as set out in the Regional Plan |

**MONITORING**

The water quality in the artificial lake and receiving water will require some level of compliance monitoring to ensure that the conditions of the consent are met.

## Artificial Lakes Check List: Part 4 (To assist the design process)

Applies to all artificial lakes with an area of 1 ha or more

### DESIGN GUIDANCE

| **Factors affecting water quality in an artificial lake include** | **Parmeters to consider** |
|---|---|
| Size of the lake | (surface area, depth, volume) |
| Solar heating | (temperature and thermal stratification) |
| Morphometry | (shape of the lake basin) |
| Position in landscape | (shelter from or exposure to prevailing wind) |
| Position in the country | (altitude and latitude) |
| Rainfall | (longitude - East coast drier than West coast) |
| Residence time | (how often the artificial lake is flushed each year) |
| Catchment size | (nutrient and sediment runoff) |
| Nutrient input | (nitrogen, phosphorus and organic carbon loads) |
| Lake bed geology | (rock or sand or clay or silt or mud) |
| Plant community (native and invasive) | (macrophytes promote clearer water, no macrophytes low clarity and phytoplankton growth) |
| Fish species (exotic pest) | (rudd, tench destroy macrophyte beds; perch predate zooplankton allowing phytoplankton to grow; catfish and koi carp destabilise the sediments and macrophyte beds) |

**Catchment land-use will affect nutrient and sediment runoff into the artificial lake**

| | **Land-use** | **Expected nutrient and sediment production** |
|---|---|---|
| ☐ | Native forest | Low nutrient and sediment runoff |
| ☐ | Exotic production forest mature | Low nutrient low sediment runoff |
| ☐ | Exotic production forest clear-fell | Low nutrient but high sediment runoff |
| ☐ | Pasture (sheep) | Medium nutrients and medium sediment runoff |
| ☐ | Pasture (beef) | Medium nutrients, high sediment runoff on hills |
| ☐ | Pasture (Dairy) | High nutrients, medium-high sediment runoff |
| ☐ | Cropping (potatoes, corn/maize, cerials) | Medium nutrients, high sediment runoff |
| ☐ | Market gardening | High nutrients, very high sediment runoff |
| ☐ | Lifestyle blocks | Variable |
| ☐ | Parks, Golf courses | High nutrients, low sediment runoff |
| ☐ | Zoo enclosures | Very high nutirents, very high sediment runoff |
| ☐ | Urban (Street stormwater disposal) | High nutrients (P), high sediment if it enters lake |
| ☐ | Urban (Reticulated stormwater disposal) | Low to medium nutrients and sediment if not into lake |
| ☐ | Other | |

**Water quality will change over the year and between rainfall events**
**Detailed information for primary source water will help predictions of expected water quality in the lake**

| | | |
|---|---|---|
| Seasonal flows ($m^3$/s) | Max: | Min: |
| Seasonal temperatures (°C) | Max: | Min: |
| Summer temperatures (°C) | Daytime Max: | Daytime mean: |
| Suspended solids ($g/m^3$) or | Max: | Min: |
| Turbidity (NTU) | Max: | Min: |
| Nitrate-N ($mg/m^3$) | Max: | Annual mean: |
| Ammonium-N ($mg/m^3$) | Max: | Annual mean: |
| Total N ($mg/m^3$) | Max: | Annual mean: |
| Phosphate-P ($mg/m^3$) | Max: | Annual mean: |
| Total-P ($mg/m^3$) | Max: | Annual mean: |
| Chlorophyll *a* ($mg/m^3$) | Max: | Annual mean: |
| Dissolved oxygen ($g/m^3$) | Daytime Max: | Night time Min: |

**Most of these parameters should be monitored in the lake too**

Need to establish beaches, planted riparian buffer zones and, where required, public access (refer to Q11)

# Artificial Lakes Check List: Part 5 (To assist the design process)

Applies to all artificial lakes with an area of 1 ha or more

## DESIGN GUIDANCE

**Artificial lakes are either shallow or deep with the water depth having a large effect on in-lake processes**

### SHALLOW LAKES

See text details

**Natural valleys**

| | |
|---|---|
| Do not form stable thermal stratification | Sediment frequently disturbed by wind waves |
| Become very hot in summer | Discharge of hot water mitigated with shading along northern banks and around outflow<br>Need deeper cooler refugia for fish |
| Highly turbid without macrophytes | Resuspended sediment releases nutrients in pore water<br>Nutrients support phytoplankton growth |

Water quality will depend on the amount of organic matter left in the lake at the time of filling
Need appropriate fish passes
Exclude stormwater runoff or road runoff where-ever possible

**Off-stream irrigation reservoirs**

Formed by raising a bund to retain the water
Exclude stormwater runoff or road runoff where-ever possible
Design should allow for paired lakes where the water level in one can be manipulated to control filamentous algae or macrophytes while the other is still in use
Water supplied from a diversion system in a nearby river
Health & Safety issues around the diversion weir, sluice gates, and water transfer canals

### DEEP LAKES

See text for details

Water quality in first 5 years will depend on the amount of vegetation and organic matter left in the lake footprint at the tme of filling. Decomposition processes will cause oxygen depletion / anoxia.

| | |
|---|---|
| Form stable thermal stratification | Bottom water may become oxygen depleted and enriched with nutrients |
| Aeration can destratify the lake | Aerator bar across the lake bed near the dam wall |
| Bottom water aeration can reduce nutrients | Aerators below thermocline in mid-lake position |
| Near bottom outtake valves | Induced draw depth currents keep lake aerated at depth provided there is sufficient flow through the system |
| Temperature induced density currents | Carry sediment to bottom of dam wall |
| Low or variable through flow | Use multiple outtakes valve depths for good water quality<br>Outtake water can be blended from several valves |

Need to be designed to cope with 1-in-100 year floods
Need spillways and special fish passes
Design scenarios can be tested using predictive modelling

### QUARRIES

| | |
|---|---|
| Steep sided deep lakes | May have little vegetation to decompose |
| Will thermally stratify | Unlikely to mix each year |
| Coal mines will have unusual issues | Decomposition of residual coal will release sulphide which may cause fish kills when the lake mixes |

Aeration / destratification should be considered to maintain acceptable water quality.
Will have long residence times giving nutrients time to accumulate and recycle.
Prevent nutrients and sediments jetting out into the lake from inflows using planted buffer zones.

# Appendix B  RMA Section 13

The following information has been extracted from the Greater Wellington Regional Council web site: http://www.gw.govt.nz/finding-your-way-to-regional-rules-using-the-resource-management-act/

# Restrictions on certain uses of beds of lakes and rivers

## Section 13 of the Resource Management Act, 1991

Section 13 of the Act applies to the beds of rivers and lakes. The terms bed, river, and lake are defined in the Act.

