LAKE BENMORE WATER QUALITY: A MODELLING METHOD TO ASSIST WITH SETTING LIMITS FOR SUSTAINABLE IRRIGATION DEVELOPMENT

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ABSTRACT

While irrigation can bring many benefits to communities, intensifying land use also causes more contaminants, such as nutrients, to enter rivers, lakes and groundwater. Unless managed carefully, this can result in cumulative adverse effects on water quality and environmental values. For lakes, such as Lake Benmore, this could mean irreversible degradation of clarity, colour and biological processes, as well as effects on ecological, recreational, commercial and tourism values. Defining the capacity of waterways to assimilate contaminants and establishing sustainable limits for water quality are recognised as key requirements for effective management (e.g., Government's New Start for Freshwater). We undertook a modelling study to provide statutory water managers Environment Canterbury with a series of options for: i) measurable planning objectives for water quality in Lake Benmore, and ii) the associated catchment nutrient load limits needed to achieve each of the objective options. The modelling study allowed science to inform the decision-making process by describing the environmental consequences of a series of options. The choice between options is beyond the role of science because it requires a value judgement that takes into account social, cultural and economic, as well as environmental consequences. However once a decision is made, setting objectives and nutrient load limits for Lake Benmore could establish a scientifically robust 'line in the sand' for managing cumulative water quality effects and allowing sustainable irrigation in the upper Waitaki catchment.

KEYWORDS

Water quality, resource management, cumulative effects, measurable objectives, irrigation

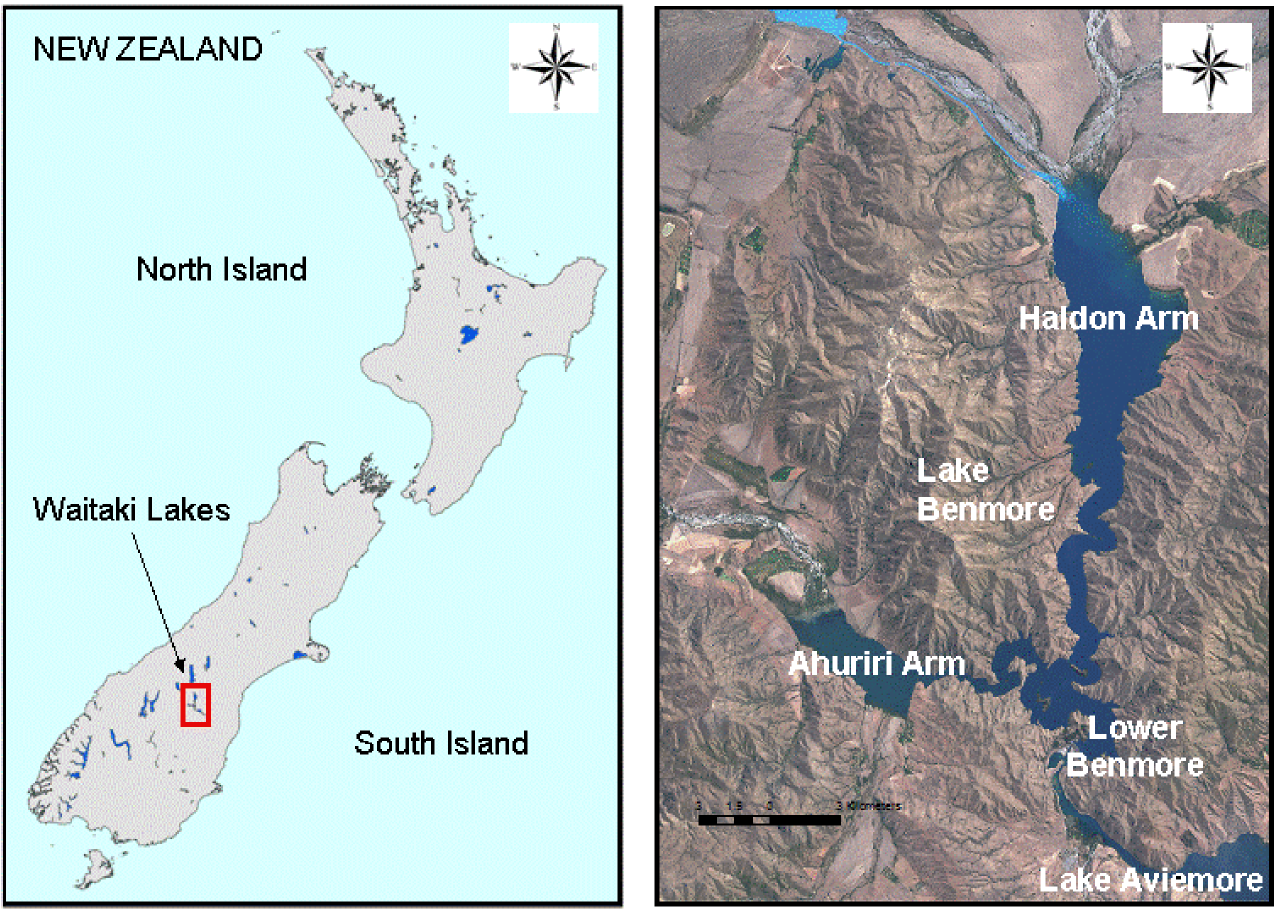
1 INTRODUCTION

This paper describes an example of how science can be used to assist with resource management problems; in this case, managing the cumulative effects of land use intensification on water quality. The paper does not focus on technical detail of the modelling method or underlying science. Instead, the intention is to: i) define the problem in resource management terms; ii) clarify the roles of science and decision-maker; iii) identify relevant science knowledge and tools; and iv) demonstrate how science can contribute effectively to resource management decision-making.

