

Lake Tutira: historic water quality, monitoring recommendations and management options



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Executive Summary

Lake Tutira is located 30 km north of Napier and is an important recreational resource for the Hawke's Bay region. The lake has an area of 1.74 km², mean depth of 21 m and maximum depth of 42 m. It has a recent history of poor water quality, and over 2011 and 2012 there were severe blooms of blue-green algae (cyanobacteria), which detracted from the ecological and aesthetic value of the lake, and impacted on its suitability for recreational use.

We analysed the recently-available (2009–2012) monitoring data for Lake Tutira, which included periods of regular (c. monthly) water quality monitoring measurements, as well as data from an automated high-frequency monitoring buoy. Poor water quality in Lake Tutira is not a recent problem and TLI values in the 1960s and 1970s were higher than those for the analysis period. High-frequency buoy data demonstrated that high-intensity rainfall events produced rapid increases in water level and increased turbidity. Increases in chlorophyll fluorescence a few days after major rainfall events indicate that rainfall events may also stimulate increases in phytoplankton biomass in the lake via increased nutrient inputs associated with stormflows.

Grass carp were introduced into Lake Tutira in 2008 to control the invasive weed *Hydrilla* which had been present in the lake for some decades. There has been a rapid reduction in *Hydrilla* beds in the lake following the grass carp introduction. We recommend that the impact of grass carp on Lake Tutira be evaluated from an ecosystem perspective, given some marked changes in other components of the lake ecosystem since the introduction.

We evaluated the suitability of Lake Tutira for application of an ecological model to assist with consideration of management options to improve lake water quality. Lake Tutira is a suitable candidate lake for both one-dimensional (1-D; vertically resolved) and three-dimensional (3-D) ecological model applications to represent the vertical variations and whole-lake water column variations, respectively. A comprehensive ecological model of Lake Tutira could be used to simulate the outcomes of various lake restoration strategies, thus acting as a decision support tool for proposed lake management actions. The likely performance of a model application and hence its value for informing management decisions could be improved considerably with substantial additional data collection (e.g. inflow water quality), as well as continuation of the current lake monitoring. A number of potential management options were considered for Lake Tutira and we recommend that these options be considered further with the 1-D and/or 3-D models in order to fully assess their feasibility, effectiveness and value for money.

Acknowledgements

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1. Introduction

1.1 Background

Lake Tutira (39° 13' 30"S; 176° 53' 30" E; Fig 1) is located 30 km north of Napier and is an important recreational resource for the Hawke's Bay region. The lake has an area of 1.74 km², mean depth of 21 m and maximum depth of 42 m (Table 1). Lake Tutira was formed at least 7,200 years before present as a result of a landslide near the present southern end of the lake, which blocked the river drainage; the most definitive guide to formation of lakes in New Zealand indicates only that its formation timeline was "prehistoric" (Harding et al. 2004).

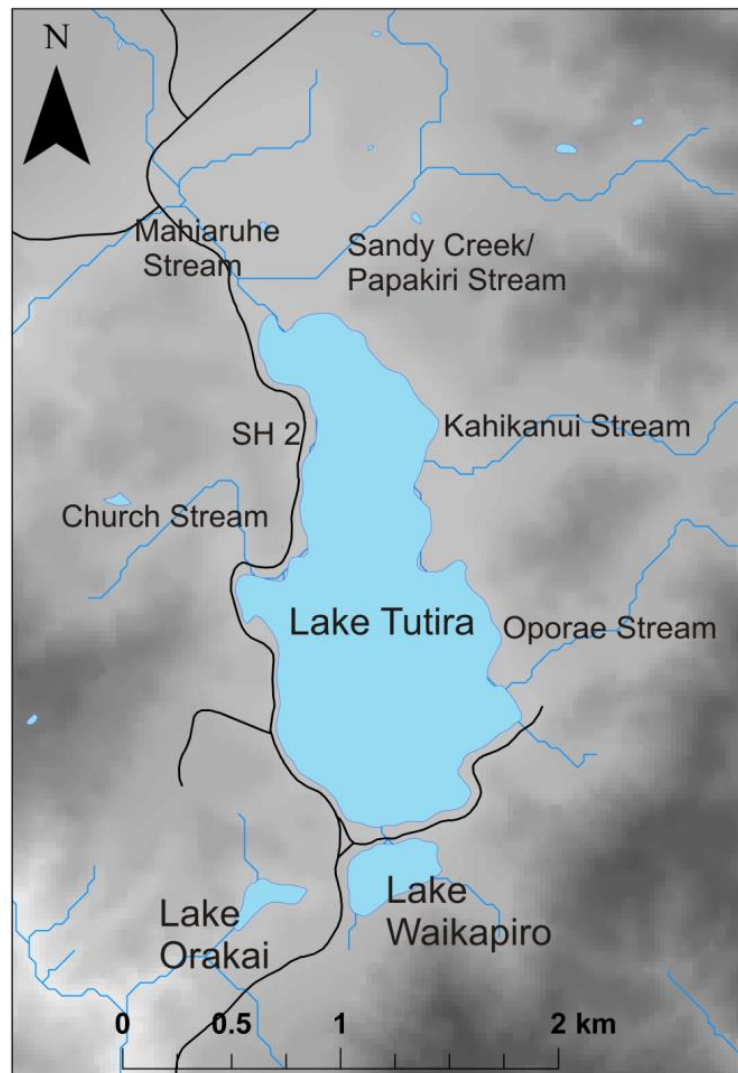


Figure 1. Lake Tutira. Stream names are reproduced from Hooper (1989).

Table 1. Lake Tutira morphological characteristics

Altitude ¹	150 m
Area ¹	1.74 km ²
Catchment (non–lake) area after diversion of Sandy Creek ²	8.44 km ²
Catchment to lake area ratio	4.9:1
Mean depth ¹	21 m
Maximum depth ¹	42 m
Residence time ¹	2 years
Shoreline length ³	8.0 km
Volume ¹	36.1 x 10 ⁶ m ³

1. McColl (1978)
2. Hooper (1989)
3. Teirney (2009)

1.2 Lake Tutira catchment

Settlers began clearing native vegetation from the lake catchment around 1880 and most of the catchment comprised pasture by 1930 (Page et al. 1994). McColl (1978) noted that farming activities caused lake water quality to decline, resulting in algal blooms and excessive weed growth by 1959, occurrence of blooms of cyanobacteria (*Microcystis aeruginosa*, *Anabaena* sp.) by 1972 and a trophic state of “moderately to highly eutrophic” in 1978.

Steep topography, high intensity rainfall and land clearance mean that the catchment is particularly sensitive to soil erosion. Rain events with a magnitude of 150–200 mm predominantly cause sediment transport to the lake and these occur on a near–annual basis (Page et al., 1994). The most recent major sediment deposition event was due to Cyclone Bola when c. 750 mm of rainfall occurred over four days. Events of such magnitude (c. 300 mm d⁻¹) are estimated to generate sediment deposition of c. 17 cm in the centre of the lake nowadays, compared to c. 3 cm prior to vegetation clearance in the catchment (Orpin et al., 2010).