Section 13 does not apply to riparian margins, artificial watercourses, river estuaries, or discharges to water.

- Rules about riparian margins are made under section 9 of the Act.
- Artificial watercourses are not rivers (by definition in the Act).
- Rules about water in a river or lake or in an artificial watercourse (such as damming and diverting water) are made under section 14 of the Act.
- River estuaries are part of the coastal marine area. Rules about disturbing the beds of river estuaries are made under section 12 of the Act.
- Discharges to water in rivers, lakes or artificial watercourses are controlled in section 15 of the Act .

The presumption of subsection 13 (1) is restrictive. This means that you must get a resource consent to do any of the activities described in this subsection unless they are specifically allowed by a regional rule.

The presumption of subsection 13 (2) is permissive. This means that you can do anything described in section 13 (2) as of right, unless it is specifically restricted by a regional rule.

We have grouped our regional rules into the sorts of activities that are described in subsections 13 (1) and (2) of the Act. These activities are:

- Section 13(1)(a) structures in, on, under or over the bed of a lake or river.
- Section 13(1)(b) excavation, drilling, tunnelling or disturbance of the bed of a lake or river.
- Section 13(1)(c) introduction of plants in, on, or under the bed of a lake or river.
- Section 13(1)(d) deposition of substances in, on, or under the bed of a lake or river.
- Section 13(1)(e) reclamation or drainage of the bed of a lake or river.
- Section 13(2)(a) entry or passage across the bed of any river or lake.
- Section 13(2)(b) disturbance, removal, damage, or destruction of any plant or part of any plant (whether exotic or indigenous) or the habitats of any such plants or of animals in, on, or under the bed of any lake or river.

Scroll down the screen to read more about the regional rules made under section 13 of the RMA.

## Structures in, on, under or over the bed of a lake or river

Structures in, on, under or over the bed of a lake or river are restricted by section 13 (1)(a) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (1)(a) of the Act is restrictive.

This means you must get a resource consent to use, erect, reconstruct, place, alter, extend, remove, or demolish any structure or part of any structure in, on, under, or over the bed of a river or lake unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Maintenance, repair, replacement, extensions, additions and alterations to structures (excluding extensions of linear rock protection and over-head cables) | Rule 22 | Permitted Activity |
| Extensions of existing linear rock protection | Rule 23 | Permitted Activity |
| Placement of vegetative bank protection structures | Rule 24 | Permitted Activity |
| Culverts, weirs, fords and small bridges in intermittently flowing streams | Rule 25 | Permitted Activity |
| Small dams | Rule 26 | Permitted Activity |
| Sediment retention weirs in intermittently flowing streams | Rule 27 | Permitted Activity |
| Laying pipes, ducts, and cables across intermittently flowing streams | Rule 28 | Permitted Activity |
| Staff gauges | Rule 29 | Permitted Activity |
| Fences | Rule 30 | Permitted Activity |
| Small bridges | Rule 31 | Permitted Activity |
| Overhead cables | Rule 32 | Permitted Activity |
| Removal or demolition of structures | Rule 33 | Permitted Activity |
| Activities in or on structures | Rule 34 | Permitted Activity |
| Maintenance, repair, replacement, extensions, additions and alterations to structures | Rule 43 | Controlled Activity |
| Removal or demolition of structures | Rule 44 | Controlled Activity |
| Cables | Rule 45 | Controlled Activity |
| Pipelines | Rule 46 | Controlled Activity |

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Culverts, weirs, fords, and bridges in rivers and streams | Rule 47 | Controlled Activity |
| Placement of impermeable erosion protection structures | Rule 48 | Controlled Activity |
| All remaining uses of river and lake beds | Rule 49 | Discretionary Activity |

## Excavation, drilling, tunnelling or disturbance of the bed of a lake or river

Excavation, drilling, tunnelling or disturbance of the bed of a lake or river is restricted by section 13 (1)(b) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (1)(b) of the Act is restrictive.

This means you must get a resource consent to excavate, drill, tunnel, or otherwise disturb the bed of a river or lake unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Clearance of flood debris from rivers and lakes | Rule 36 | Permitted Activity |
| "Beach" recontouring | Rule 37 | Permitted Activity |
| Minor sand and gravel extraction | Rule 38 | Permitted Activity |
| Maintenance of drains | Rule 39 | Permitted Activity |
| Urgent works | Rule 42 | Permitted Activity |
| All remaining uses of river and lake beds | Rule 49 | Discretionary Activity |

The following rules apply to any "associated disturbance" of the bed.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Urgent works | Rule 42 | Permitted Activity |
| Removal or demolition of structures | Rule 44 | Controlled Activity |

## Introduction of plants in, on, or under the bed of a lake or river

Introduction of plants in, on, or under the bed of a lake or river is restricted by section 13 (1)(c) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (1)(c) of the Act is restrictive.

This means you must get a resource consent to introduce or plant any plant or any part of any plant (whether exotic or indigenous) in, on, or under the bed of a river or lake unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Planting | Rule 41 | Permitted Activity |
| All remaining uses of river and lake beds | Rule 49 | Discretionary Activity |

## Deposition of substances in, on, or under the bed of a lake or river

Deposition of substances in, on, or under the bed of a lake or river is restricted by section 13 (1)(d) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of 13 (1)(d) of the Act is restrictive.

This means you must get a resource consent to deposit any substance in, on, or under the bed of a river or lake unless the activity is specifically allowed by a regional rule.

"Deposition of substances" is different from the discharge of contaminants, which are restricted by section 15 of the Act.

There is no specific rule relating to the deposition of substances in, on, or under the bed of any lake or river, but the rules below provide for any "associated deposition".

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Minor diversion of water from an intermittently flowing stream | Rule 9 | Permitted Activity |
| Maintenance, repair, replacement, extensions, additions and alterations to structures (excluding extensions of linear rock protection and overhead cables) | Rule 22 | Permitted Activity |
| Extensions of existing linear rock protection | Rule 23 | Permitted Activity |
| Placement of vegetative bank protection structures | Rule 24 | Permitted Activity |
| Removal or demolition of structures | Rule 33 | Permitted Activity |
| Urgent works | Rule 42 | Permitted Activity |

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Maintenance, repair, replacement, extensions, additions and alterations to structures | Rule 43 | Controlled Activity |
| Removal or demolition of structures | Rule 44 | Controlled Activity |
| Culverts, weirs, fords, and bridges in rivers and streams | Rule 47 | Controlled Activity |
| Placement of impermeable erosion protection structures | Rule 48 | Controlled Activity |
| All remaining uses of river and lake beds | Rule 49 | Discretionary Activity |

## Reclamation or drainage of the bed of a lake or river

Reclamation or drainage of the bed of a lake or river is restricted by section 13 (1)(e) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (1)(e) of the Act is restrictive.