2 BACKGROUND

The lakes of the Upper Waitaki Basin (Fig. 1) are a local, regional and national asset for their ecological, recreational, commercial and tourism values. The waters of the lakes are currently classified as "microtrophic" to "oligotrophic" (Meredith & Wilks, 2006), meaning that the lakes have low biological productivity, and have relatively high water quality, i.e., low nutrients, high clarity and limited phytoplankton productivity (Burns et al. 2000, Davies-Colley et al. 1993). It is these characteristics that give the lakes their colour and high aesthetic value.

Figure 1: Location maps. The left-hand image shows the location of Lake Benmore amongst the Waitaki lakes. The right-hand satellite image shows the two Arms of Lake Benmore.

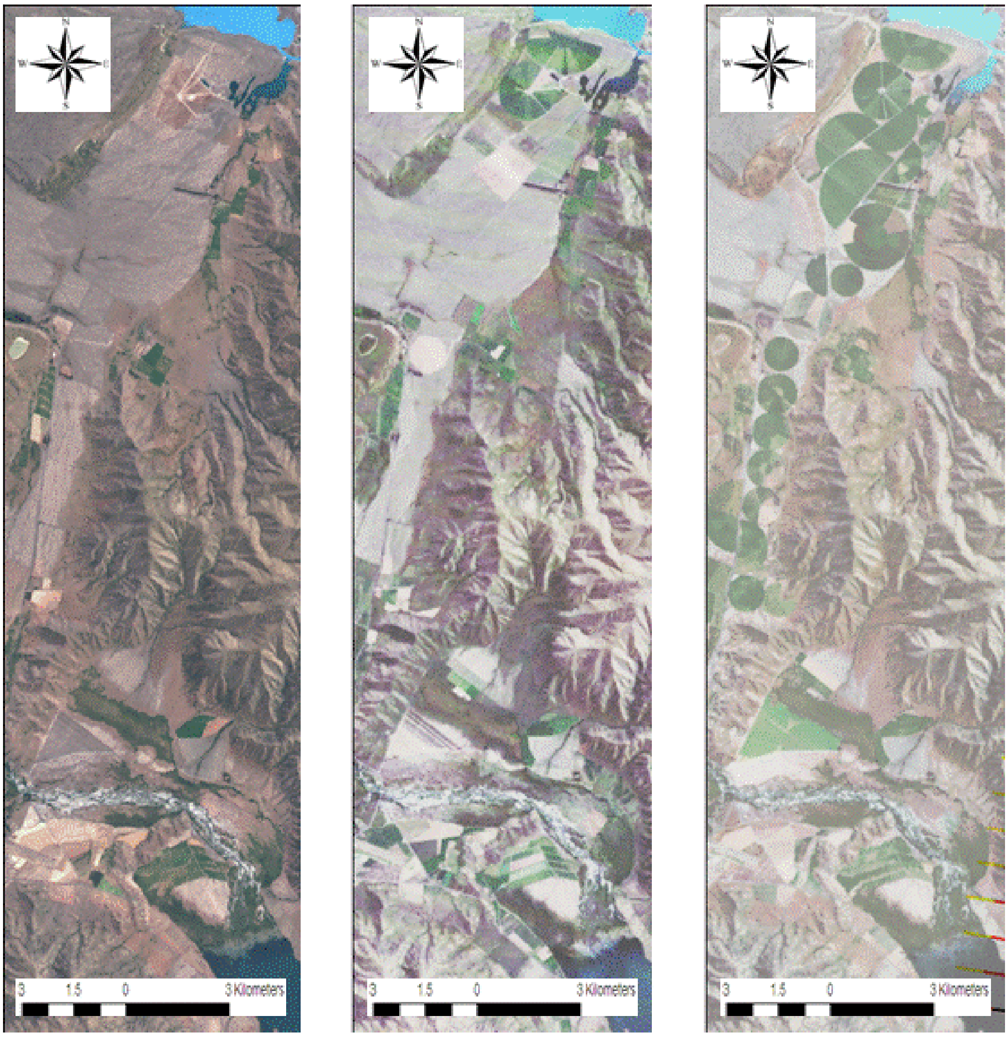


Historically, most land-use in the catchment has been low-intensity, dryland sheep farming, with little irrigated land. However in recent years there has been a shift to irrigation and associated intensive land uses such as dairying and dairy support. Land use changes have occurred since 2003, as can be seen in satellite images (Fig. 2). In addition to the present development, Environment Canterbury (ECan) is also currently considering 60 further water permit applications for irrigation in the Upper Waitaki Basin.

Water quality is a key concern when land use is intensified. In order to maintain the values of the downstream lakes, there is a need to manage increased contaminant loads entering waterways from multiple diffuse sources (e.g. nutrients, sediment and microorganisms). The focus of this paper is on potential increases in nutrient loads entering the lakes as this could lead to degradation of clarity, colour and biological processes, which may impact on ecological, recreational and commercial values.