2 Historical water quality of Lake Tutira

Water quality monitoring data collected since 1974 during separate studies of Lake Tutira (Table 2) have been analysed to provide context to assess current lake water quality. Historic data have been used to calculate the annual Trophic Level Index (TLI; Burns et al. 1999) of the lake for years for which data were available. The TLI (Table 3) provides an integrated measure of lake water quality based on measurements of the following variables: total nitrogen (TN) concentration, total phosphorus (TP) concentration, chlorophyll *a* concentration and Secchi depth. The TLI was based on annual average values for the four water quality variables listed above, using equations defined by Burns et al. (1999). Following Burns et al. (1999), data for surface water samples were used when the water column was isothermal (mixed), whilst an average of one surface and one hypolimnion (bottom water; TN and TP data only) sample was used in calculations when the lake was stratified. If the vertical temperature profile of the lake at the time of sampling (i.e. whether it was mixed or stratified) was not recorded then it was assumed that the lake was isothermal during June–October inclusive and stratified between November–May (e.g. see Teirney 2009).

Changes in Trophic Level Index (TLI; Burns et al. 1999) over time are presented in Figure 2. Four periods were considered:

1. 1974–1976. Based on data reported in Teirney (2009)
2. 1985–1987. Based on data published in Hooper (1989)
3. 1992–1996. Based on TLI reported in Ministry for the Environment (2006)
4. 2008–2012. Based on data collected by Hawkes Bay Regional Council as part of their lake monitoring programme.

Sampling regime, collection method, and availability of TLI constituent parameters varied between sampling periods and, as such, values provided are indicative and caution is warranted when drawing comparisons. Nevertheless the data provide a valuable historic record of water quality in Tutira. The derived TLI values are presented in Figure 2.

It is evident from the TLI analysis that Lake Tutira has been eutrophic since at least the 1970s. Recent TLI values are not the highest amongst the historic record, suggesting that water quality may have been worse, but TLI may not necessarily accurately reflect changes in other constituents that can markedly affect perceptions of water quality, for example, changes in the relative proportion of the phytoplankton community comprising cyanobacteria. Monthly sampling may also not accurately capture the dynamics of lakes subject to, for example, short-lived intense cyanobacteria blooms. The monitoring buoy record (see section 3.3) is valuable in this regard.

Table 2. Summary of data sources used for analysis of Lake Tutira water quality

Period	Data source	Notes
1974–1976	Teirney (2009)	Average values for Secchi depth, TP, and chl <i>a</i> were calculated using records for two monitored sites (1 and 4). Surface water samples were calculated as the average of samples collected at depths of 0 and 1 m. TN was not measured hence this variable was omitted from TLI calculations.
1985–1987	Hooper (1989)	TN and TP collected for 5–m intervals through the water column. Annual Secchi depth and chlorophyll <i>a</i> concentrations were estimated from values for summer periods (Dec – Feb) that fell within the calendar year.
1992–1996	Data collected by NIWA at c. monthly intervals and provided by N. von Westernhagen (HBRC).	Data for three monitoring sites were combined.
2008–2012	Data collected by HBRC at c. monthly intervals and provided by N. von Westernhagen (HBRC).	–

Table 3. Summary of the Trophic Level Index values used to quantify lake trophic status (Burns et al. 1999).

Trophic state	Trophic Level Index	Productivity	Perceived water quality
Ultra–microtrophic	0–1	Very low	Excellent
Microtrophic	1–2	↓	↓
Oligotrophic	2–3		
Mesotrophic	3–4		
Eutrophic	4–5		
Supertrophic	5–6		
Hypertrophic	6–7	Very high	Very bad

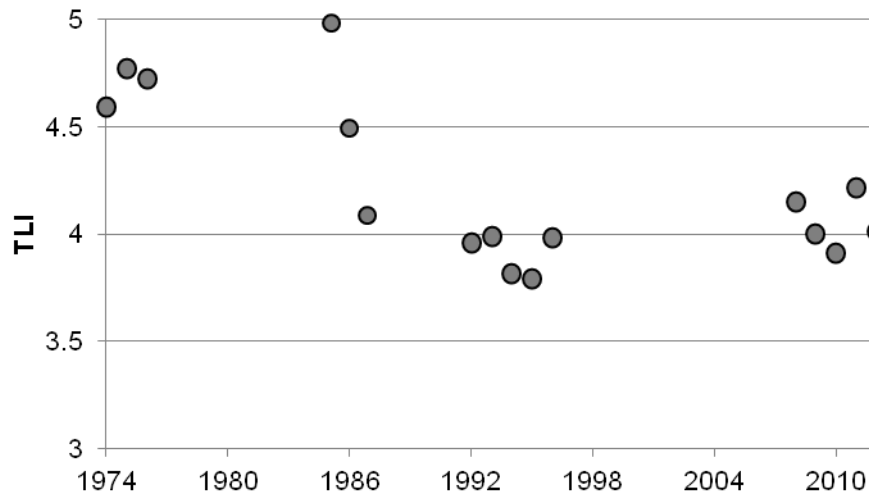


Figure 2. Annual Trophic Level Index 1974–2012. Methodology, sampling frequency and variables measured vary between decades (see Table 2), hence, differences in TLI values between years are indicative only.

3 Recent history and present water quality monitoring

3.1 Recent water quality monitoring

Water samples for determination of concentrations of nutrients and chlorophyll *a* have been collected from the surface and bottom layer of Lake Tutira at approximate monthly intervals over February 1992 – June 1996 (by Burns and Rutherford 1998) and in May 2008 – July 2012 (by HBRC). A detailed summary and comparison of these data are available in Verburg et al. (2012).

3.2 *Hydrilla* eradication programme and introduction of grass carp

The exotic macrophyte *Hydrilla* *sp.* is known to have invaded and formed extensive beds in Lake Tutira by 1963. It has had a significant detrimental effect on recreational and ecological values of the lake. In order to prevent the potential spread of *Hydrilla* to other ecosystems and to improve ecological values of Lake Tutira, a joint project was established between the (then) Ministry of Agriculture and Fisheries (MAF) and Biosecurity New Zealand. The objective of the project was to eradicate the weed from the lake with the introduction of grass carp (*Ctenopharyngodon idella*) and the application of herbicide (endothall) in December 2008 (Hofstra & Smith, 2009). The carp were expected to eradicate *Hydrilla* (along with other submerged vegetation) and an Assessment of Environmental Effects predicted that “no discernible decline in water quality is expected following the stocking of grass carp” (Hofstra & Rowe, 2008).

Grass carp are not considered to be an invasive threat to New Zealand waters as “they will not breed in New Zealand waters” (Hofstra and Rowe 2008). They have specific spawning and larval habitat requirements including long river runs, high water temperatures and flows, and large water level fluctuations (Clayton et al. 1999). Self-sustaining wild populations of non-indigenous grass carp are present in the Tone River (Japan), Mississippi and Illinois Rivers (U.S.A.) and the Danube River (Hungary) (Chen et al. 2012).

Grass carp are voracious feeders on macrophytes, and hence during the phase of high food availability they grow quickly. With reference to experiences overseas, Jeppesen et al. (2009) note that “a shift to a turbid state is a typical side effect” of grass carp introductions due to sediments and nutrients becoming increasingly mobilised in the water column in association with feeding. The ecosystem impacts of grass carp reducing or eliminating macrophyte beds from New Zealand lakes have not, however, been widely documented. No submerged macrophytes were present in Lake Ōmāpere in 2007 following grass carp introductions in 2000 and 2002. The TLI reached a peak of 7.5 in 2007 and neither native nor invasive vegetation has re-established in the lake following the grass carp releases (Gray 2012).