This means you must get a resource consent to reclaim or drain the bed of a river or lake unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Reclamation of the beds of lakes or rivers, excluding Lake Wairarapa | Rule 50 | Non-complying Activity |
| Reclamation of the bed of Lake Wairarapa | Rule 51 | Prohibited Activity |

## Entry or passage across the bed of any river or lake

Entry or passage across the bed of any river or lake is allowed by section 13 (2)(a) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (2)(a) of the Act is permissive.

This means no resource consent is required to enter or pass across the bed of any river or lake unless the activity is specifically restricted by a regional rule. Note that allowing entry or passage does not allow "disturbance" of the bed (see section 13(1)(b) above).

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Entry or passage | Rule 35 | Permitted Activity |

## Disturbance, removal, damage, or destruction of any plant or part of any plant (whether exotic or indigenous) or the habitats of any such plants or of animals in, on, or under the bed of any lake or river

Disturbance, removal, damage, or destruction of any plant or part of any plant (whether exotic or indigenous) or the habitats of any such plants or of animals in, on, or under the bed of any lake or river is allowed by section 13 (2)(b) of the Resource Management Act and covered in the Regional Freshwater Plan. The presumption of section 13 (1)(e) of the Act is permissive.

This means no resource consent is required to disturb, remove, damage, or destroy any plant or part of any plant (whether exotic or indigenous) or the habitats of any such plants or of animals in, on, or under the bed of any lake or river unless the activity is specifically restricted by a regional rule.

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Removal of vegetation | Rule 40 | Permitted Activity |

# Appendix C RMA Section 14

The following information has been extracted from the Greater Wellington Regional Council web site : http://www.gw.govt.nz/finding-your-way-to-regional-rules-using-the-resource-management-act/

# Restrictions relating to water

## Section 14 of the Resource Management Act, 1991

Section 14 of the Act restricts all taking, use, damming and diverting water, and using heat or energy from water, including water in the coastal marine area. " Water" is defined in the Act, and includes all water, whether it is in a river, lake, artificial watercourse, wetland, an underground aquifer or the sea. Discharges to water are controlled in section 15 of the Act. Activities in the beds of rivers and lakes are controlled in section 13 of the Act.

The presumption of subsection 14 (1) is restrictive. This means that you must get a resource consent to do any of the activities described in this subsection unless they are specifically allowed by a regional rule.

The presumption of subsection 14 (2) is permissive. This means that you can do anything described in section 14 (2) as of right, unless it is specifically restricted by a regional rule.

We have grouped our regional rules into the sorts of activities that are described in subsections 14 (1) and (2) of the Act. These activities are

- Section 14(1)(a) taking, using, damming and diverting water (except open coastal water).
- Section 14(1)(b) taking, using, damming and diverting heat or energy from water (except open coastal water).
- Section 14(1)(c) taking, using, damming and diverting heat or energy from the material surrounding any geothermal water.
- Section 14(2)(a) taking, using, damming and diverting open coastal water.
- Section 14(2)(b) taking or using heat or energy from any open coastal water.

Scroll down to read the regional rules that have been adopted for each of these sections.

## Taking, using, damming and diverting water (except open coastal water)

Taking, using, damming and diverting water (except open coastal water) is restricted by section 14 (1)(a) of the Resource Management Act and covered in the Regional Freshwater Plan and the Regional Coastal Plan. The presumption of section 14 (1)(a) of the Act is restrictive.

This means you must get a resource consent to take, use, dam, or divert any water (other than open coastal water) unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Takes or uses of water (except in any river, stream, estuary or lake within the coastal marine area) | Rule 73 | Permitted Activity |
| Operational needs of ships (taking and using) | Rule 74 | Permitted Activity |
| Minor takes or uses from significant rivers or lakes in the coastal marine area | Rule 75 | Controlled Activity |
| Other taking, use, damming, or diversions of water outside any Areas of Significant Conservation Value | Rule 76 | Discretionary Activity |
| Other taking, use, damming, or diversion of water in Areas of Significant Conservation Value | Rule 77 | Non-complying Activity |

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Minor abstractions | Rule 7 | Permitted Activity |
| Damming and diversion of water by existing structures | Rule 8 | Permitted Activity |
| Minor diversion of water from an intermittently flowing stream | Rule 9 | Permitted Activity |
| Diversion of water from an artificial watercourse | Rule 9A | Permitted Activity |
| Diversion of groundwater | Rule 9B | Permitted Activity |
| Taking, use, damming or diversion of water, or the transfer to another site of any water permit to take or use water | Rule 16 | Discretionary Activity |
| Damming water in rivers with a high degree of natural character | Rule 17 | Non-complying Activity |
| Diverting water from wetlands with a high degree of natural character | Rule 18 | Non-complying Activity |

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Taking more than 32.85 million cubic metres per year water from the Lower Hutt Groundwater Zone | Rule 19 | Non-complying Activity |
| Minimum operating level for the Lower Hutt Groundwater Zone | Rule 20 | Standard |
| Minimum operating level for the Moroa Groundwater Zone | Rule 21 | Standard |

## Taking, using, damming and diverting heat or energy from water (except open coastal water)

Taking, using, damming and diverting heat or energy from water (except open coastal water) is restricted by section 14 (1)(b) of the Resource Management Act and covered in the Regional Freshwater Plan and the Regional Coastal Plan. The presumption of section 14 (1)(b) of the Act is restrictive.

This means you must get a resource consent to take, use, dam, or divert any heat or energy from water (other than open coastal water) unless the activity is specifically allowed by a regional rule.

There is no rule that specifically allows taking, using, damming or diverting heat or energy from water, so these activities will require a water permit.

## Taking, using, damming and diverting heat or energy from the material surrounding any geothermal water

Taking, using, damming and diverting heat or energy from the material surrounding any geothermal water is restricted by section 14 (1)(c) of the Resource Management Act and covered in the Regional Freshwater Plan and the Regional Coastal Plan. The presumption of section 14 (1)(c) of the Act is restrictive.

This means you must get a resource consent to take, use, dam, or divert any heat or energy from the material surrounding any geothermal water unless the activity is specifically allowed by a regional rule.

There is no rule that specifically allows taking, using, damming and diverting heat or energy from the material surrounding any geothermal water, so these activities will require a water permit.