ECan is responsible for the management of water quality in the Waitaki lakes as part of its functions under the Resource Management Act (RMA). ECan commissioned a modelling study (Norton et al. 2009) to provide scientific tools to assist with those functions. The broad goal of the study was to increase understanding of the links between catchment land use changes, associated nutrient loads to the lakes, in-lake processes, lake water quality and associated values. The specific purpose of the study was to provide options for ECan’s regional plan provisions.

Figure 2: Satellite images showing increased irrigated land (green areas) over time. The West (Ahuriri) Arm of Lake Benmore is visible at the bottom right corner of each image. Lake Ruataniwha is visible at the top right corner of each image. Dates are NZST, 10:00. These are unprocessed images, no atmospheric or colour corrections have been made and differences in lake colour should not be interpreted as real. All images are from NASA Landsat Program and provided by US Geological Survey, Sioux Falls, South Dakota, USA; from left to right: Landsat ETM+ scene LE70750912002365EDC00, Landsat ETM+ scene LT50750912005013HOA00, Landsat ETM+ scene L7107509120090201.



1 January 2003 14 January 2005 2 February 2009

3 THE PROBLEM - LIMITS FOR MANAGING CUMULATIVE EFFECTS

Managing the cumulative effects of multiple diffuse discharges on water quality is a national challenge facing water managers in New Zealand. Defining the capacity of waterways to assimilate contaminants and establishing sustainable limits for water quality are recognised as key requirements for effective management. For example, the New Zealand Government's Cabinet paper proposing a *New Start for Fresh Water* (Offices of the Minister for the Environment and Minister of Agriculture (ME & MA) 2009) stated: "*… New Zealand is approaching some water resource limits, which can be seen in areas with deteriorating water quality, water demand outstripping supply, and constrained economic opportunities.*" In particular the Cabinet paper identified that "*water resource limits*" were needed "*to shape actions on quantity and quality*" and also identified the importance of "*supplementary measures to address the impacts of land use intensification on water quality, and manage urban and rural demand*". However, setting water quality limits is a complex task - there are currently no such limits set at the national level in New Zealand and few cases where limits in regional plans have yet come into force.

A precursor to setting limits for water quality is defining the capacity of waterways to assimilate contaminants or, put another way, the capacity for use of the resource; i.e. the amount of resource that can be used by people *while* sustaining all competing values at some identified acceptable level. It has been suggested (e.g. by Norton et al. 2010 and others) that the capacity for use of the resource depends partly on value judgements, that should establish the level at which all competing values will be sustained, i.e., the environmental state or outcomes sought. When desired outcomes are clearly defined, for example as regional plan objectives, technical methods can be used to justifiably set limits such as water quality standards and nutrient load limits for achieving the stated objectives. Thus, setting water quality limits requires both value judgements (the role of decision-makers) and technical input (the role of science).

4 SCIENCE KNOWLEDGE AND TOOLS CAN ASSIST

Science can assist by quantifying the relationships between water quality contaminants and the effects they cause on environmental state; for example the effects of increasing nutrients on water clarity, colour and ecological health. It is useful if science knowledge can be presented in a way that provides decision-makers with options to choose from. One way of doing this is to simplify the information so that it can be presented in an x-y relationship (Fig. 3). A range of options for environmental states can be portrayed on the y-axis, while the related causative variable (e.g. nutrients) is shown on the x-axis. This is helpful for a number of reasons:

i) The plots makes it clear that there is a choice to be made, by decision-makers, from options on the y-axis;

ii) Once the choice is made, there is a technical basis for determining the appropriate limit (e.g. for nutrients) by reading off the x-axis;

iii) The implications of choices for other values (e.g. economic and social) can be assessed in a similar way to fully inform decision-making (Fig. 4);

iv) Presenting information in this way makes the consequences of choices transparent to decision makers and the community.

Freshwater science has described many relationships between environmental state and causative variables, such as depicted in Fig. 3. These relationships underlie many of the national water quality guidelines that are in current use (e.g. MfE 1992, 1994, 2000, 2003, ANZECC 2000).

For lakes, such relationships have been quantified through detailed research that has informed the development of models; the models can be used to predict the effects of nutrient increases on a range of environmental variables such as dissolved oxygen and the Trophic Level Index (TLI). The TLI is a function of nitrogen and phosphorus concentrations, Secchi depth (~ clarity) and chlorophyll *a* concentration (Burns et al. 2000). The TLI provides a convenient and pragmatic numeric scale describing lake condition. Choices for the desired environmental state of the lake (e.g. clarity, colour, ecological health) can be equated with a numeric value on the TLI scale and depicted in x-y plots like that shown in Fig. 3. Note that plotted curves shown in Figures 3 and 4 do not imply exact relationships – these are conceptual diagrams. The importance of identifying and managing uncertainty with these relationships is considered in section 9.