Other lakes in Hawke's Bay where grass carp have been introduced include Lake Parkinson, where they were subsequently removed with rotenone treatment (Mitchell et al. 1984) and Lake Elands where there was "minimal" decline in water quality but where the post-treatment monitoring period (1988–1993) was at least one decade prior to the complete removal of *Hydrilla* in 2003 (Hofstra and Rowe 2008). Approximately one decade after *Hydrilla* removal in Lake Elands, macrophytes are almost completely absent from the lake aside from turf communities in water of depth <1 m (Hofstra and de Winton 2012).

3.3 High frequency monitoring buoy

In order to provide comprehensive monitoring data for Lake Tutira and aid analysis of the effects of the *Hydrilla* eradication program, HBRC commissioned the installation of a high-frequency monitoring buoy in Lake Tutira. The buoy was built and deployed by the University of Waikato, and is maintained by HBRC and Limnotrack. Daily summary data for the monitoring buoy for c. 3 years are presented in Figures 3 and 4. The lake is strongly stratified for much of the year, with an isothermal period (daily average surface – bottom temperature < 1 °C) of less than 55 days for each of 2011 and 2012. Dissolved oxygen (DO) is consumed very rapidly in bottom waters following set-up of stratification when circulation between surface and bottom waters is strongly hindered. Even in the isothermal period, however, DO is low (c. 50 – 80% saturation); oxygen exchange between the bottom waters and surface waters is not generally considered to be impeded by lack of water circulation during persistent isothermal periods. A water level recorder was installed at the buoy in October 2009 and data recorded by this instrument clearly show the rapid response of lake water level to periods of high rainfall (Figure 3).

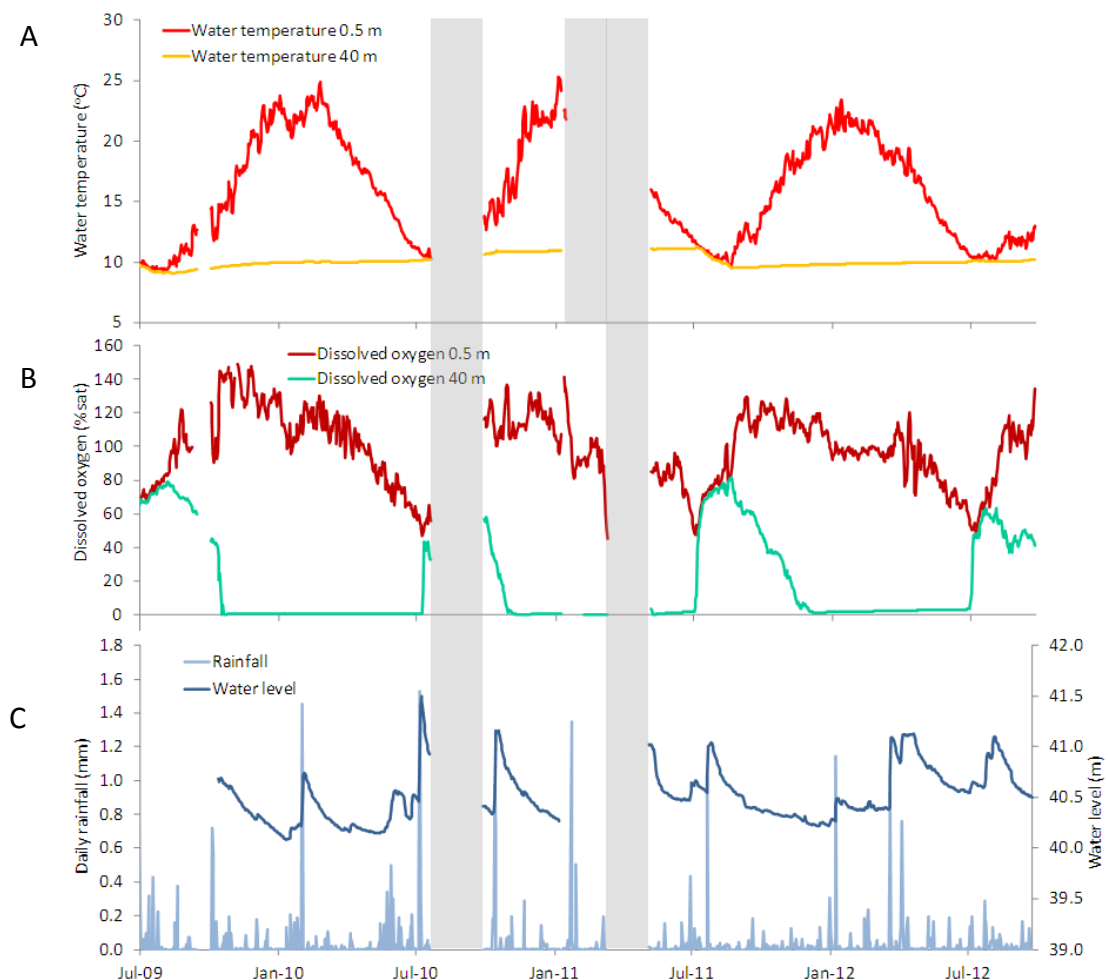


Figure 3. Daily summary data from the Lake Tutira monitoring buoy for A) surface and bottom water temperature, B) surface and bottom dissolved oxygen, and C) rainfall and water level.