## Taking, using, damming and diverting open coastal water

Taking, using, damming and diverting open coastal water is allowed by section 14 (2)(a) of the Resource Management Act and covered in the Regional Coastal Plan. The presumption of this section of the Act is permissive.

This means no resource consent is required to take, use, dam, or divert any open coastal water unless the activity is specifically restricted by a regional rule.

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Takes or uses of water (except in any river, stream, estuary lake within the coastal marine area) | Rule 73 | Permitted Activity |
| Operational needs of ships (taking and using) | Rule 74 | Permitted Activity |

## Take or use any heat or energy from any open coastal water

Taking or using heat or energy from any open coastal water is allowed by section 14 (2)(b) of the Resource Management Act and covered in the Regional Coastal Plan. The presumption of this section of the Act is permissive.

This means no resource consent is required to take or use any heat or energy from any open coastal water unless the activity is specifically restricted by a regional rule. There are no rules about taking or using heat or energy from any open coastal water in the Regional Coastal Plan.

# Appendix D RMA Section 15

The following information has been extracted from the Greater Wellington Regional Council web site: http://www.gw.govt.nz/finding-your-way-to-regional-rules-using-the-resource-management-act/

## Discharges to the environment

### Section 15 of the Resource Management Act, 1991

Section 15 of the Act restricts the discharge of water or contaminants to water, including water in the coastal marine area, and restricts the discharge of contaminants to land or air. The taking, use, damming and diverting of water is controlled in section 14 of the Act, and the disturbance of the bed of any river or lake is controlled in section 13 of the Act.

The presumption of subsection 15 (1) is restrictive. This means that you must get a resource consent to do any of the activities described in this subsection unless they are specifically allowed by a regional rule.

The presumption of subsection 15 (2) is permissive. This means that you can do anything described in section 15 (2) as of right, unless it is specifically restricted by a regional rule.

We have grouped our regional rules into the sorts of activities that are described in subsections 15 (1) and (2) of the Act. These activities are:

- Section 15(1)(a) discharging contaminants to water (including water in the coastal marine area).
- Section 15(1)(b) discharging contaminants to land where they may enter water.
- Section 15(1)(c) discharging contaminants to air from industrial or trade premises.
- Section 15(1)(d) discharging contaminants to land from industrial or trade premises.
- Section 15(2) discharging contaminants to land or air other than at industrial or trade premises.

The Ministry for the Environment's National Environmental Standards for air quality also restrict some discharges of contaminants to air. These can be viewed from this site.

Scroll down to read the regional rules that have been adopted for each of these sections.

### Discharges to water

Discharges to water are restricted by section 15 (1)(a) of the Resource Management Act and covered in the Regional Freshwater Plan and the Regional Coastal Plan. The presumption of section 15 (1)(a) of the Act is restrictive.

This means you must get a resource consent to discharge any contaminant, or water, into water, including coastal water, unless the activity is specifically allowed by a regional rule.

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Stormwater | Rule 53 | Permitted Activity |
| Operational needs of ships | Rule 54 | Permitted Activity |
| Other discharges from ships | Rule 55 | Permitted Activity |

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Other discharges of water | Rule 56 | Permitted Activity |
| Discharges (other than human sewage) with significant adverse effects outside any Area of Significant Conservation Value | Rule 57 | Discretionary and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) outside any Area of Significant Conservation Value | Rule 58 | Discretionary and Restricted Coastal Activity |
| Discharges (other than human sewage) with significant adverse effects within any Area of Significant Conservation Value | Rule 59 | Non-complying and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) within any Area of Significant Conservation Value | Rule 60 | Non-complying and Restricted Coastal Activity |
| Other activities involving discharges to land and water outside Areas of Significant Conservation Value | Rule 61 | Discretionary Activity |
| Other activities involving discharges to land and water in Areas of Significant Conservation Value | Rule 62 | Non-complying Activity |

| Type of activity (Regional Freshwater Plan) | Rule | Classification |
|---|---|---|
| Discharges of water and minor contaminants [affected by plan change] | Rule 1 | Permitted Activity |
| Stormwater discharges [affected by plan change] | Rule 2 | Permitted Activity |
| Stormwater discharges | Rule 3 | Controlled Activity |
| Discharges to groundwater which are contaminated only by heat | Rule 4 | Controlled Activity |
| All remaining discharges to fresh water | Rule 5 | Discretionary Activity |
| Discharges to wetlands, lakes and rivers, with surface water to be managed in its natural state | Rule 6 | Non-complying Activity |

# Discharging contaminants to land where they may enter water

Discharging contaminants to land in circumstances which may result in that contaminant (or any other contaminant emanating as a result of natural processes from that contaminant) entering water is restricted by section 15 (1)(b) of the Resource Management Act and covered in the Regional Plan for Discharges to Land and the Regional Coastal Plan. The presumption of section 15 (1)(b) of the Act is restrictive.

This means you must get a resource consent to discharge any contaminant onto or into land in circumstances which may result in that contaminant (or any other contaminant emanating as a result of natural processes from that contaminant) entering water, unless the activity is specifically allowed by a regional rule.

| **Type of activity (Regional Coastal Plan)** | **Rule** | **Classification** |
|---|---|---|
| Stormwater | Rule 53 | Permitted Activity |
| Operational needs of ships | Rule 54 | Permitted Activity |
| Other discharges from ships | Rule 55 | Permitted Activity |
| Other discharges of water | Rule 56 | Permitted Activity |
| Discharges (other than human sewage) with significant adverse effects outside any Area of Significant Conservation Value | Rule 57 | Discretionary and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) outside any Area of Significant Conservation Value | Rule 58 | Discretionary and Restricted Coastal Activity |
| Discharges (other than human sewage) with significant adverse effects within any Area of Significant Conservation Value | Rule 59 | Non-complying and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) within any Area of Significant Conservation Value | Rule 60 | Non-complying and Restricted Coastal Activity |
| Other activities involving discharges to land and water outside Areas of Significant Conservation Value | Rule 61 | Discretionary Activity |
| Other activities involving discharges to land and water in Areas of Significant Conservation Value | Rule 62 | Non-complying Activity |
| **Type of activity (Regional Plan for Discharges to Land)** | **Rule** | **Classification** |
| Discharges into or onto land not otherwise provided for by a rule in the Plan | Rule 2 | Discretionary Activity |