5 APPROACH USED FOR THE LAKE BENMORE STUDY

Here we describe a modelling study commissioned by ECan to help better understand the links between proposed land use changes in the Upper Waitaki Basin, associated nutrient loads to the lakes, in-lake processes, lake water quality and associated values (Norton et al. 2009). The purpose was to provide ECan with technical information and options for regional plan provisions, including options for:

(i) Measurable planning objectives for water quality in Lake Benmore; and

(ii) Catchment nutrient load limits associated with achieving each of the objective options.

Figure 3: Schematic representation of the relationship between nutrient concentrations and lake algal biomass. Note the arrow on the y-axis indicates worsening environmental state as algal biomass increases. Modified from Norton et al. (2010) with permission.

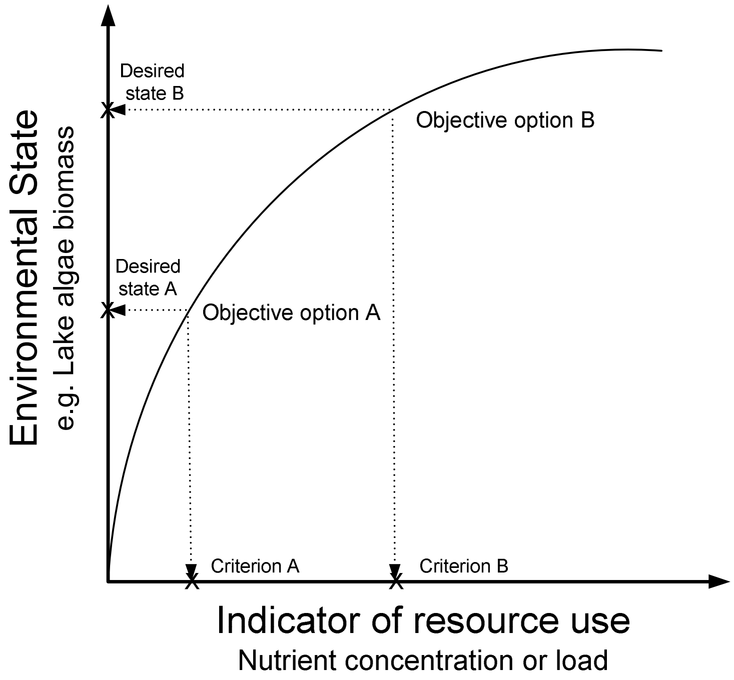
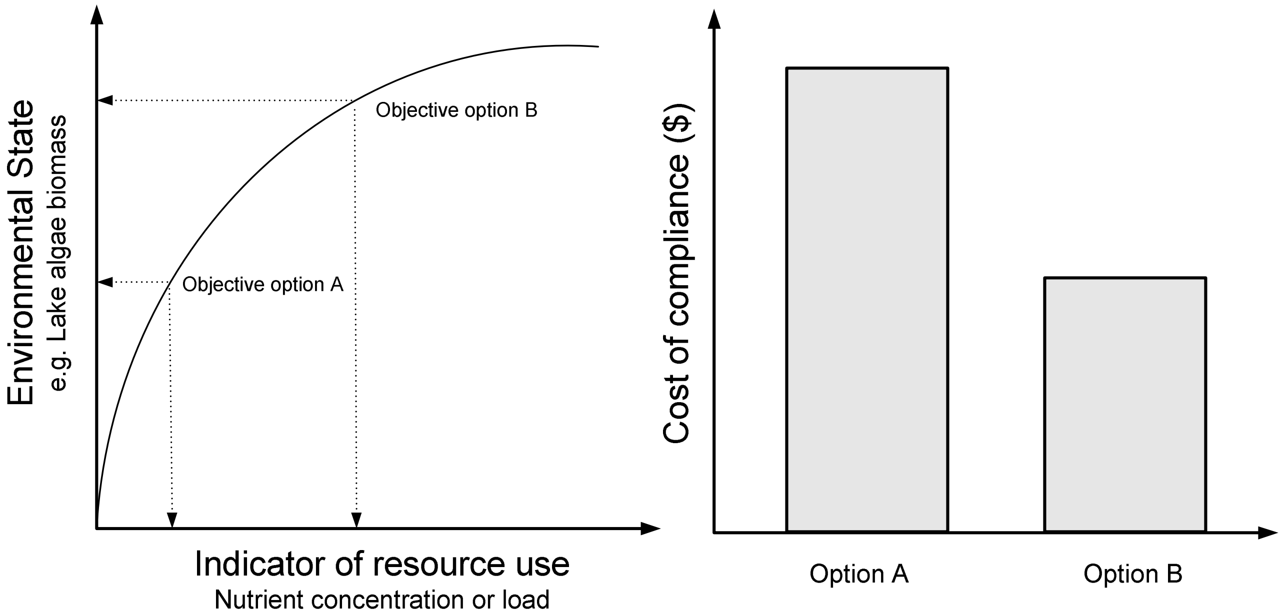


Figure 4: Schematic diagram showing options for measurable objectives and water quality limits, and the economic consequences of each option. The left-hand plot shows the relationship between options for algal biomass objectives (i.e., A and B) and water quality limits (nutrient concentration or load). The right-hand plot shows the short-term cost to agriculture of having to comply with water quality limits A and B. Modified from Norton et al. (2010) with permission.