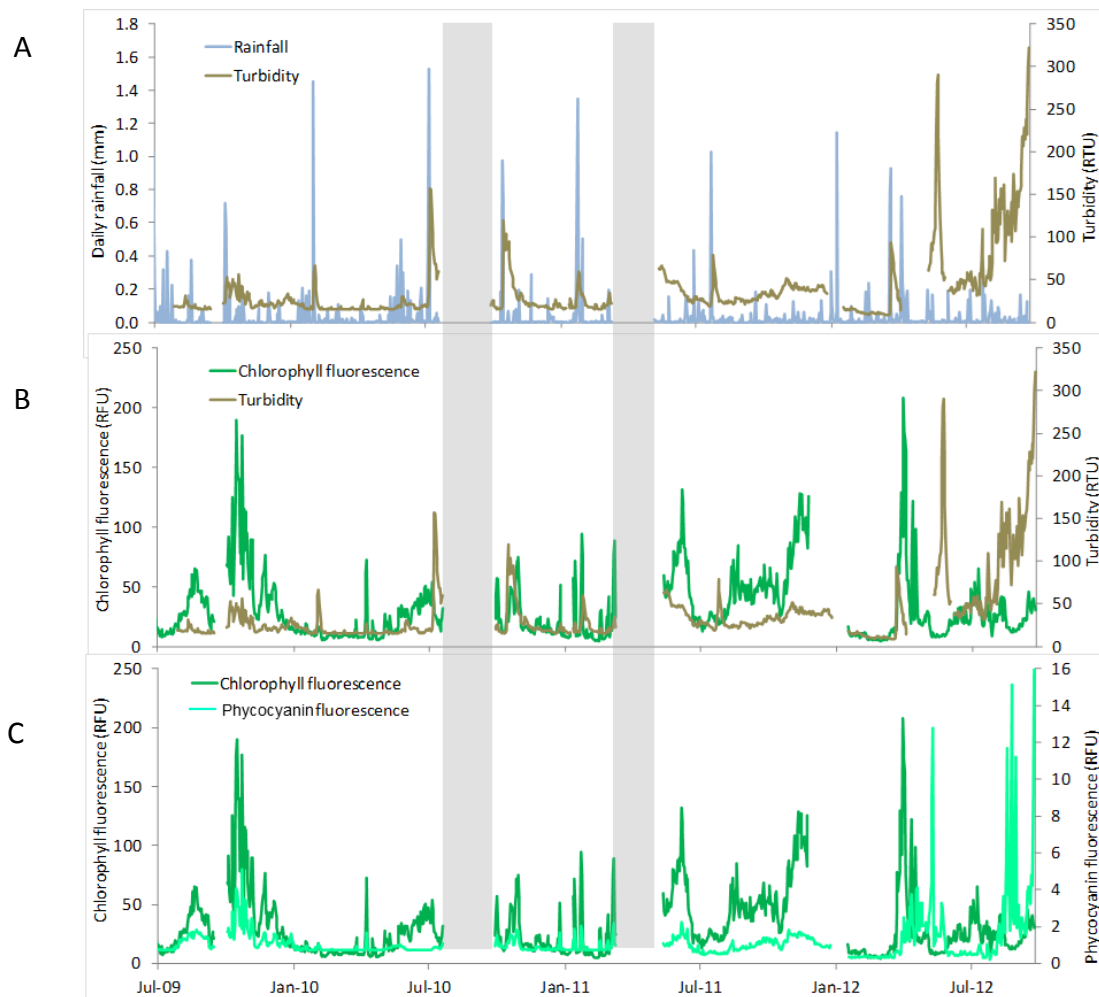


Figure 4. Daily summary data from the Lake Tutira monitoring buoy for A) rainfall and turbidity, B) chlorophyll and turbidity, and C) chlorophyll and phycocyanin fluorescence. Chlorophyll and phycocyanin are presented in relative units (RFU) as well as turbidity (RTU). Shaded areas represent extended periods when buoy measurements were not available due to maintenance. Phycocyanin fluorescence is a proxy for blue-green algae (cyanobacteria) abundance.

Periods of elevated turbidity in the lake corresponded with periods of high daily rainfall. Turbidity is attributed to scattering by both organic material (e.g., phytoplankton and detritus) and inorganic material (e.g., mineral sediments). The correspondence of turbidity and rainfall (Figure 4A) likely reflects increased suspended sediment concentrations in stormloads associated with intense rainfall events. Such events are also likely to be associated with elevated loads of total nitrogen and phosphorus. Some periods of elevated chlorophyll and phycocyanin (using fluorescence as a proxy) occur concurrently with or immediately following rapid rises in turbidity, e.g., winter 2011 and autumn 2012 (Figure 4), but to varying extent through the record. It may thus be inferred that intense rainfall events may decrease water clarity directly through addition of sediments to the lake but also indirectly, albeit with some lag, through nutrient-stimulated increases in phytoplankton abundance. It is beyond the scope of this report to separate these two mechanisms

but we recommend that further examination is given to pulses of nutrients associated with storm events, and their relationship with phytoplankton production in Lake Tutira.

3.4 Cyanobacteria blooms, 2012

Much attention was given to water quality in Lake Tutira in 2011–2012 due to occurrence of particularly severe cyanobacteria blooms. Blooms were reported to occur in winter 2011 and 2012. The blooms have impacted upon recreational use of the lake, and contact with the lake water is not recommended during these periods due to the potentially toxic nature of the blooms (HBRC 2012). The occurrence of major blooms has provided an imperative for understanding the drivers of bloom formation and how they may be controlled. Many cyanobacteria have anatomical and physiological attributes that enable them to be highly successful and to out-compete many other phytoplankton. For example: gas vesicles allow for buoyancy of cyanobacteria; carbohydrate accumulation and utilisation allow for (mostly daily) vertical migrations due to deployment of the carbohydrate as ballast, and; aggregations of cells into colonies or filaments allow for faster rates of migration (Oliver et al. 2012). These factors, together with vertical stratification, can be very important in the temporal dynamics of bloom formation.

Visual observations of the lake are supported by the monitoring buoy record. Phycocyanin fluorescence measurements from the buoy were much higher in 2012 than in prior monitoring years (Figure 4). Phycocyanin fluorescence was low over the 2011–12 summer but strongly elevated phycocyanin levels were observed from the beginning of March, following an intense rainfall–runoff event. Phycocyanin values were relatively low during the (isothermal) winter mixing period of 2012 but with the onset of stratification levels increased dramatically, coincident with observations of algal blooms at the lake (Figure 5).

A



B



Figure 5. Photos of Lake Tutira (A. Uytendaal) on 31 October 2012. Note monitoring buoy (orange colour) in background in B.

4 Monitoring recommendations for setting up a hydrodynamic–ecological model for simulating effects of lake management options

4.1 Modelling as a decision support tool for lake management

Hydrodynamic–ecological models provide a tool to aid understanding of lake processes and to simulate the potential effects of different lake and catchment management actions. Figure 6 illustrates how lake modelling can be incorporated into the decision–making process to inform the identification of feasible management actions (step 4). Such an approach can aid community engagement and help provide justification for lake management decisions.

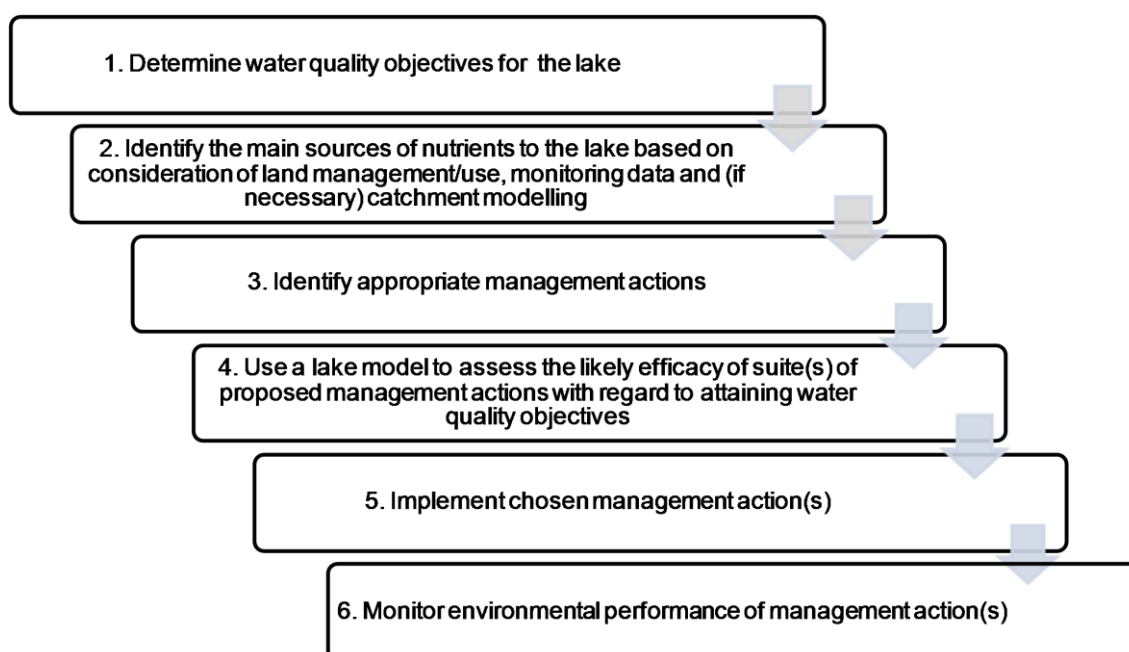


Figure 6. Example of how lake modelling can contribute to the implementation of lake management actions during a consultative process. Adapted from Elliot & Sorrell (2002).