|  |  |  |
|---|---|---|
| Stormwater and reticulation systems [affected by plan change] | Rule 3 | Permitted Activity |
| Greywater | Rule 4 | Permitted Activity |
| Pit latrines | Rule 5 | Permitted Activity |
| Aerobically treated sewage | Rule 6 | Permitted Activity |
| On-site sewage onto or into land | Rule 7 | Permitted Activity |
| All other discharges of human effluent | Rule 8 | Discretionary Activity |
| Domestic and farm waste disposal and composting | Rule 9 | Permitted Activity |
| All other refuse disposal including at landfills, rubbish dumps and tips | Rule 10 | Discretionary Activity |
| Offal pits and silage | Rule 11 | Permitted Activity |
| Fertiliser | Rule 12 | Permitted Activity |
| Effluent from dairy sheds, piggeries, poultry farms, etc. | Rule 13 | Controlled Activity |
| Stock dip effluent | Rule 14 | Permitted Activity |
| Specified hazardous substances | Rule 15 | Non-complying Activity |
| Land-based applications of pesticides as solids or pastes | Rule 16 | Permitted Activity |
| Aerial applications of pesticides as solids or pastes | Rule 17 | Controlled Activity |
| Discharges associated with roading and other sealed areas | Rule 18 | Permitted Activity |
| **Type of activity (Regional Coastal Plan)** | **Rule** | **Classification** |
| Water treatment plant waste | Rule 19 | Controlled Activity |
| Waste oil | Rule 20 | Discretionary Activity |

| | | |
|---|---|---|
| On-site discharges from contaminated sites | Rule 21 | Permitted Activity |
| Removal of material from contaminated sites | Rule 22 | Controlled Activity |

## Discharging contaminants to air from industrial or trade premises

Discharging contaminants to air from industrial or trade premises is restricted by section 15 (1)(c) of the Resource Management Act and covered in the Regional Air Quality Management Plan and the Regional Coastal Plan. The presumption of section 15 (1)(c) of the Act is restrictive.

This means you must get a resource consent to discharge any contaminant from any industrial or trade premises into air unless the activity is specifically allowed a regional rule. Some rules in the Regional Air Quality Management Plan apply only to discharges from industrial or trade premises, some apply regardless of the type of premises.

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Operational needs of ships | Rule 63 | Permitted Activity |
| Operational needs of the port | Rule 64 | Permitted Activity |
| Construction and maintenance of structures | Rule 65 | Permitted Activity |
| Venting of drainage systems | Rule 66 | Permitted Activity |
| Flaring of hydrocarbons | Rule 67 | Permitted Activity |
| Discharge of human sewage (except from vessels) outside any Area of Significant Conservation Value | Rule 68 | Discretionary and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) within any Area of Significant Conservation Value | Rule 69 | Non-complying and Restricted Coastal Activity |
| Open burning of cables, cars etc. | Rule 70 | Prohibited Activity |
| Discharges from industrial or trade premises outside Areas of Significant Conservation Value | Rule 71 | Discretionary Activity |
| **Type of activity (Regional Coastal Plan)** | **Rule** | **Classification** |
| Discharges to air in areas of Significant Conservation Value | Rule 72 | Non-complying Activity |

| Type of activity (Regional Air Quality | Rule | Classification |
|---|---|---|

| **Management Plan)** | | |
|---|---|---|
| Agrichemical spray and powder application (land based) | Rule 1 | Permitted Activity |
| Agrichemical spray and powder application (aerial application) | Rule 2 | Permitted Activity |
| Fumigation | Rule 3 | Permitted Activity |
| Agricultural effluent and other on-farm processes [affected by plan change] | Rule 4 | Permitted Activity |
| Processing of animal and plant matter | Rule 5 | Permitted Activity |
| Small combustion engines, heating and electrical generation processes | Rule 6 | Permitted Activity |
| Medium sized combustion engines, heating and electrical generation processes | Rule 7 | Controlled Activity |
| Processing, storage and transfer and flaring of hydrocarbons and biogas | Rule 8 | Permitted Activity |
| Fuel conversion processes | Rule 9 | Discretionary Activity |
| Mineral extraction and the sorting and storage of powdered and bulk products [affected by plan change] | Rule 10 | Permitted Activity |
| The drying and heating of minerals | Rule 11 | Permitted Activity |
| Metal production and processing | Rule 12 | Permitted Activity |
| Chemical processes | Rule 13 | Permitted Activity |
| Use of small quantities of di-isocyanates or organic plasticisers | Rule 14 | Permitted Activity |
| **Type of activity (Regional Coastal Plan)** | **Rule** | **Classification** |
| Coating processes, including spray painting | Rule 15 | Permitted Activity |
| Abrasive blasting processes (mobile and stationary) | Rule 16 | Permitted Activity |

| | | |
|---|---|---|
| Cooling towers/ventilation | Rule 17 | Permitted Activity |
| Burn-offs and burning associated with land clearance | Rule 18 | Permitted Activity |
| Burning not associated with land clearance | Rule 19 | Permitted Activity |
| Landfilling and composting | Rule 20 | Permitted Activity |
| Sewage and trade waste conveyance and treatment processes | Rule 21 | Permitted Activity |
| Miscellaneous processes (permitted activities) | Rule 22 | Permitted Activity |
| General rule (discretionary activity) | Rule 23 | Discretionary Activity |

## Discharging contaminants to land from industrial or trade premises

Discharging contaminants to land from industrial or trade premises is restricted by section 15 (1)(d) of the Resource Management Act and covered in the Regional Plan for Discharges to Land and the Regional Coastal Plan. The presumption of section 15 (1)(d) of the Act is restrictive.

This means you must get a resource consent to discharge any contaminant from any industrial or trade premises onto or into land unless the activity is specifically allowed by one of the regional rules below. The rules in the Regional Plan for Discharges to Land and the Regional Coastal Plan have been included here because they apply to all premises, not only industrial or trade premises.