The modelling study was designed to provide information, at least initially, in an x-y format such as depicted in Figures 3 and 4. The TLI was chosen as a convenient and pragmatic numeric scale to describe options for objectives (y-axis), with nutrient concentrations and total annual loads represented on the x-axis. Environment Bay of Plenty established a precedent for using TLI in regional plan objectives for lakes in the Bay of Plenty Regional Water and Land Plan that became effective on 1 December 2008 (www.envbop.govt.nz). ECan officers proposed use of the TLI in regional planning objectives for all Canterbury lakes (Hayward et al. 2009).

Lake Benmore is the critical downstream receiving basin for nutrients from both the Ahuriri (West) Arm and Haldon (North) Arm catchments and is therefore likely to be the first of the Waitaki Lakes to show water quality effects. Lake Benmore is also likely to be more vulnerable to adverse effects from increased nutrient loads than downstream Lakes Aviemore and Waitaki, due primarily to the longer water residence time in Lake Benmore. Therefore, setting objectives and nutrient load limits for Lake Benmore could establish the ‘line in the sand’ basis for effectively managing the cumulative water quality effects of multiple activities in the Upper Waitaki catchment, for all downstream lakes.

6 THE MODELS

A coupled hydrodynamic-ecosystem modelling approach was used to predict the relationship between nutrient load (total nitrogen [TN] and total phosphorus [TP]) and measures of lake condition in Lake Benmore such as dissolved oxygen and TLI. Several hypothetical future scenarios that involved increasing nutrient loads were modelled to allow predictions of effects on measures of lake condition.

Three models that were used for this study were developed by the Centre for Water Research, University of Western Australia (CWR) – DYRESM (DYnamic REservoir Simulation Model), ELCOM (Estuary Lake and Coastal Ocean Model) and CAEDYM (Computational Aquatic Ecosystem Dynamics Model). These are complex, process-based (mechanistic) models that simulate coupled hydrodynamic, water quality and biogeochemical cycles in aquatic ecosystems. They were chosen for this study because of their ability to explicitly represent the physical, chemical and biological processes that control trophic state, and to resolve these processes spatially and temporally to account for the complexity of the Lake Benmore ecosystem. A diagram showing some of the components accounted for in these models is shown in Fig. 5.

A large amount of input data is required to run the models including daily lake inflow volumes, temperatures and nutrients, and hourly or daily climate data. Site locations for flow and climate data are shown in Fig. 6. Inflow data were supplied by Meridian Energy Limited and the National Hydrologic Archive for the period 1994 – 2008. Climate data were obtained from the nearby Tara Hills and Lauder climate stations. Many other variables in the model are represented by default values from the literature (e.g. biological species composition; chemical exchange functions) and these can be overridden when local data are available.

Executable codes for these models are available by request through the CWR website (http://www.cwr.uwa.edu.au). Complete documentation, including science manuals and user guides that describe the processes, governing equations and parameters in the models, are also available by request.

7 RESULTS - MODEL OUTPUTS

Key outputs from the modelling study were plots showing the relationship between nutrient loads and measures of environmental state such as TLI and dissolved oxygen. An example set of these plots is shown in Fig. 7. The four plots represent four modelled sites in Lake Benmore; the Haldon (North) Arm, the Ahuriri (West) Arm, a Lower Benmore site, and the average of all sites representing the whole lake. The plots show the consequences, for lake TLI, of increasing nutrient loads by 1-fold to 12-fold compared to current loads. These plots could be used in two different ways. First, given information about a specific proposal such as the nutrient load increases estimated to arise from an irrigation scheme, the plots could be used to predict the consequences for TLI and thus assess whether the effects of the proposal are acceptable. Alternatively, given a chosen TLI objective (i.e. a desired environmental state for the lake), the plots could be used to select nutrient load limits (for TN and TP) to ensure the desired objective is achieved. The latter was the main purpose of the study in this case.

Figure 5: Diagram showing some of the components accounted for in the DYRESM, ELCOM and CAEDYM models. As shown on the CWR website (http://www.cwr.uwa.edu.au).