The bathymetry and thermal dynamics of Lake Tutira make it a highly appropriate candidate system for the application of a one–dimensional coupled hydrodynamic–ecological model. Such models represent a lake as a series of horizontally integrated layers (with no latitudinal or longitudinal variations), and have been used elsewhere in New Zealand as a lake management tool (e.g. Burger et al. 2008; Norton et al. 2009; Özkundakci et al. 2011). The DYRESM–CAEDYM model (developed at the Centre for Water Research (CWR), Western Australia) is a one–dimensional model that has been widely applied worldwide and more extensively in New Zealand than other models.

Accurate lake–specific data are required for a range of variables to configure a model that is able to reliably simulate scenarios. Poor–quality or insufficient data greatly

reduce the applicability of model output for informing management decisions. This section describes the typical data requirements for a one-dimensional model application, comparing these requirements with data available from current monitoring of Lake Tutira. Gaps in data availability are highlighted and details are provided regarding suitable steps to address current deficiencies. The final section considers potential advantages along with the additional data required to implement a more sophisticated three-dimensional modelling approach.

4.2 Time period

Ideally, forcing data should be available for a minimum of four years. This enables model calibration over a two-year period, and an additional two-year period with which to validate the predictive power of the model. It is, however, possible to establish a functional model with periods as short as one year. It is possible to model forcing data for long periods using shorter periods of monitoring data, e.g., established relationships between inflow discharge and measured nutrient loads can be used to estimate nutrient loading during periods when inflow water quality was not monitored. Such inferences assume steady state conditions (e.g. no change to land management practices) and therefore it is desirable to have measurements of forcing data throughout the entire modelling period.

4.3 Bathymetry

The most recent bathymetric map available for Lake Tutira is based on a survey conducted in 1974, as presented in Irwin (1978; Figure 7). The bathymetry of the lake is likely to have changed significantly following Cyclone Bola in 1988 (von Westernhagen, *pers. comm.*). An updated bathymetric survey of the lake using multi-beam or side scanning sonar (e.g. Scarfe & Immenga 2004) would likely improve model performance with respect to simulating recent lake conditions, and would be particularly important for 3-D simulations.

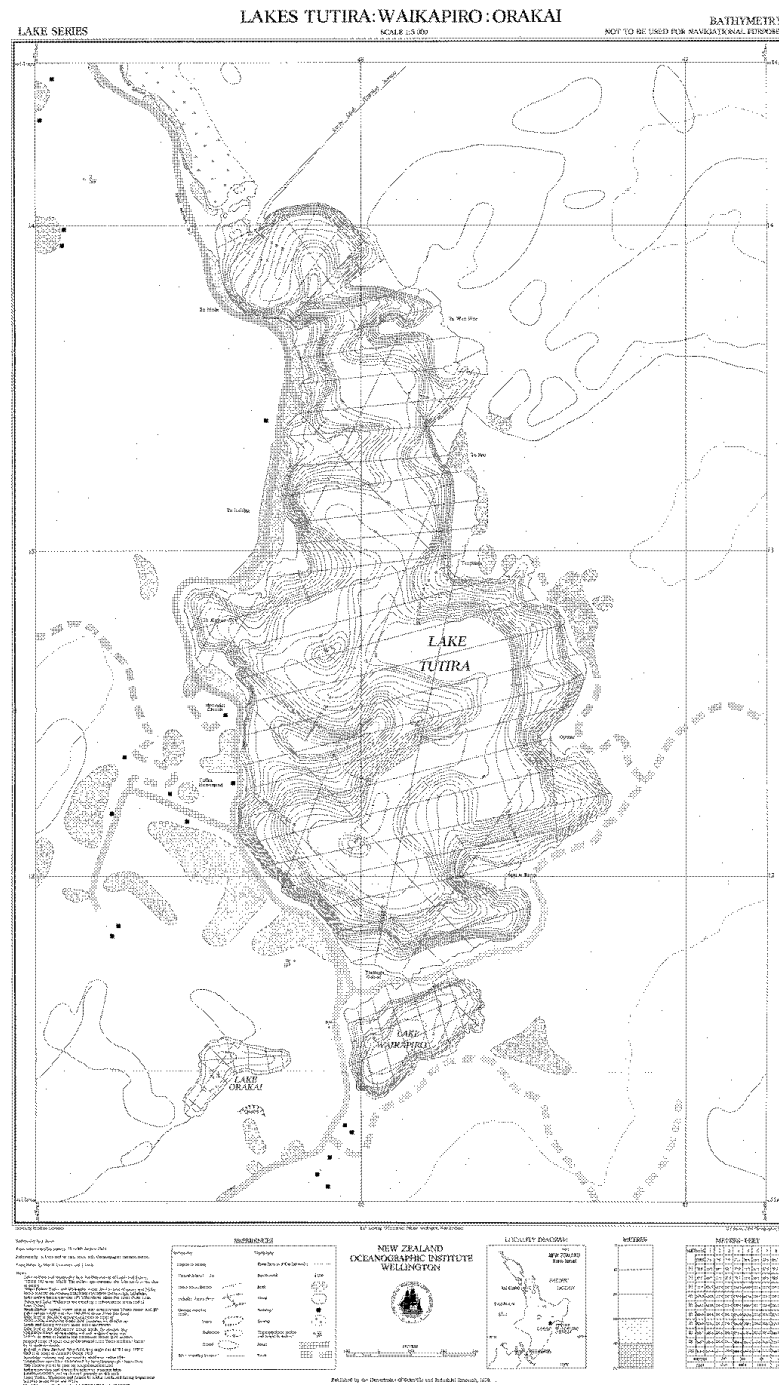


Figure 7. Bathymetry of Lakes Tutira, Waikapiro and Orakai. Reproduced from Irwin (1978).

4.4 Meteorological boundary conditions

The following meteorological measurements are required as daily average or total values as model forcing data for DYRESM–CAEDYM and GLM–FABM–AED:

- total daily rainfall (m d^{-1})
- average daily air temperature ($^{\circ}\text{C}$)
- average daily wind speed (m s^{-1})
- average daily short wave radiation (W m^{-2})
- average daily cloud cover (%; necessary to estimate long wave solar radiation)
- average daily water vapour pressure (hPa)

These meteorological variables have been recorded at Napier Airport (39.468°S 176.872°E ; c. 30 km south of the lake) since 1949 (see <http://cliflo.niwa.co.nz>). Also, there are two climate stations (Te Pohue and Kaiwaka) operated by HBRC that monitor the requisite variables (except daily cloud cover). Both stations are < 20 km from Lake Tutira. Vapour pressure can be derived using values of relative humidity and air temperature, or wet and dry bulb air temperature and barometric pressure (station pressure, not mean sea level pressure). Cloud cover can be estimated from measurements of shortwave radiation and estimated theoretical clear–sky shortwave radiation. Meteorological data are required at one hour intervals for 3-D simulations.

4.5 Hydrological boundary conditions

The following hydrological data are required:

- Lake water level (m).

Water level is currently measured every 15 minutes by a pressure sensor installed on the central lake monitoring buoy (see daily average values presented in Figure 3c).

- Daily average discharge ($\text{m}^3 \text{d}^{-1}$) of the lake outflow (Mahiaruhe Stream).

Hooper (1989) noted that a weir was installed on the lake outlet in 1981 and the lake outlet has been observed to ‘backflush’ into the lake. Measurement of current would permit quantification of both the direction and volume of water discharged at the outlet. Relative water levels of the lake and outlet may also be used to infer direction of flow.