| Type of activity (Regional Plan for Discharges to Land) | Rule | Classification |
|---|---|---|
| Discharges not entering water in a river, lake, wetland, farm drain, water supply race or aquifer | Rule 1 | Permitted Activity |
| Discharges into or onto land not otherwise provided for by a rule in the Plan | Rule 2 | Discretionary Activity |
| Stormwater and reticulation systems [affected by plan change] | Rule 3 | Permitted Activity |
| **Type of activity (Regional Plan for Discharges to Land)** | **Rule** | **Classification** |
| Grey water | Rule 4 | Permitted Activity |
| Pit latrines | Rule 5 | Permitted Activity |

| | | |
|---|---|---|
| Aerobically treated sewage | Rule 6 | Permitted Activity |
| On-site sewage onto or into land [affected by plan change] | Rule 7 | Permitted Activity |
| All other discharges of human effluent | Rule 8 | Discretionary Activity |
| Domestic and farm waste disposal and composting | Rule 9 | Permitted Activity |
| All other refuse disposal including at landfills, rubbish dumps and tips | Rule 10 | Discretionary Activity |
| Offal pits and silage | Rule 11 | Permitted Activity |
| Fertiliser | Rule 12 | Permitted Activity |
| Effluent from dairy sheds, piggeries, poultry farms, etc. | Rule 13 | Controlled Activity |
| Stock dip effluent | Rule 14 | Permitted Activity |
| Specified hazardous substances | Rule 15 | Non-complying Activity |
| Land-based applications of pesticides as solids or pastes | Rule 16 | Permitted Activity |
| Aerial applications of pesticides as solids or pastes | Rule 17 | Controlled Activity |
| Discharges associated with roading and other sealed areas | Rule 18 | Permitted Activity |
| Water treatment plant waste | Rule 19 | Controlled Activity |
| Waste oil | Rule 20 | Discretionary Activity |

| Type of activity (Regional Plan for Discharges to Land) | Rule | Classification |
|---|---|---|
| On-site discharges from contaminated sites | Rule 21 | Permitted Activity |
| Removal of material from contaminated sites | Rule 22 | Controlled Activity |

# Discharging contaminants to land or air other than at industrial or trade premises

Discharging contaminants to land or air other than at industrial or trade premises is allowed by section 15 (2) of the Resource Management Act and covered in the Regional Air Quality Management Plan, the Regional Plan for Discharges to Land and the Regional Coastal Plan. The presumption of section 15 (2) of the Act is permissive.

This means no resource consent is required to discharge any contaminant into the air, or into or onto land, from any place, or any other source, whether moveable or not, unless the activity is specifically restricted by a regional rule.

The rules included here apply to all premises, regardless of whether they are industrial or trade premises.

| Type of activity (Regional Plan for Discharges to Land) | Rule | Classification |
|---|---|---|
| Discharges not entering water in a river, lake, wetland, farm drain, water supply race or aquifer | Rule 1 | Permitted Activity |
| Discharges into or onto land not otherwise provided for by a rule in the Plan | Rule 2 | Discretionary Activity |
| Stormwater and reticulation systems [affected by plan change] | Rule 3 | Permitted Activity |
| Grey water | Rule 4 | Permitted Activity |
| Pit latrines | Rule 5 | Permitted Activity |
| Aerobically treated sewage | Rule 6 | Permitted Activity |
| On-site sewage onto or into land | Rule 7 | Permitted Activity |
| All other discharges of human effluent | Rule 8 | Discretionary Activity |
| Domestic and farm waste disposal and composting | Rule 9 | Permitted Activity |
| All other refuse disposal including at landfills, rubbish dumps and tips | Rule 10 | Discretionary Activity |
| Offal pits and silage | Rule 11 | Permitted Activity |
| Fertiliser | Rule 12 | Permitted Activity |
| Effluent from dairysheds, piggeries, poultry farms, etc. | Rule 13 | Controlled Activity |

| Type of activity (Regional Plan for Discharges to Land) | Rule | Classification |
|---|---|---|
| Stock dip effluent | Rule 14 | Permitted Activity |
| Specified hazardous substances | Rule 15 | Non-complying Activity |
| Land-based applications of pesticides as solids or pastes | Rule 16 | Permitted Activity |
| Aerial applications of pesticides as solids or pastes | Rule 17 | Controlled Activity |
| Discharges associated with roading and other sealed areas | Rule 18 | Permitted Activity |
| Water treatment plant waste | Rule 19 | Controlled Activity |
| Waste oil | Rule 20 | Discretionary Activity |
| On-site discharges from contaminated sites | Rule 21 | Permitted Activity |
| Removal of material from contaminated sites | Rule 22 | Controlled Activity |

| Type of activity (Regional Coastal Plan) | Rule | Classification |
|---|---|---|
| Operational needs of ships | Rule 63 | Permitted Activity |
| Operational needs of the port | Rule 64 | Permitted Activity |
| Construction and maintenance of structures | Rule 65 | Permitted Activity |
| Venting of drainage systems | Rule 66 | Permitted Activity |
| Flaring of hydrocarbons | Rule 67 | Permitted Activity |
| Discharge of human sewage (except from vessels) outside any Area of Significant Conservation Value | Rule 68 | Discretionary and Restricted Coastal Activity |
| Discharge of human sewage (except from vessels) within any Area of Significant Conservation Value | Rule 69 | Non-complying and Restricted Coastal Activity |

| Type of activity (Regional Plan for Discharges to Land) | Rule | Classification |
|---|---|---|
| Open burning of cables, cars etc. | Rule 70 | Prohibited Activity |
| Discharges from industrial or trade premises outside Areas of Significant Conservation Value | Rule 71 | Discretionary Activity |
| Discharges to air in areas of Significant Conservation Value | Rule 72 | Non-complying Activity |

| Type of activity (Regional Air Quality Management Plan) | Rule | Classification |
|---|---|---|
| Agrichemical spray and powder application (land based) | Rule 1 | Permitted Activity |
| Agrichemical spray and powder application (aerial application) | Rule 2 | Permitted Activity |
| Fumigation | Rule 3 | Permitted Activity |
| Agricultural effluent and other on-farm processes [affected by plan change] | Rule 4 | Permitted Activity |
| Small internal or external combustion engines, heating appliances and electrical generation plants | Rule 6 | Permitted Activity |
| Medium sized internal or external combustion engines, heating appliances and electrical generation plants | Rule 7 | Controlled Activity |
| Use of small quantities of di-isocyanates, or organic plasticisers | Rule 14 | Permitted Activity |
| Coating processes, including spray painting | Rule 15 | Permitted Activity |
| Abrasive blasting processes (mobile and stationary) | Rule 16 | Permitted Activity |
| Burn-offs and burning associated with land clearance | Rule 18 | Permitted Activity |

| Type of activity (Regional Air Quality Management Plan) | Rule | Classification |
|---|---|---|
| Burning not associated with land clearance | Rule 19 | Permitted Activity |
| Landfilling and composting | Rule 20 | Permitted Activity |
| Sewage and trade waste conveyance, treatment and disposal | Rule 21 | Permitted Activity |

# Appendix E Hazard associated with bottom opening weirs

## New Zealand Herald 20 January 2012.

### Teen drowns when caught against river gate

A young woman who drowned at a popular Canterbury swimming spot is thought to have been pinned against a gateway by fast-flowing water.

The 18-year-old was swimming with friends in an irrigation waterway in the Waimakariri River about 1.30pm on Wednesday when she became trapped against the gateway, which feeds a water storage pond.