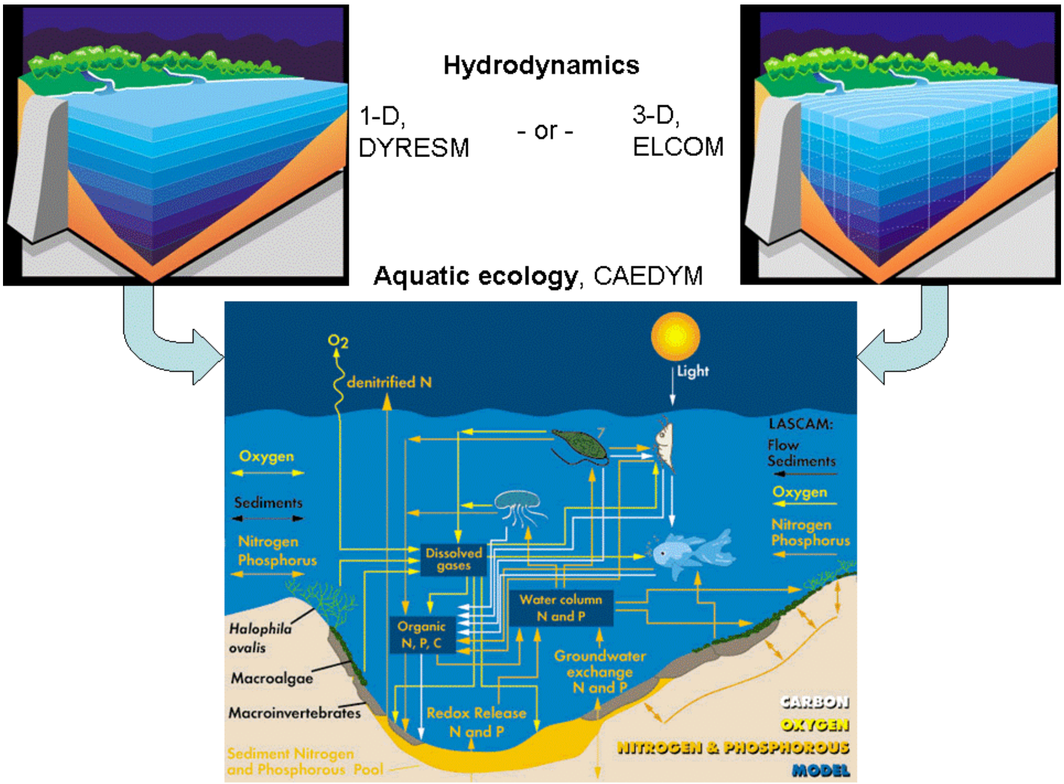


Figure 6: Map showing Lake Benmore and other Upper Waitaki Basin lakes. Locations of climate stations (blue squares) and inflow recorders (red triangles) are shown where data was collected for input into the model.

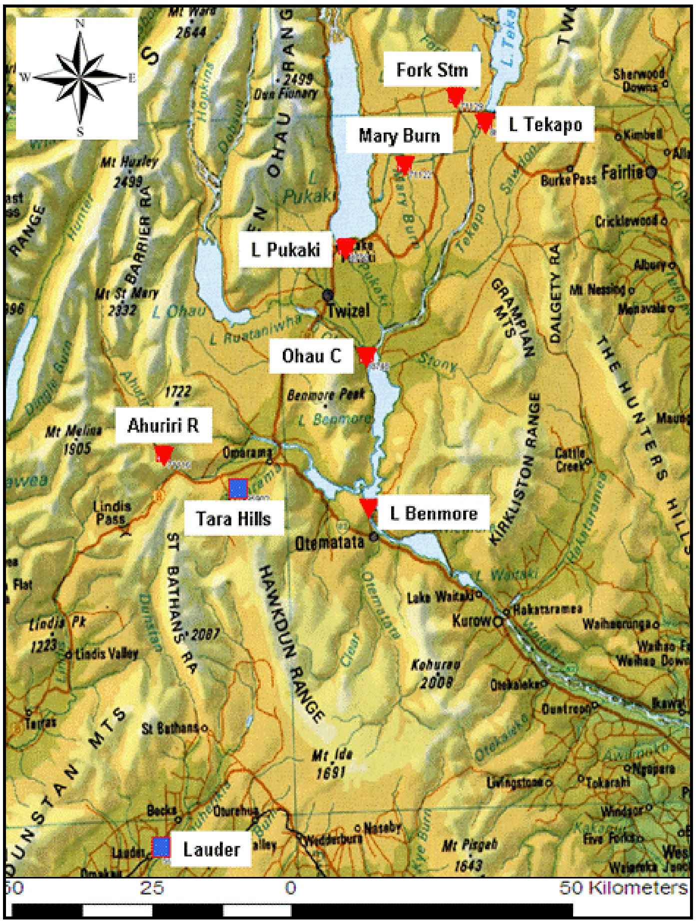
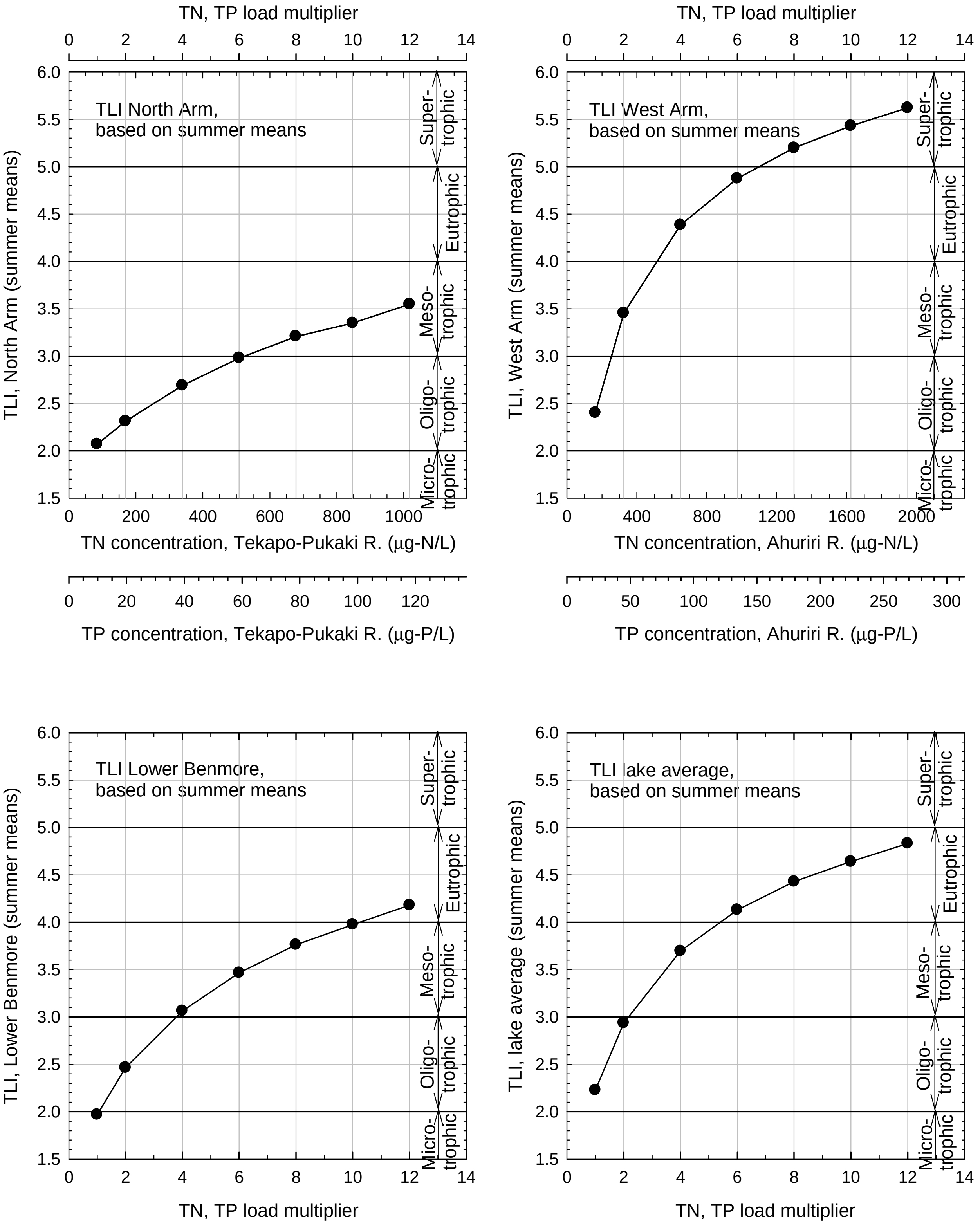