- Daily average discharge ($\text{m}^3 \text{d}^{-1}$) of each significant lake surface inflow.

Hooper (1989) described hydrological monitoring undertaken in the 1980s and Hooper’s summary of the mean discharge of inflows is reproduced in Table 4.

Table 4. Mean discharge of lake inflows, reproduced from Hooper (1989). Overland represents seepage and overland flow from the catchment.

Inflow	Mean discharge ($\text{m}^3 \text{s}^{-1}$)	Percentage of total water inflow (following Sandy creek diversion)
Kahikanui Stream	0.0152	35
Overland	0.0139	32
Oporae Stream	0.0052	14
Western Streams	0.0050	12
Waikopiro Inlet	0.0016	4
Hutt Stream	0.0018	4

Inflows to Lake Tutira are not presently monitored. Detailed monitoring of stream discharge typically involves installation of a weir and stage (water level) recorder, followed by undertaking water velocity measurements at different stage measurements to construct a rating curve. Where stream discharge measurements are not available, it may be possible to approximate average annual discharge from the catchment model CLUES (NIWA) although this model does not provide the sort of temporal resolution required by the lake model.

It is notable that the mean discharge of all stream inflows to Lake Tutira is low and overland flow and/or groundwater has been estimated to make a large relative contribution to the total inflow. This hypothesis is supported by the local rainfall characteristics and the small, steep nature of the catchment. Overland flow generally cannot be measured directly and additional hydrological modelling of the catchment may therefore be necessary to adequately estimate direct water input from the lake from overland flow or groundwater seepage. Such modelling would require high-resolution digital elevation data (e.g. 5-m horizontal resolution data obtained by LIDAR). Catchment-specific rainfall data (e.g. via a rainfall sensor installed at the monitoring buoy) could be used along with continuous lake level, inflow and outflow data to estimate the contribution of overland flow. At this scoping stage, it is assumed that the surface and groundwater catchments are contiguous and hence, with complete knowledge of surface hydrology, groundwater inputs could be estimated by difference. This assumption requires validation.

- Connection with Lake Waikapiro.

Lake Tutira is connected to adjacent Lake Waikapiro, and under certain hydrological conditions that two lakes exchange water. If water from Waikapiro represents a significant contribution to inflows for Lake Tutira, then quantification or estimation of water exchange between the lakes, as well as (ideally) monthly measurements of water quality for Lake Waikapiro would be desirable.

- Temperature of inflowing streams.

Knowledge of inflow temperature is important for modelling heat transfer in a lake. While it is possible to use empirical relationships (e.g. with air temperature) to estimate stream temperature, measurements of stream temperature (e.g. via in situ temperature probes) throughout diurnal and annual cycles are useful for model configuration.

4.6 Lake inflow water quality data

Nutrient (total and dissolved fractions of nitrogen and phosphorus) and suspended sediment concentrations of significant inflows are required.

The extent of current stream water quality monitoring is unknown. Hooper (1989) presents stream water chemistry data from the 1980s. These data provide useful reference although a more intensive data collection regime would be required to adequately estimate surface catchment inputs of nutrients to the lake. Given the particular importance of episodic high-intensity rainfall events to material transport in the lake catchment (e.g. Page et al. 1994), event-based sampling will be useful to derive relationships between discharge and determine concentrations for stream and overland flows, to permit accurate estimation of nutrient loads to the lake and have confidence in model simulations.

A suitable monitoring regime for inflows could include continuous gauging of discharge and temperature for major inflows, monthly sampling of inflow concentrations of dissolved inorganic and total nutrients and total suspended solids, as well as event-based (high rainfall) sampling (three or four times per year) of inflows and overland flows for a similar set of variables.

4.7 In-lake water quality data

In-lake monitoring of the following water quality variables is necessary to aid calibration of model parameters and validate model simulations. Sampling programmes should reflect vertical (and horizontal if necessary) heterogeneity in the lake.

- Dissolved oxygen
- Temperature
- pH (optional)
- chlorophyll *a* concentration
- Nutrient concentrations (NH_4 , NO_3 , PO_4 , TN, TP). Concentrations of SiO_2 are also useful if silica concentration is sufficiently low to potentially limit primary production by diatoms.
- Total and inorganic suspended sediment concentrations
- Phytoplankton species composition, abundance and biovolume
- Zooplankton species composition and abundance

Providing that the current monitoring is continued, data collected at the monitoring buoy and in the current monthly sampling programme are considered adequate to calibrate a one-dimensional coupled hydrodynamic-ecological model. It is, however, recommended that calculations to estimate phytoplankton biovolume are applied to existing and future phytoplankton monitoring based on cell counts. Biovolumes for cyanobacteria can be measured directly, or estimated using previously published values (see Wood et al. 2008), and would allow further insight to be obtained from phycocyanin fluorescence measurements made at the lake monitoring buoy. Such information would be valuable for validating simulations of cyanobacteria population dynamics.

4.8 Zooplankton, macrophytes and fish

Often, many model applications do not explicitly represent zooplankton biomass as data for this variable are limited. Instead, it is possible to substitute the effect of grazing by zooplankton with an increase in phytoplankton respiration rates. Zooplankton are often, however, an important component of food-webs in lakes and to adequately simulate zooplankton dynamics would require collection of monthly (optimally) or quarterly (minimum) species composition and abundance data. Representation of grass carp (and potentially macrophytes) in a model application could provide insight into the potential contribution of introduction of grass carp to lake water quality. Modelling higher trophic levels is typically difficult, however, due to compounding uncertainties and assumptions through the simulated food chain. Nevertheless, a model application to Lake Tutira represents a unique opportunity

because carp abundance in the lake is considered to be known (i.e. from the original introduction), and consumption/excretion rates may be able to be estimated from the literature. The presence and abundance of other fish such as rainbow trout, shortfin eels, common bully, goldfish, and *Gambusia* (Hofstra et al. 2008) could need to be considered along with simulations of grass carp. Macrophyte survey data (e.g. Hofstra and Champion 2008) would also be required for accurate simulations of grass carp grazing.

4.9 Potential for three-dimensional modelling

While the above discussion concerns one-dimensional models, lake managers may also wish to consider the potential value of applying a three-dimensional model to Lake Tutira. An example of such a model is ELCOM–CAEDYM which uses the ecological model (CAEDYM) common to DYRESM–CAEDYM. Advantages of applying a 3–D model include the ability to:

- Simulate horizontal phytoplankton distribution, including accumulations of buoyant cyanobacteria cells adjacent to the shoreline (important for recreational lake use).
- Simulate the pathways of lake inflows through the lake. This application may be useful, for example, if considering the effects of inflow diversions.
- Develop understanding of horizontal heterogeneity of lake water quality variables (e.g. chlorophyll *a* concentration).
- Improve understanding of horizontal and vertical circulation processes in the lake that drive transport of materials such as catchment–derived sediments.

Three-dimensional lake models generally require similar forcing data to one-dimensional models, but at hourly (rather than daily) temporal resolution.

Calibration and validation of horizontal variability ideally requires in-lake measurements at multiple sites. Empirical relationships between spectral satellite images and water quality variables can be used to assess the accuracy of 3–D simulation of surface horizontal variability (e.g. Allan et al. *in preparation*).

5 Overview of available catchment and lake management options

Lake restoration programmes typically comprise a suite of actions; objectives are rarely attained by implementing isolated actions alone. Long-term changes to catchment land management are usually required to achieve sustainable improvement of water quality in lakes that have been subject to eutrophication. However, shorter-term gains may be achieved using various in-lake actions.