Selwyn District Council chief executive Paul Davey said her friends tried to save her but the current was too strong.

A council contractor arrived in about 15 minutes and opened the gate to release her body, which was recovered downstream.

Mr Davey said the waterway, which is near Kirwee in the Selwyn district, was considered safe and had been used by swimmers for many years.

"However, like any river there are significant flow variations and at times of higher flow things can get a lot different."

The council was considering what to do to prevent deaths.

"We've got a problem with warning signs because when we put them up they get vandalised because it's a highly trafficked area and a very popular recreational site, so we're thinking about whether we need to put up more robust signage that will withstand the rigours of vandalism.

"We can't stop people from swimming in rivers. What we need to do is just to show them the risk of rivers in higher flow because they're a much more dangerous beast than when they're flowing normally."

There was already a warning sign about 100 metres from where the young woman drowned, he said.

Council engineers were looking at whether there needed to be structural alterations to the waterway.

"We've also got to remember that this is an important economic waterway for wider Canterbury and we've got to make sure that we don't limit our ability to service the farmers who rely heavily on this water source."

But it was important to make sure no other swimmers drowned. — *APNZ*

The young woman's friends tried to save her but the flow pushed her against the gate on the Waimakariri River.

NZ Herald 20 Jan 2012

# Appendix F Fish kills

### Waikato Times 18 Feb 2011.

Lowering the level of a lake can be used to kill macrophyte weeds but if the level is left down long enough for terrestrial plants to grow, decomposition processes that occur when those plants are submerged can cause oxygen depletion that may be severe enough to kill fish (Waikato Times, 18 February 2011).

www.waikatotimes.co.nz REGION

18 Feb 2011, p5

## Masses of wetlands fish die

Recent heavy rains and artificially adjusted water levels at Whangamarino have resulted in a huge number of fish deaths. **Tony Stevens** reports.

Hundreds of thousands of fish were found dead in the Whangamarino Wetland, near Te Kauwhata, last week.

The fish were killed by low levels of dissolved oxygen in the water, according to the Conservation Department.

DOC spokesman Kevin Hutchinson said numerous reports had come in from residents and wetland users about the deaths, numbering possibly in the hundreds of thousands. Though most were pest fish such as koi carp and catfish, native species mullet, bullies and eels had also been found dead.

"The drought at the end of 2010 exposed large areas of the wetland and rapid plant growth occurred in areas usually under water," Mr Hutchinson said. "High rainfall in January, compounded by the baked dry ground in the catchment, meant water rapidly ran off into the wetland and water levels remained consistently high for about three consecutive weeks."

Mr Hutchinson said resulting decomposing plant matter started a bacterial process which depleted oxygen in the water.

"This was shown further by the layer of oily scum present on the surface of the water, which was natural oils released by decomposing plants, the dark black colour of the water and the soft, wilting emergent vegetation starting to break down," he said. "The decomposition is also identifiable by an unpleasant smell, very similar to that from a compost bin."

But a wetland resident, who did not want to be named, said the decomposition smelled more like sewage: "I have lived here since the 50s and I have never seen anything this bad before," he said. "It's an environmental disaster. This wetland is dying."

Mr Hutchinson said water levels in the wetlands were kept higher than the natural level during the recent big-rain events by the operation of established regional flood control measures.

"Things are unlikely to improve until either the water level drops right down, exposing the wetland floor, or we get another significant rainfall event flushing the water through the wetland system," Mr Hutchinson said.

"This event has a positive side with the removal of a large amount of pest fish biomass. However, largescale fish diebacks have been known to cause negative impacts on some bird populations, for example shags and heron."

The department said the event was natural but was compounded by the artificial manipulation of water levels.

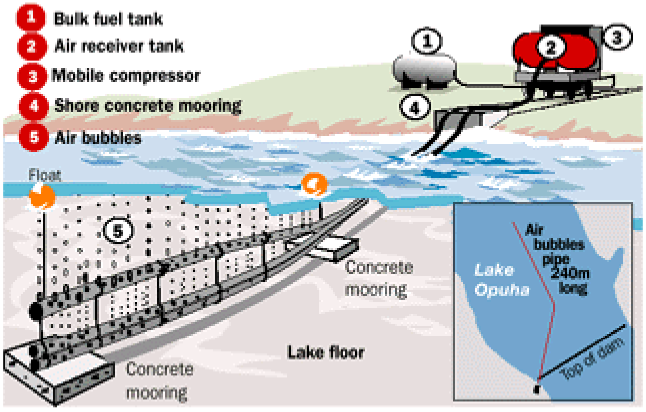
**Mass death:** Hundreds of dead fish lie decomposing on the wetland fringes.

# Appendix G  Opuha Dam Aeration

### New Zealand Herald 17 October 2003.

## Air pump urged to help dying lakes

5:00 AM Friday Oct 17, 2003



Herald graphic / Gary Roberts

By JO-MARIE BROWN

Engineers who have designed an aeration system to improve the water quality of a South Island lake believe the technology could be used to save Lake Rotoiti.

From tomorrow, thousands of bubbles will be blown into the bottom waters of Lake Opuha, 15km north of Fairlie, to restore oxygen levels. This will limit the amount of nutrients available for algal growth.

The bottom waters of several lakes in the central North Island, including Rotoiti, are also starved of oxygen in summer.

In those conditions, phosphorus is released from the sediments, allowing toxic blue-green algal blooms to flourish.

Harrison Grierson's director of engineering, Colin Cranfield, said the aeration system was designed to mix Lake Opuha up so that its cooler waters - which normally stratify in summer and remain on the bottom - reach the surface and absorb oxygen from the atmosphere.

"The air bubbles will force their way up to the surface and in doing so they induce currents in the water body itself," Mr Cranfield said.

"It's slow and it takes a while for the momentum to develop but once it's under way it doesn't require much energy at all to keep it going."

Lake Opuha was created in 1998 when a dam and power station were built for electricity and farm irrigation.

Mr Cranfield said the lakebed was rich in nutrients and the water quality had begun to deteriorate - although not to the extent seen in Rotorua's lakes.

"I think the important thing to note from Rotoiti's perspective is that if the decision was made [to install an aeration system], it can be put together in a matter of a few months."

But Professor David Hamilton, who is leading scientific research into the state of Rotorua's lakes, said artificial aeration was unlikely to work on a lake the size of Rotoiti.

Aside from high running costs, there was a risk that more algal blooms could occur if nutrients were stirred up from the sediments and rose to the surface with the oxygen-depleted water.

"I wouldn't discount it as an option at this stage but I would say it's highly unlikely to be feasible."