Figure 7: Trophic Level Index (TLI) based on summer mean data (15 Nov 2003 - 15 Mar 2004) in the Haldon (North) Arm (top left), Ahuriri (West) Arm (top right), Lower Benmore (bottom left) and averaged for the whole lake (bottom right). Load multipliers (1x, 2x, 4x etc) refer to multiples of the current loads measured in lake inflows. Note that plotted curves do not imply exact relationships – see discussion about uncertainty in section 9. Reproduced with permission Norton et al. (2009).



8 INTERPRETATION FOR RESOURCE MANAGEMENT

While the TLI is a convenient and pragmatic numeric scale for describing options for objectives, it is a technical index and not meaningful to most people without further interpretation. Therefore, it was necessary to describe environmental characteristics and values associated with points on the TLI scale, so that choices could be more clearly understood by most people (columns 1 and 2 in Table 1). The nutrient load limits that could apply for each TLI option are shown in columns 4 and 6 of Table 1, for the Haldon and Ahuriri Arms of Lake Benmore, respectively. The consequences of each option for dissolved oxygen in the lake hypolimnion (bottom water layer) are also shown (columns 3 and 5) to assist decision-making; dissolved oxygen should be above zero to avoid adverse effects of anoxia in bottom sediments, greater than 5 mg/L to support fish life (ANZECC 2000), and 80% saturation or higher to maintain optimal conditions for aquatic life (Third Schedule RMA).

*Table 1: Summary of relationships between options for TLI objectives and associated nutrient load limits for nitrogen and phosphorus in the Haldon and Ahuriri Arms. Nutrient load limits for each TLI value were obtained from model output plots for summer mean values (Fig. 7). Dissolved oxygen (concentration and % saturation) was obtained from model output plots for hypolimnion annual minimums (data not shown). 1x, 2x etc refers to multiples of the current nutrient loads measured in lake inflows. Existing baseline nutrient loads and trophic state are highlighted in blue. Colour bar behind the TLI scale indicates extracted chlorophyll a colour (data not shown) and represents visual changes with shifts in TLI. * = trophic level below the boundary of modelled scenarios; ** = trophic level higher than the boundary of modelled scenarios.*