A range of catchment (Table 5) and lake-based (Table 6) actions is described below. Where possible, potential relevance to Lake Tutira has been noted but the aim here is to provide examples of the range of potential actions that exist to set a basis for assessing potential suitability for Lake Tutira and identifying specific costs and benefits. The majority of actions are designed to reduce the concentrations of nutrients in the lake either by managing external (from the catchment) or internal (from the lake bed sediments) nutrient loads. An exception is bio-manipulation which is designed to control nuisance plants (macrophytes and algae) by ‘top-down’ control.

Table 5. Catchment-based actions to reduce in-lake nutrient loads.

Action	Details	Specific relevance to Lake Tutira
Land use change	Nutrient export varies with land use hence the redesign of catchment land use can greatly reduce external loads.	Nutrient export from hill pasture is high, particularly for phosphorus (P); e.g. mean P export from hill pasture ($1.98 \text{ kg P ha}^{-1}$) is twice that of dairy (1.0 kg P ha^{-1}) (Elliott & Sorrell, 2002).
Adoption of Best Management Practices (BMPs) by farmers	Examples include: <ul style="list-style-type: none"> Detailed soil testing (e.g. of Olsen P) to inform paddock-scale fertiliser requirements Use of nitrification inhibitors to reduce nitrogen leaching. The nitrification inhibitor dicyandiamide (DCD) has been withdrawn from the NZ market until standards have been introduced with regards to levels of DCD in milk. Use of low-solubility P fertiliser 	Current farm management practices were not considered during this study. Applicability of individual BMPs will vary and can be identified during development of individual Environmental Farm Plans in consultation with agri-environment specialists.
Soil conservation	Actions to minimise soil erosion will reduce sediment and particulate phosphorus loads. Examples include: <ul style="list-style-type: none"> Stabilising steep slopes with 	Particularly relevant to the catchment due to known problems of erosion and subsequent excess sediment and particulate nutrient loading during storms. Recommendations to retire erosion prone areas from farming and promote forestry at such sites were made in

	<p>planting or engineering interventions</p> <ul style="list-style-type: none"> • Incorporation of vegetative buffer strips alongside raceways or in ephemeral flow paths 	<p>the 1970s (Hooper, 1989). This study has not reviewed the status of these recommendations.</p>
Creation of riparian buffers	<p>Excluding stock access and planting in riparian margins reduces stream bank erosion and attenuates nutrient export.</p>	<p>A recommendation to “fence the lake reserve and streams to exclude stock” was made in the 1970s (Hooper, 1989). This study has not reviewed the current status of fencing.</p>
Wetland construction	<p>Constructed wetlands trap sediments and particulate nutrients, in addition to attenuating dissolved nutrients via processes such as plant uptake and denitrification. A wetland comprising 2.5–5% of the area of the upstream catchment may be expected to remove 40–50% of influent nitrate (Tanner et al., 2010).</p>	<p>The treatment performance of constructed wetlands is greatly reduced during periods of overland flow due to reduced water residence time. The suspected high relative importance of overland flow processes for sediment and nutrient transport in the catchment of Lake Tutira may therefore limit the potential value of this action.</p>
Drainage network manipulation	<p>‘Soft-engineered’ structures can be incorporated into agricultural landscapes to promote nutrient and sediment attenuation primarily by enhancing sediment settling rates. Such methods are established in Australia but are currently being developed for use in New Zealand (McDowell & Nash, 2012). Examples include sediment traps incorporated into agricultural drains and detainment dams designed to treat ephemeral streams.</p>	<p>The suspected high relative importance of overland flow processes for sediment and nutrient transport in the catchment of Lake Tutira suggests that detainment dams could be beneficial. Such structures are currently being trialled in high-rainfall areas west of Lake Rotorua. They are designed to temporarily pond ephemeral streams to attenuate sediment transport and storm flow discharge with minimal detriment to pasture quality.</p>
Installation of denitrification beds	<p>Denitrification beds comprise containers or excavated areas filled with a carbon source such as woodchips. They promote the conversion of nitrate to di-nitrogen gas by microbes.</p> <p>Trials elsewhere in New Zealand have shown that denitrification beds can provide a low-cost solution for near complete removal of nitrate from dairy shed effluent (Schipper et al. 2010). Results will depend on local soil type and topography.</p>	<p>The small size of stream inflows to Lake Tutira (Table 6) suggests that this action may be suitable for base-flow treatment but further scoping is necessary to assess potential for application.</p>

Table 6. Lake-based actions designed to improve water quality in eutrophied lakes

Action	Details	Specific relevance to Lake Tutira
Sediment capping / phosphorus inactivation	Addition of certain materials such as potassium aluminium sulphate ('alum') and proprietary products made by modification of clays can render nutrients unavailable for plant growth and 'seal' lake bed sediments. Bay of Plenty Regional Council has trialled a range of products to both reduce sediment nutrient release over annual time scales and control individual pre-empted algal blooms (Özkundakci et al., 2010).	Further work would be necessary to assess potential for this action to be applied to Lake Tutira. Alum application would require consideration of buffering to prevent pH related toxicity issues. Consultation with the community would be necessary as the issue of adding chemicals to waterways is potentially culturally sensitive.
Oxygenation/ destratification	Delivering oxygen directly to the bottom waters of a lake can prevent oxygen depletion and associated nutrient release from bottom sediments. Aeration can also be used to disrupt lake stratification and prevent the formation of oxygen-depleted bottom waters.	Six 'aerohydraulic guns' were previously deployed in 1975–1977 with the aim to prevent or disrupt the formation of vertical thermal stratification and thus prevent oxygen depletion in the bottom waters. The exercise was only partly successful (Teirney, 2009) but information gained could inform improved application of this technique. The bottom waters of Lake Tutira have a very high oxygen consumption rate which could make application of this technique challenging.
Dredging	Removes nutrients from the lake bed, reducing cycling through and from the sediments. A recognised method worldwide although it is expensive and a major logistical undertaking. Identifying a receptor site for dredged material can be difficult.	Sedimentation and consequent accumulation of nutrients in the bottom sediments are a known problem for Lake Tutira (Page et al. 2004).

<p>Diversion of nutrient rich inflows</p>	<p>Reduces nutrient inputs to the lake. May adversely affect water bodies downstream.</p>	<p>Sandy Creek has been diverted.</p>
<p>Hypolimnetic discharge</p>	<p>Involves removal of nutrient-rich water from the bottom layers while a lake is stratified and oxygen near the lake bed is depleted. Withdrawn water is then transported downstream of the withdrawal location.</p>	<p>Anoxic conditions and associated elevated dissolved nutrient concentrations are known features of the bottom waters of Lake Tutira during summer (Verberg, 2012). Hypolimnetic siphoning may be able to be used to reduce pumping costs but would require a more detailed consideration regarding feasibility.</p>
<p>Bio-manipulation</p>	<p>Organisms such as the freshwater mussel (<i>Hyridella menziesii</i>) can assimilate nutrients or consume algae. The efficacy and the potential for adverse ecological impacts are uncertain.</p>	<p>Grass carp have previously been introduced to Lake Tutira to graze on invasive macrophytes.</p>
<p>Construction of floating wetlands</p>	<p>Floating wetlands are being trialled in lakes Rotoehu and Rotorua in the Bay of Plenty. Aquatic plants remove dissolved nutrients from the water column.</p>	<p>In isolation, such an action is unlikely to result in attainment of ambitious restoration objectives for Lake Tutira. Such an action may, however, provide a focal point to help engage lake stakeholders in water quality issues.</p>