An alternative for Rotoiti would involve injecting liquid oxygen into the lake's bottom waters to restore oxygen levels without mixing the lake, Professor Hamilton said.

"The idea is that the liquid oxygen will hopefully dissolve completely in the water without the formation of bubbles."

Environment Bay of Plenty's Paul Dell, who is co-ordinating efforts to save Rotorua's lakes, said both techniques had been used here and around the world.

# Appendix H Integrated tube sampler

For Lake Horowhenua with a maximum depth of 1.6 m and being sampled from a small boat, the integrated tube sampler consists of a 1.8 m length of ~20 mm diameter **transparent flexible** plastic (PVC) tube (Figure H-1). Considered vertically, the top is trimmed to be a smooth right-angled end and fitted with a plastic plumping ball-valve which can close the tube with a $90^{o}$ turn. A length of cord is tied around the tube just below the tap leaving about 2 m of free end – this is the safety tether. Another length of cord is run the full length of the tube to the bottom, leaving about a metre spare at each end – this is the retrieval cord. The lower end of the cord is tied through one small hole drilled through the wall of the tube just above the bottom so that the cord has minimal effect on the inside diameter of the tube. The remaining free end of this cord is tied to a lead weight (e.g., one or two 8 oz. fishing sinker(s) or equivalent) so that the weight hangs about 20 cm below the bottom end of the tube. Allow enough length to accommodate soft sediment so that if the weight sinks into the sediment, the bottom end of the tube is still 20 cm above the lake bed. (Trial and error first time only). Tie a small plastic float to the top end of the long retrieval cord so that it can be easily recovered if it falls out of the boat. Before and after use, wash the tube thoroughly with tap water and store it out of sunlight.

The integrated sample is ready to use. A 5-litre sample bottle and a funnel with a wide spout that will fit into the sample bottle are also needed.

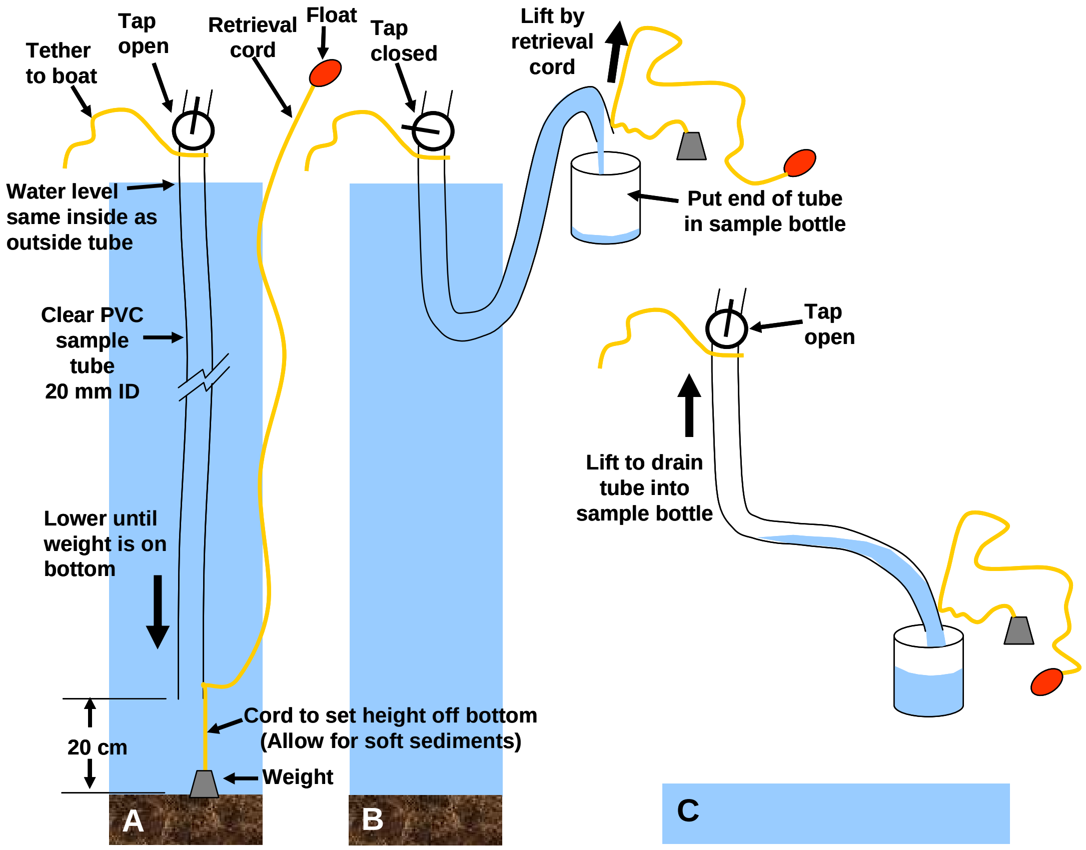


**Figure H-1: Integrated tube sampler operation schematic.** A) collecting sample, B) retrieving sample, and C) transferring sample to sample bottle. See text for details.

Operating the integrated tube sampler on the boat is as follows:

1. Rinse all sampling gear and the sample bottle with surface lake water.
2. **Open the tap** and tie the safety tether cord to the boat leaving plenty of slack line.
3. Lower the weighted end of the tube slowly through the water column **so that the water level inside the tube remains at the same level as the water outside the tube**. (Figure H-1 A).
4. Stop when the tube feels lighter as the weight reaches the lake bed. The bottom end of the tube will be within 20 cm of the lake bed.
5. **Close the tap** and let the tap end lie in the bottom of the boat.
6. Use the retrieval cord to lift the bottom end of the tube to the surface and immediately put the bottom end of the tube in the sample bottle (Figure H-1 B).
7. Raise the top end of the tube above the rest of the tube before **opening the tap**.
8. Drain the water into the sample bottle (Figure H-1 C).
9. Repeat steps 3 to 8 twice more to collect three integrated tube samples and combine them in the sample bottle to form a composite sample.
10. Mix well before filling the sample bottle via the funnel.

If more than one site is being sampled, unless spatial differences are required water from all sites can be combined in the bucket before filling the sample bottle. A composite sample from all sites would be appropriate for Lake Horowhenua as being more representative of the whole lake for the TLI estimate.

To prevent the spread of nuisance algal species, the integrated tube sampler for Lake Horowhenua should not be used on any other lake.

For deeper lakes, the integrated tube sampler can be adjusted to suit by using a longer tube. However, there is a limitation to the length of 20 mm diameter tube that can be handled comfortably (and safely) in a small boat. To sample greater depths greater than 15 m, it is recommended that a messenger-closing water sampler e.g., van Dorne bottle is used to take discrete samples at fixed depths.