General description of environmental characteristics for the specified trophic state	**Options for Objective (TLI)**	**Haldon Arm Annual minimum DO (hypolimnion)**		**Haldon Arm Associated nutrient load caps for N & P (tonnes/yr)**	**Ahuriri Arm Annual minimum DO (hypolimnion)**		**Ahuriri Arm Associated nutrient load caps for N & P (tonnes/yr)**
Oligotrophic Clear water (visually appealing) Very low risk visual phytoplankton (e.g. green colour) Low-moderate periphyton on bed & margins Healthy macrophyte beds No risk of toxic blooms Healthy invertebrate & fish communities High biodiversity value High contact recreation value High amenity value	2.0	>9.8 mg/L	>90%	TN = * TP = *	>9.3 mg/L	>90%	TN = * TP = *
	2.1	9.8 mg/L	90%	1.00xTN = 646.3 1.00xTP = 67.63	>9.3 mg/L	>90%	TN = * TP = *
	2.4	9.1 mg/L	84%	2.47xTN = 808 2.47xTP = 86.4	9.3 mg/L	89%	1.00xTN = 173.3 1.00xTP = 23.92
	2.5	9.0 mg/L	82%	2.99xTN = 866 2.99xTP = 93.2	9.1 mg/L	87%	1.09xTN = 190 1.09xTP = 26.2
	2.9	8.2 mg/L	75%	5.45xTN = 1138 5.45xTP = 125	9.0 mg/L	85%	1.47xTN = 256 1.47xTP = 35.3
Mesotrophic Clear tending green water (variable appeal) Moderate risk of phytoplankton blooms Moderate periphyton on bed & margins Increase stress to macrophyte beds Potential shift to phytoplankton dominated community Some risk of toxic blooms Increased invertebrate & fish productivity Good biodiversity value Good contact recreation value Good amenity value	3.0	8.1 mg/L	75%	6.18xTN = 1219 6.18xTP = 134	8.7 mg/L	85%	1.57xTN = 272 1.57xTP = 37.6
	3.5	7.8 mg/L	71%	11.5xTN = 1808 11.5xTP = 202	8.5 mg/L	81%	2.10xTN = 364 2.10xTP = 50.3
	3.6	7.7 mg/L	71%	12.0xTN = 1860 12.0xTP = 208	8.5 mg/L	80%	2.21xTN = 382 2.21xTP = 52.8
	3.9	**	**	TN = ** TP = **	8.0 mg/L	75%	2.96xTN = 513 2.96xTP = 70.9
Eutrophic Turbid green water (visually unappealing) High risk of sustained phytoplankton blooms Low-moderate periphyton on bed & margins High risk of macrophyte bed collapse Likely phytoplankton dominated system Moderate risk of toxic blooms Shifts to invertebrate & fish community composition Compromised biodiversity value Compromised contact recreation value Compromised amenity value	4	**	**	TN = ** TP = **	7.9 mg/L	75%	3.18xTN = 551 3.18xTP = 76.0
	4.5	**	**	TN = ** TP = **	7.3 mg/L	70%	4.48xTN = 776 4.48xTP = 107
	4.9	**	**	TN = ** TP = **	6.8 mg/L	63%	6.17xTN = 1070 6.17xTP = 148

Thus, Table 1 provided a set of options for environmental objectives for Lake Benmore that spanned TLI scores from 2 (oligotrophic ~ current state) to 5 (eutrophic ~ highly degraded). The TLI is a continuous scale so any decimal number could be chosen (e.g., 2.9, 3, 3.1, 3.25, etc.) and the associated TN and TP load limits calculated for that TLI value. Table 1 shows a selection of discrete TLI options. The model results strongly indicated that:

(i) The Ahuriri and Haldon Arms of Lake Benmore behave differently in response to nutrient loads; and

(ii) The Ahuriri Arm is more sensitive to nutrient increases than the Haldon Arm, due primarily to the relatively smaller inflow and relatively longer water residence time in the Ahuriri Arm.

Consequently, if the same TLI objective were chosen for both Arms of the lake, the load limits necessary to achieve that objective would be significantly lower for the Ahuriri Arm catchment area than for the Haldon Arm catchment area (Table 1). In other words, there would be less potential for further intensification of land use in the Ahuriri Arm catchment than the Haldon Arm catchment.

It was not the purpose of the technical study to recommend any particular TLI objective and associated nutrient load limits, because that decision is ECan’s responsibility and would be developed in the context of the RMA planning provisions. Generally, the higher the TLI number the greater the risk of associated degradation of environmental values.

9 MANAGING UNCERTAINTY

The modelling method involved numerous assumptions as well as data limitations that inevitably contribute to some uncertainty around the predictions. Models only provide estimates of reality. For example, the modelling results that were presented graphically (e.g. Fig. 7) show a smoothed increasing response to increased nutrients but this is unlikely to be the case in reality. In the real world lakes tend to respond to nutrient increases in a non-linear way; i.e. as nutrient loads increase, little change may be observed initially in a lake, but at some tipping point large changes in trophic state (~TLI) can occur rapidly. Nonetheless, the modelled increasing response to nutrients represents increasing risk of environmental changes and loss of desirable values, thus providing a useful tool for management. All of these sources of uncertainty were described by Norton et al. (2009) as part of informing decision-makers, which is a key step for managing uncertainty (Rouse & Norton, 2010).

10 CONCLUSION

The modelling study allowed science to inform the decision-making process by describing the environmental consequences of a series of options. The choice between options is beyond the role of science because it requires a value judgement that takes into account social and economic, as well as environmental consequences. It was beyond the scope of this particular study to undertake an assessment of social and economic consequences. However once such assessments are carried out and a decision is made, setting measurable objectives and nutrient load limits for Lake Benmore could establish a scientifically robust ‘line in the sand’ for managing cumulative water quality effects and allowing sustainable irrigation in the upper Waitaki catchment. At time of writing no decision had been made on objectives or nutrient load limits for Lake Benmore.

ACKNOWLEDGEMENTS

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