6 Conclusions

Poor water quality in Lake Tutira is not a recent problem. Several periods of regular (c. monthly) water quality measurements provide a vital record of the history of the lake. High frequency data collected by the lake monitoring buoy can aid in understanding the lake dynamics, particularly the occurrence of nuisance algal blooms which greatly detract from the recreational value of the lake but may not be captured well by routine monthly monitoring. Such data also highlight the significant effects of high-intensity rainfall events on lake water quality, in delivering large quantities of suspended particulate material to the lake. These events may be associated with increased delivery to the lake of bioavailable nutrients as well as nutrients in other forms that may be readily transformed into bioavailable forms. The highest recorded TLI values, however, occurred in the 1960s and 1970s. It would appear timely to review the recommendations made to improve lake water quality soon after this period in order to understand whether the recommendations were less effective than expected, whether they had not been enacted upon adequately, or whether some other factor is responsible for the observed increase in algal blooms in 2011–12.

There is evidence to suggest that nuisance cyanobacterial blooms have increased in recent years, both in New Zealand (Hamilton et al. 2013) and globally (Carey et al. 2012), possibly in association with a warming climate. Recent blooms in Lake Tutira could be driven at least in part by immediate climatic conditions. Observations in New Zealand and overseas lakes where grass carp have been introduced indicate a tendency towards increased trophic status following macrophyte removal by grazing (Gray 2012; Jeppesen et al. 2009). Further investigation would be required to establish if there is a link between grass carp introductions and algal blooms in Lake Tutira. The current lack of extensive submerged vegetation in Lake Tutira, together with recent observations of grass carp consumption of native emergent vegetation, indicates an urgent need to evaluate the ecosystem-wide effects of the grass carp introduction to the lake.

Lake Tutira is a good candidate for 1-D and/or 3-D model applications for detailed evaluation of a range of potential management options. Continuation of current monitoring and significant further data collection (e.g. inflow water quality) are essential to support configuration of such models. There are a wide range of lake management actions that are potentially suitable, but further work is necessary to fully assess feasibility and costs of individual actions. A lake model could be used to simulate the outcomes of various lake restoration measures, both individually and collectively, and would provide a suitable decision support tool for proposed lake management actions.

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8 Appendices

8.1 EnviroLink small grant application (HBRC: von Westernhagen)

**EnviroLink application for small advice grants
(up to \$5,000 excluding GST)**



Regional Council Advice number: 1274–HBRC183

Date:

15/11/12

Regional Council:

Hawke's Bay Regional Council

Advice requested by:

Nina von Westernhagen

Phone number: 06 833 8034

Email address: nina@hbrc.govt.nz

Proposed research organisation:

University of Waikato

Researcher nominated to provide the advice: Chris McBride

Type of ecosystem involved: Freshwater Terrestrial Atmospheric Marine

Please answer all questions so that your application can be fully considered.

1. Please give a short description that outlines the environmental management issue about which you are seeking advice:

Lake Tutira is a popular recreational resource in Hawke's Bay region. It has been subject to anthropogenic impact over a prolonged period. A number of interventions have occurred, aimed at improving water quality. These have included diversion of the primary inflow to the lake to reduce nutrient inputs and introduction of grass carp to reduce or eliminate Hydrilla infestation.

To date, none of the interventions have achieved the outcome desired. Permanent signposts now advise recreational users to avoid contact with lake water because of the incidence of potentially toxic cyanobacteria. Currently the lake is experiencing a severe cyanobacterial bloom. The grass carp have eliminated all macrophytes. The bottom waters of the lake experience prolonged periods of anoxia, which promotes nutrient release from sediments and fuels algal blooms.

Considerable monitoring data exists for the lake, including “continuous” depth profile data derived from a buoy equipped with state of the art thermistors, dissolved oxygen probes and a fluorescent phycocyanin (accessory pigment to chlorophyll) sensor. The phycocyanin concentration may be used as a surrogate for cyanobacteria concentration.

We believe that combining these temperature, dissolved oxygen concentration and algal concentration data with other long-term monitoring data (including climate, rainfall and inflow loads), coupled with application of recent assessment techniques will allow management options likely to improve lake water quality to be identified.

2. How will the advice allow you to positively address this issue to create benefit for your local community?

Nutrient enrichment of lakes, algal blooms and general decline in lake water quality is an international issue and is becoming increasingly common in New Zealand. The impact of grass carp on lake ecology was previously observed in Lake Omapare, Northland. The relationships between poor water quality of lake inflows, climate and rainfall events, ecological responses and management options have been studied extensively. Coupled hydrodynamic-ecological models (e.g. DYRESM-CAEDYM) have been developed.

Following assessment of the data available for Lake Tutira, the research team will be well-positioned to identify management actions most likely to improve lake water quality. Suitable land (i.e. catchment) and lake management actions will be identified.

They will also be able to recommend appropriate monitoring strategies.

Future improvement of lake water quality will only be possible if the incidence and severity of algal blooms is reduced. These conditions are only likely to change if management in the catchment and of the lake is altered. The advice will identify the actions required and who should undertake these actions.

3. How do you intend to use this advice?

The advice will provide the following information:

- a brief summary of the results of lake water quality monitoring
- a brief discussion of the changes in lake water quality in response to key human activities, rainfall events and climate variability
- a brief review of the literature to provide a context that links management actions with lake water quality improvements

- a discussion of management actions that may lead to an improvement in the condition of Lake Tutira, along with an indication of the timescale over which improvement may be anticipated
- a current water quality “report card”, with specific reference to recent occurrences of blooms of cyanobacteria
- an assessment of the short- and long-term impacts of grass carp introduction (respecting the limitations of available data), with reference to the impact of previous introductions of grass carp in New Zealand.

This information will guide HBRC and other stakeholders as follows:

- future lake monitoring will be optimised to allow lake improvement to be assessed
- management actions most likely to benefit lake water quality will be identified
- the implementation of various management options may be prioritised in terms of cost, overall efficacy and the time likely before improvement in lake water quality is observed.

4. Please choose which service(s) you would like the research organisation to provide.

- | | | |
|----------------------------------------------|--------------------------------------------|-------------------------------------------------------|
| <input type="checkbox"/> Seminar | <input type="checkbox"/> Training | <input type="checkbox"/> Informal Verbal Consultation |
| <input checked="" type="checkbox"/> Services | <input type="checkbox"/> Literature Survey | <input type="checkbox"/> Collating Research Material |

Other (Please specify) Collation of monitoring data, assessment and reporting.

Estimated budget:

Item	Description	Cost	Qty	Total
FTEs	Data collation, assessment and reporting	\$5000	1	\$5000
Subcontractor				
Materials				
Travel/ Accommodation				
Other				
Total (GST excluded)				\$5000

Can you attest that this request, to your knowledge, has not been answered in the past by either your council or another council's activities? Yes

This application has been sighted by your Council's Envirolink Coordinator?

Yes

Name of person completing form:
Westernhagen

Nina von

Please email completed form to the Envirolink contact for your selected research organisation.

To be filled in by research organisation

Approval is contingent upon the request for advice meeting Envirolink criteria and the ability of selected research organisation to fulfil the request.

Approval: Decision not made yet Approval date:

If no, give brief explanation: