NIWA
Taihoro Nukurangi

Updated model assessment of the effects of increased nutrient loads into Lake Benmore

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Ohau C Canal inflow entering Haldon Arm, Lake Benmore. [Donna Sutherland, NIWA]

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Extended summary

Lake Benmore, New Zealand's largest artificial lake, is located in the semi-arid and sparsely settled Mackenzie Basin in the central South Island. It is operated by Meridian Energy Limited as part of the Waitaki hydroelectricity power scheme. Lake Benmore is valued as a local, regional and national asset for its scenic, ecological, recreational, fishery and tourism values. The lake has two arms – the Haldon Arm and Ahuriri Arm – that are quite different in terms of their water quality and the character of their inflows. The smaller, western Ahuriri Arm receives inflow primarily from the Ahuriri River that drains the eastern flanks of the Southern Alps and flows through recently irrigated farmland before entering the lake. Additional flow enters the Ahuriri Arm from many small streams that drain the surrounding farmland. Inflow to the larger, northern Haldon Arm is dominated by water originating in mountains and glaciers of the Southern Alps, entering the Arm via diversions from Lake Tekapo, Lake Pukaki and Lake Ohau. The Haldon Arm also receives flow from its local catchment via the Tekapo River and the Twizel River, as well as several small streams. Although runoff from irrigated farmland also enters the Haldon Arm, land-use intensification has so far not matched the degree of intensification that has occurred in the Ahuriri Arm's catchment. Both arms join to form the Lower Benmore Basin which ends at the dam wall.

In 2009 NIWA provided, under contract, a model of Lake Benmore for Environment Canterbury (ECan) to assist with assessments of nutrient loadings on the lake ecosystem (Norton et al. 2009). The goal 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. 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 such as the Trophic Level Index (TLI).

More recently community participation in the Upper Waitaki Zone Committee deliberations has identified new opportunities for agricultural development in the basin and an assessment of the effects of these on the Lake Benmore ecosystem required a new modelling approach. This report completes a Contract (20th November 2013) between ECan and NIWA to "Produce an updated model assessment of the effects of increased nutrient loads into Lake Benmore on water quality".

As this project developed it became clear that the original set of contract objectives needed refinement because early modelling runs with updated lake inflow data raised questions about the adequacy of model validation. In addition, comparison of measured concentrations from river samples for some nutrients versus higher concentrations from in-lake samples pointed to possible insufficiencies in the input data for nutrient loading. The investigation of the areas of model performance that we were concerned with focused on:

1. Deficiency of the Lake Benmore model calibration;
2. Errors in laboratory analyses of water samples;
3. Input data not accounting for all of the important nutrient loads, due to:
   - changes to some of these subsequent to the 2008-09 data set;
   - relatively long time intervals between sampling; or/and;
   - failure to include all of the important sources in the sampling programme.

In August 2014, ECan requested a change to the way in which land use development scenarios were to be modelled. At this time ECan had, through a separate project, contracted NIWA to carry out catchment modelling to predict flows and N and P loads throughout the Waitaki catchment using the CLUES model. As a result ECan requested us to provide additional steps to those included in the original list of contract objectives:

1. NIWA to compare the input nutrient data from the model with the inputs from CLUES once these became available and check on any discrepancies and the reasons for these.
2. NIWA and ECan to agree on the inflow loads.
3. ECan to provide NIWA with the input scenarios for increasing N and P as land-use increases. We understood that the 2011-13 scenarios would be more prescriptive and complex in terms of increasing N and P than those used in the 2008-09 model.

Following these variations from the original contract specifications, our understanding of ECan's requirements for finalising this project were as follows:

- Assemble new input files for the coupled ELCOM-CAEDYM model. Run the model for the period July 2011 – March 2013 using the input files assembled in additional step 1, with the same model version and calibration used for the 2009 study. This provides an opportunity to validate the model and its calibration based on more recent data assembled in new input files.
- Use scenarios for land-use (and hence nutrient-loads) generated by ECan through their Upper Waitaki consultation process for CLUES modelling and adapt them for use with the lake model ensuring compatibility, as far as possible, between CLUES loads and flows and concentrations used for input to the lake model.
- Run the model for nutrient-load scenarios supplied by ECan and present results for lake ecosystem health attributes as a function of the nutrient-load scenarios.
- Provide graphs for model output (time series).
- Post-process model output time series to generate TLIs, and any other model parameters requested, and discuss results.

Input data

Daily hydrological and hourly meteorological input data used for the 2011-13 application were taken from the same sites as in the 2008-09 study. Nine sets of water quality samples were collected in the Ahuriri River, the Tekapo River and the Ohau C Canal where these inflows enter the lake at approximately fortnightly intervals from 20 December 2011 – 17 April 2012. In-lake samples at three depths were also collected on the same dates at the same sampling sites as used in 2008-09 in the Ahuriri Arm, Haldon Arm and Lower Benmore Basin. Sample collection and analyses followed the same protocols as for the 2008-09 study. Sample collection and analyses followed the same protocols as for the 2009 study. A more limited sampling and analytical programme was undertaken from 12 June 2012 – 27 February 2013, during which nine sets of samples were collected at approximately monthly intervals from the inflow sites and 0-10 m integrated tube samples collected at the in-lake sites. An effort was made to incorporate time-dependence in the nutrient input files instead of using average values over the model run period as in the 2008-09 study. Regression equations for phosphorus concentrations as a function of flow were established for the Ahuriri River, allowing daily values of phosphorus concentrations to be generated for the Ahuriri River input file. However, no meaningful relations for concentration vs. flow could be established for nitrogen or carbon in the Ahuriri River, or for any nutrient in the Tekapo River or the Ohau C Canal. For these inputs, linear interpolation between sample point values in time was used to assemble input files for the model.

In order to address potential errors in laboratory analytical methodology, and therefore variability of observed values of sampled water quality variables, a one-off inter-laboratory comparison was undertaken at four laboratories that routinely carry out both chlorophyll-*a* (Chl-*a*) and TN analyses. The results gave us no cause for concern that laboratory analytical results were a significant issue that would affect the interpretation of model results.

In order to address the concern over input data not accounting for all of the important nutrient loads, we identified ungauged flows in the Ahuriri Arm catchment as potential high nutrient sources, and a water quality survey of the small ungauged streams entering the Ahuriri Arm undertaken in June 2014 showed high nutrient concentrations in these streams. These were used in the load calculations for ungauged flows that entered the Ahuriri Arm. We also identified an unaccounted-for source of nutrients from a major aquatic weed-kill event (spraying of 74 ha of *Lagarosiphon major* with Diquat) in the upper Ahuriri Arm in March 2012, and incorporated the effects of nutrient release from *L. major* decay in the model input.

Results

Model validation

The model validation involved comparing observed versus simulated nutrient and Chlorophyll-*a* (Chl-*a*) concentrations over the time period of the study.

In the Haldon Arm the model under-estimated observed concentrations of Chl-*a*, TN and dissolved organic nitrogen (DON) in the lake surface waters by as much as one half at some times. The model was able to adequately simulate surface nitrate-N (NO_3-N) and ammonium-N (NH_4-N). The model tracked the annual pattern of increasing bottom water (50 m depth) NO_3-N during the lake's summer stratified period but simulated concentrations were lower than observed. TP and dissolved reactive phosphorus (DRP) were adequately simulated by the model except for DRP in Haldon Arm bottom waters in summer. The largest organic constituents of the Haldon Arm were all adequately simulated in the model with the exception of dissolved organic nitrogen (DON).

In the Ahuriri Arm, Chl-*a* and nutrient levels were generally higher than in the Haldon Arm but again the model tended to under-predict Chl-*a* concentrations and did not reproduce several of the higher observed Chl-*a* values. In contrast, concentrations and annual patterns of NO_3-N, TP and DRP were well represented by the model. The model also adequately simulated the organic components of the Ahuriri Arm with the exception (as in the Haldon Arm) of DON, particularly in winter.

In the Lower Benmore Basin results of observed and simulated values for Chl-*a*, TN and DON followed the same patterns as those in the Haldon and Ahuriri Arms such that simulations of these three variables were lower than the observed values. The model simulations of the other variables closely matched observed values.

In general the matching of the in-lake observations for Chl-*a* was not as good as it was in the 2008-09 modelling, with a tendency in the present study to under-predict Chla-*a*. DON and hence TN were also under-predicted. This suggests that the 2011-13 model results for scenarios must be considered as likely to underestimate impacts of nutrient increases on lake trophic state.

The underestimation of TN in the modelling runs was attributed to the high contribution of DON. It appears from the input data that DON concentrations in the lake were almost double those in the measured inflows (ca. 0.1 g m^{-3} in the Haldon Arm vs. ca. 0.05 g m^{-3} in Haldon inflows)' and for the Ahuriri Arm (ca. 0.15 g m^{-3} in the lake vs. ca. 0.07 g m^{-3} in the inflows). This indicates either the formation of DON in the lake waters at levels that cannot be accounted for in the model, or the existence of an unaccounted-for source in the inflows. One potential source was shown to be small ungauged streams entering the Ahuriri Arm. However, clarification of this is impossible until all inflow sources have been properly accounted for. Note, however, DON in lake waters is generally regarded as refractory and unlikely to contribute directly to phytoplankton growth.

Modelling of the Trophic Level Index (TLI) was the primary mechanism for assessing effects of the changing land-use scenarios. In 2008-09 the mean summer TLI in both the Haldon and the Ahuriri Arms calculated from model output was slightly lower than observed TLI calculated from observed samples.

In 2011-13, model predictions for summer TLI were calculated from model output averaged over two summers – 2011-12 and 2012-13 – while measured TLIs have been calculated separately for each summer. This is because of the different sampling protocols used in the two summers (see Section 2.2), and because only three samples were collected for summer 2012-13, compared with seven samples for 2011-12. In the Ahuriri Arm, the TLI calculated from 2011-12 samples agreed well with modelled 2011-13 (two-summer) TLI, but TLI calculated from 2012-13 samples was significantly higher than the modelled 2011-13 TLI. The three samples collected in the summer of 2012-13 yielded significantly higher TLI values than in the previous years. In the Haldon Arm, modelled mean summer TLI results were similar to observed mean summer TLI results, although TLI-TP (the TLI component calculated from TP) was over-predicted due largely to a significant flood event and TLI-Chl-*a* was under-predicted. Overall it appears that modelled TLI in both 2008-09 and 2011-13 years is slightly underestimated relative to observed values.

Analysis of diagnostic model results showed that the model predictions for the production of Chl-*a* (diatom phytoplankton growth) in the Ahuriri Arm for 2011-13 were controlled in summer by low P concentrations. This contrasted with the situation in 2008-09, when the phytoplankton growth in the model was limited by availability of both N and P. Co-limitation by both N and P was apparent in the Haldon Arm in both modelling studies. Variability in nutrients limiting phytoplankton growth between sampling occasions points to the need for a precautionary approach to single nutrient catchment controls. Results from our two sets of modelling (2008-09 and 2011-13) suggest that both N and P have the potential to limit growth in different time periods.

Although the time series data showed some discrepancies between observed and modelled individual values for some of the parameters (eg Chl-*a*, TN, DON), the close overall fit between modelled and observed in TLI calculations provides comfort that, at the general indicator level that TLI provides, we were able to successfully model the effects of nutrient additions on overall lake water quality.

Estimation of catchment loading

Although efforts were made to include previously unaccounted-for nutrient sources in the inputs to the Ahuriri Arm, and to incorporate time dependence in the input time series, the failure of the model to more closely predict observed in-lake concentrations of Chl-a and TN in both arms points to the difficulties of accurate estimations of nutrient load inputs to the lake model.

During the course of the work reported here it became apparent that further land-use intensification had taken place in the Lake Benmore catchment since the 2009 work had been reported. This is illustrated in an analysis of remote sensing data undertaken by Mathew Allan and David Hamilton, University of Waikato. Much of the potential nutrient loading that may have been introduced by these recent developments may not have been assessed by the monitoring programme that was originally designed for the 2009 study. Sampling and analysis of small ungauged catchments to the north and south of the Ahuriri Arm on one occasion in June 2014 showed high nutrient concentrations. To better predict nutrient loads to the Arm we recommend improved nutrient monitoring of small surface and groundwater inflows to improve understanding of the ungauged catchment nutrient loads.

We note that nutrient loads input to the lake model, while mostly of a similar magnitude to those predicted by the CLUES model, were not identical in value to those predicted by the CLUES model. This is because of fundamental differences between how the lake model and CLUES operate, the time scales that the two models focus on, and the level of detail they produce. We have tried to make the CLUES and lake model loads as compatible as possible, both for the model validation run and for the scenario runs.

Scenario testing

Four increased-nutrient-load scenarios were provided by ECan, referred to as 1a, 2a, 2b and 1a2a (a variation of loadings from 1a and 2a). The relative complexity of the 2011-13 scenarios, with varying N and P levels depending on the types and locations of agricultural activity, made it necessary to present the modelling results in both table and graphical forms. The much simpler graphical format utilised in 2008-09, where scenario N and P loads in both Arms could be characterised by a single load multiplier (Norton et al. 2009, Fig. 16 and 17), could not be used for the present study. The results for the scenarios showed that in the Haldon Arm the mean TLI increased from 2.59 to 2.71 from Scenario 1a to 2a and then only slightly to 2.72 in Scenario 2b. Values were higher in the Ahuriri Arm, increasing continuously from 2.91 in Scenario 1a to 3.25 in Scenario 2b. Modelled TLIs for the Lower Benmore Basin were slightly less than in the Haldon Arm.

The scenario testing showed trends of rising TLIs with scenario load inputs in a pattern that was expected and explainable. The scenarios suggest that in the case of Scenarios 2a and 2b, there is a need for close management of nutrients in the Ahuriri Arm catchment as the results show a strong potential for the TLI exceeding 3.0.

Final Comments

The sensitivity of the Ahuriri Arm to nutrient additions has been confirmed. Modelling results from both the current study and the 2009 study suggest the need for dual nutrient control involving both N and P in the Waitaki catchments.

The model predictions for lake change, particularly with regard to Chl-*a*, are under-estimates. This could be due to underestimation of nutrient input loads, deficiencies in model calibration / formulation, or a combination of both. Given that the model was better able to simulate Chl-*a* in

2008-09 and that for parameters modelled in 2011-13 it was only DON and Chl-*a* that were consistently underestimated, it is more likely that we have not correctly accounted for inflow loads rather than there being a significant issue with model formulation.

Given these caveats the study shows that lake ecosystem health as defined by the Trophic Level Index (TLI) will decline in the face of several of the scenarios for change that the model was asked to evaluate. This detailed modelling study has emphasised the need for precaution in the management of nutrients in the upper Waitaki lake catchments and particularly the catchment leading to the Ahuriri Arm.

1 Introduction

1.1 Background

The lakes of the Upper Waitaki Basin are a local, regional and national asset for their ecological, recreational, commercial and tourism values. The waters of the lakes are currently classified as oligotrophic, although the Ahuriri Arm is close to the boundary of oligotrophy / mesotropy and, at times, enters into the mesotrophic level (Meredith and Wilks, 2006, Sutherland et al. 2013).

Land-use in the Upper Waitaki catchment has historically been low-intensity, dryland sheep farming, with little irrigated land. However, in recent years there has been a shift in land-use to dairying and dairy support with associated increased irrigation. Water quality is a key concern when land-use is intensified because there is a need to manage increased contaminant loads (e.g. nutrients, sediments and microorganisms) entering the waterways in order to maintain the values of the downstream lakes. The impact of land-use intensification on water quality in the lakes and rivers of the Upper Waitaki Basin was the central focus of an Environment Canterbury consent hearing in 2009, where approximately 100 water application rights were sought in the Upper Waitaki Basin.

In an effort to better understand the likely effects of cumulative land-use intensification on the water quality of Lake Benmore, Meridian and Environment Canterbury (ECan) co-funded the Lake Benmore Water Quality model and field study described in Norton et al. (2009). The model study assessed the impacts of increasing loads of nitrogen (N) and phosphorus (P) on water quality in the individual basins of Lake Benmore. The model was used to predict the relationship between nutrient load, in particular total nitrogen (TN) and total phosphorus (TP), and measures of lake condition, such as phytoplankton chlorophyll-*a* (Chl-*a*) and the Trophic Level Index (TLI). The outputs from the model were intended to be used as an aid to assist ECan with assessments of effects in Lake Benmore when setting nutrient load limits in the catchment. The model and its parameters are described in Section 2.1, below.

The model was calibrated against one intensive summer-time water quality monitoring dataset. Unfortunately, no other suitable water quality data for the Upper Waitaki Catchment was available at the time of the model development. The calibration summer-time dataset was collected in 2008-09, a summer period that was marked by high rainfall in the catchment, resulting in frequent medium sized floods in the Ahuriri catchment and a prolonged spill period (approximately one month) from Lakes Tekapo and Pukaki in the Haldon catchment.

Conclusions drawn from the 2009 model strongly indicated that the Ahuriri and Haldon Arms of Lake Benmore behaved differently in response to increased nutrient loads, with the Ahuriri Arm being more sensitive to nutrient increases than the Haldon Arm. This was primarily due to the relatively smaller inflow and longer residence time in the Ahuriri Arm compared to the Haldon Arm, as well as the significantly larger glacial derived inflows into the Haldon Arm that are largely unaffected by catchment development. As a result, Norton et al. (2009) recommended that the two arms be considered separately in terms of setting management objectives and nutrient load caps. In addition to this, the model predicted that water quality in the Lower Benmore Basin was strongly influenced by the Ahuriri Arm. Thus, by managing the Ahuriri Arm, the Lower Benmore Basin is likely to be managed by default.

Since the 2009 model study, a number of meetings involving various stakeholders and the Upper Waitaki Zone Committee were held and new opportunities for agricultural development in the Upper

Waitaki Basin were identified. Therefore, in order to better understand how these developments may impact on the water quality and the associated lake biota of Lake Benmore, a new modelling effort was required. ECan commissioned NIWA to produce an updated model assessment of the effects of increased nutrient loads into Lake Benmore on the lake's water quality.

1.2 Scope of Work

1.2.1 Initial contract specification and investigations

Initially, NIWA was contracted to "produce an updated model assessment of the effects of increased nutrient loads into Lake Benmore." This consisted of three steps:

1. Assemble new input files for the coupled ELCOM-CAEDYM model. These input files included metrological, hydrological and water quality data that span the period December 2011 – February 2013, incorporating the intensive fortnightly sampling from December 2011 – April 2012, and the less intensive monthly sampling from June 2012 – February 2013.

2. Run the model for the period December 2011 – February 2013 using the input files assembled in step 1, with the same model version and calibration used for the 2009 study. This would provide an opportunity to validate the model and its calibration based on more recent data.

3. Generate land-use (and hence nutrient-load) scenarios as in the 2009 study, but with inflow nutrient concentrations for the scenarios based on the new input files developed in step 1 above. Run the model for these scenarios as in the 2009 study using hydrological and meteorological data for the period 1 August 2003 – 31 July 2004, a year that best typified climate, inflow and output variables for the Upper Waitaki Basin.

The initial contract specified a completion date of 31 March 2014 with the understanding that the scenarios were to follow the relatively simple format of the 2008-09 work, where a single nutrient multiplier was sufficient to characterise the complete scenario configuration for both N and P loads and for both Arms of the lake. A subsequent contract was then to be considered following ECan's development of more complex scenarios. These scenarios were to account for more extensive and detailed knowledge gained since the 2008-09 study of potential loads in terms of both quantity and spatial variability. This knowledge would reflect results of ECan's consultation process as well as findings from expanded research undertaken since 2009.

Modelling did not start until mid-March 2014 because of delays in receiving flow and water level data from several sites monitored by Meridian Energy Limited. Data had been requested as soon as the contract with ECan was signed in November 2013, but the complete dataset was not available until mid-February 2014.

Unsatisfactory model predictions for some variables from the initial model run, when compared with 2011-13 observed lake water quality data, raised early questions about the adequacy of model validation in step 2. In addition, discrepancies between nutrient concentrations measured in river inflows compared to those measured in-lake pointed to possible insufficiencies in the river inflow input data for nutrient loading. Our concerns were conveyed in a presentation to Mr Ned Norton and Dr Adrian Meredith of ECan on 23 May 2014. Following that meeting, it was agreed that it was necessary to resolve these issues before running the model with increased nutrient-load scenarios for step 3. Investigation of the reasons for the unsatisfactory model performance delayed the start of scenario testing until late September 2014. Concurrently, a different NIWA project had developed the complex scenarios required to predict potential annual loads of TN and TP to rivers and lakes throughout the Waitaki catchment. This was achieved using the CLUES runoff model (Palliser et al. 2015).

Three areas of concern were identified as potential explanation for the unsatisfactory initial predictions of the lake model. These areas of concern were:

i. Deficiency of the model calibration, i.e., incorrect values of some model parameters, used for the 2008-09 model runs;

ii. Errors in laboratory analyses of water samples;

iii. Input data not accounting for all of the important nutrient loads, due to: (a) changes to some of these subsequent to the 2008-09 data set; (b) relatively long time intervals between sampling; or/and (c) failure to include all of the important sources in the sampling programme.

Detailed discussion of these areas of concern are given in Section 2.2 below. We point out here that the main problem was found to be that described in (iii), and most of our efforts to improve model performance focussed on trying to improve the representation of input data. This effort concentrated chiefly on the Ahuriri Arm, due to reduced model performance for the Ahuriri Arm compared to the Haldon Arm, as well as due to the Ahuriri Arm's greater sensitivity to increases in nutrient load than the Haldon Arm. Our emphasis on the issues raised in (iii) is consistent with increased development in the lake catchment that has occurred since the 2008-09 study.

1.2.2 Revised contract specifications

At a meeting in July 2014, ECan suggested that we re-examine correlations between P concentrations and flow in the Ahuriri River. The purpose of this was to develop regressions that would allow a better representation of daily P concentrations for model input than was possible by linearly interpolating between values from fortnightly or monthly samples. Examination of scatter-plots for nutrient concentrations versus flow in all inflows had indicated lack of meaningful correlation for all nutrients, with the exception of P in the Ahuriri River (see Appendix A).

At a meeting in August 2014, ECan requested a change to the way in which scenarios were to be modelled. The difficulties that we had encountered in adequately representing nutrient loads for the 2011-13 model runs had made it clear that input files needed to account for a more complex distribution of loads than that used in the 2008-09 study. The modified loadings that made it possible to obtain a satisfactory validation of model predictions accounted for variations between sub-catchments as well as variability in weather and flow over time. These additional complexities meant that the relatively simplistic approach for establishing scenario loadings used in 2008-09, and as envisioned in the initial contract for the 2011-13 work, was no longer adequate to provide useful predictions of future conditions.

At the time, ECan had contracted NIWA to carry out catchment modelling to predict flows and N and P loads throughout the Waitaki catchment using the CLUES model. At the August 2014 meeting ECan requested that we ensure that CLUES loads were made as compatible as possible to our methods for providing input loads to the lake model.

The agreed changes were:

- NIWA to compare the input nutrient data from the model with the inputs from CLUES once these were available and check on any discrepancies and the reasons for these;
- NIWA and ECan to agree on the inflow loads;
- ECan to provide NIWA with the input scenarios for increasing N and P as land-use intensified. The 2008-09 model scenarios were based on simple multiples of TN and TP loads from current land-use, with an adjustment that allowed for a relative increase in soluble nitrogen and phosphorus species at higher levels of intensification. We understood that the 2011-13 scenarios would be specified in greater detail in terms of the amounts and locations of increased N and P loads.

The loadings for scenario testing were initially presented to NIWA by ECan at a meeting on 23 September 2014. Some refinements and clarifications were made subsequently, but the basic strategy of using loadings from the CLUES model remained the same. However, there are fundamental differences between the way the lake model and CLUES model operate, the time scales they focus on, and the level of detail they provide. As a result, transforming CLUES model output into a form suitable for running the lake model was not completely straightforward. Differences between the two models, and between output from CLUES model and input for the lake model, are discussed in more detail in Section 2.7. The same meteorological and flow data were used for validation of, and scenario testing with, the lake model. The measured nutrient inflow data used for the validation stage provided the basic framework for the scenario input files, but the *relative* increases in annual TN and TP loads for each scenario were obtained from the CLUES model output. Further detail is given in Section 2.7.

Following these variations from the original specifications, the following list of objectives for modelling the future water quality in Lake Benmore under land-use intensification were agreed:

1. Assemble new input files for the coupled ELCOM-CAEDYM model. These input files include:
   - Hourly metrological and daily hydrological data from 2011-2013,
   - Water quality data that span the period December 2011 – February 2013, incorporating the intensive fortnightly sampling from December 2011 – April 2012, and the less intensive monthly sampling from June 2012 – February 2013, plus incorporating additional data from sampling around Ahuriri Arm (9 June 2014), plus the additional nutrient inputs from aquatic weed control,
   - Results from correlations between river inflow discharges and nutrient concentrations.
2. Run the model for the period July 2011 – March 2013 using the new assembled input files, with the same model version and calibration used for the 2009 study. This provided an opportunity to validate the model and its calibration based on more recent data.
3. Use scenarios for land-use (and hence nutrient-load) generated by ECan through their upper Waitaki consultation process for CLUES modelling and adapt them for use with

the lake model ensuring compatibility as much as possible of CLUES flows and loads with flows and concentrations used for input to the lake model.

4. Run the model for nutrient-load scenarios supplied by ECan as modelled by CLUES; present results for ecosystem health attributes as a function of the nutrient-load scenarios. The scenarios would run over the same time period as used for the model validation (1 July 2011 – 26 March 2013) and use the full validation-run input data-set as the basis for assembling new input files for increased N and P loads.

5. Provide graphs for model output (time series).

6. Post-process model output time series to generate TLIs and any other model parameters requested.

2 Methods

2.1 The models

The models that were used for this study were developed by the Centre for Water Research (CWR), University of Western Australia (UWA) – ELCOM (**E**stuary **L**ake and **C**oastal **O**cean **M**odel) and CAEDYM (**C**omputational **A**quatic **E**cosystem **D**ynamics **M**odel). These are complex, process-based (mechanistic) models that simulate coupled hydrodynamic, water quality and biogeochemical cycles in aquatic ecosystems. They were used 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.

NIWA's use of the executable and source codes for these models was subject to a contract between the University of Western Australia and NIWA.

ELCOM is a three-dimensional hydrodynamics model used for predicting the velocity, temperature and salinity distributions in lakes, reservoirs and coastal systems. ELCOM models hydrodynamic and thermodynamic variables in three dimensions in individual grid cells. For the Lake Benmore application, the ELCOM grid consisted of cells with horizontal dimensions of 400 m by 400 m and depths of 2.5 m (Figure 2-1); a time step of 300 seconds was used. Because of its extensive demands on computer processing and memory resources, ELCOM was originally designed for simulations on time scales of days to weeks, although it can be run for much longer periods depending on available time and computing resources.

CAEDYM is a complex ecological model that simulates the cycles of carbon (C), N, P, silicon and dissolved oxygen (DO) in freshwater or marine ecosystems; phytoplankton dynamics; and inorganic suspended solids. The model has been used largely for assessments of eutrophication, being of the nutrients – phytoplankton – zooplankton model format, but it also includes several other state variables not used in the present application to Lake Benmore.

CAEDYM is not operated as a stand-alone model; it is usually coupled with a hydrodynamic model that provides a framework for basin structure and bathymetry, water movements (mixing and circulation), river inflows, outflows, and heat exchange with the atmosphere. In this study, CAEDYM was run coupled with ELCOM. A three-dimensional modelling approach was necessary to account for the complex shape of Lake Benmore and the possible interactions between its basins. This was confirmed in simulations with ELCOM in the 2008-09 modelling process that showed extensive water exchange between the Haldon, Ahuriri and Lower Benmore basins (Norton et al. 2009).

The model runs for the present study all start at noon on 1 July 2011, and end at noon on 25 March 2013 (633 days); this covers the period during which water quality samples were collected from river and lake sampling sites (20 Dec 2011 – 27 Feb 2013), with a lead-in period starting with uniformly mixed conditions in winter. As noted in the 2009 report (Norton et al. 2009), computational demands of the three-dimensional model, together with the time-frame specified for project completion, precluded the use of ELCOM-CAEDYM for long-term (multi-year) runs.

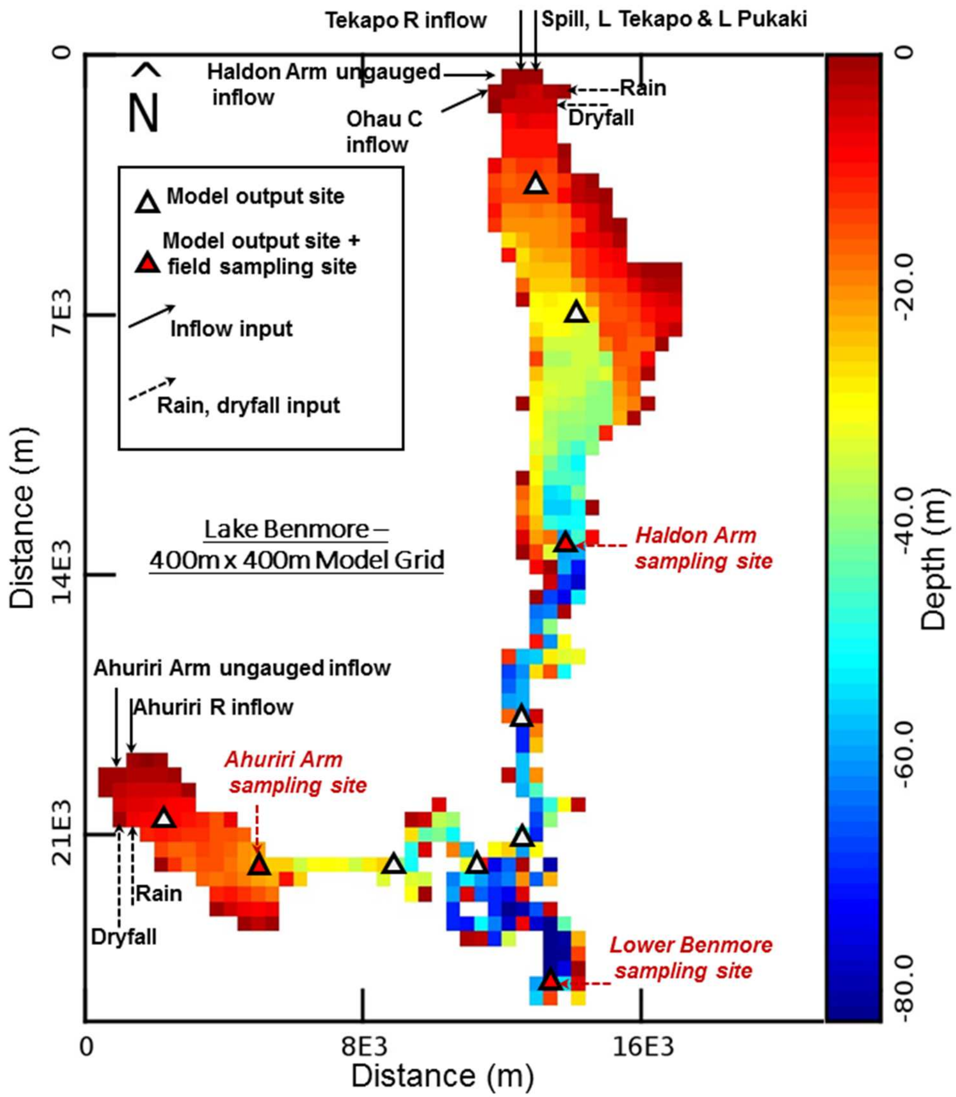

Figure 2-1: 400 m x 400 m model grid used for the Lake Benmore model application. The following locations are shown: boundary input sites for gauged river flows, ungauged flows from water balance residual, rainfall and dryfall); in-lake sites where field samples were collected and model output saved for post-processing (red triangles); and in-lake sites where additional model output was saved for post-processing (white triangles).

We used stable executable code provided by CWR under the terms of a contract between NIWA and UWA for the coupled models ELCOM-CAEDYM (release 19 June 2006).

CWR's first lake model – DYRESM (Dynamic Reservoir Simulation Model) – was originally developed the 1970's; DYRESMWQ, the precursor to DYRESM-CAEDYM, in the 1980's; and CAEDYM and ELCOM in the 1990's. Although CWR has recently closed down (in June 2015), the models have been, and continue to be, used extensively and actively developed by the international modelling community. The quality and reputation of the models is reflected by the number of publications in the international scientific literature describing research that uses the models. A more comprehensive list of these publications prior to 2008 is provided in the 2008-09 report to ECan (Norton et al 2009).

2.2 Input data

2.2.1 Introduction and commentary

Daily hydrological and hourly meteorological input data used for the 2011-13 application were taken from the same sites as in the 2008-09 study (see Figure 3 in Norton et al. 2009), and most of the description in Section 3.2 of Norton et al. (2009) is still applicable to the present study; changes will be noted below. The boundary sites on the model grid where inflows enter the lake in the model are also the same (Figure 2 in Norton et al. (2009) and Figure 2-1 above). The location of water quality sampling sites for inflowing rivers (Ahuriri River at Ahuriri Arm, Ohau C Canal at Haldon Arm, and Tekapo River at Haldon Arm) are the same as in the 2008-09 study, as described in Section 3.2 of Norton et al. (2009). In the present study, additional water quality samples were collected on 9 June 2014 (one day only) from ungauged streams entering the Ahuriri Arm for two purposes: (1) in an effort to better estimate nutrient loads from ungauged (and previously unsampled) inflows to the Ahuriri Arm, and (2) for purposes of inter-laboratory comparison of analytical results. Both of these aspects are referred to below and have been mentioned in Section 1.2. In-lake sites where field data for water quality were collected for model validation are also the same as in 2008-09 (Figure 2 in Norton et al. (2009) and Figure 2-1 above).

Ungauged inflows of water, including any net groundwater inflow to the lake, were estimated as residuals from a lakewide water balance that accounted for all gauged inflows and outflows, rainfall, evaporation and changes in lake storage. A single point source was included for ungauged inflows in each Arm (locations shown in Figure 2-1, inflow time-series in Figures 2-2 and 2-3). In order to decide how much of the total ungauged (residual) inflow should be apportioned to the Haldon Arm and how much to the Ahuriri Arm, we used the CLUES model (Woods et al. 2006) to estimate mean annual inflows to both Arms from all streams and rivers. Based on the relative proportions of the inflows predicted by CLUES, in 2008-09 we allocated 90% of the total ungauged (residual) inflow to the Haldon Arm and 10% to the Ahuriri Arm. However, updating of CLUES since 2009, including its modification to account for diversions of flows for the Waitaki hydroelectricity scheme, has produced a revised estimate for ungauged inflow to the Haldon Arm, and hence a change to our partitioning of the water balance residual between the two arms of the lake; in the present study we have allocated 76% of the total water balance residual as ungauged inflow to the Haldon Arm, and 24% as ungauged inflow to the Ahuriri Arm. However, since the completion of this study further review of the lake's water balance compared with CLUES flow predictions have led us to conclude that these percentages should be revised again, as discussed below in the final paragraph in this section

As in the 2008-09 study, nutrient concentrations from the Tekapo River samples were assigned to the ungauged inflows to the Haldon Arm – i.e., while the daily flows in the input file for the Haldon

Arm ungauged inflow were derived from water balance, the daily nutrient concentrations were the same as those in the Tekapo River input file.

In the 2008-09 study, ungauged inflows to the Ahuriri Arm were assigned concentrations measured in the main channel of the Ahuriri River mouth. However nutrient concentrations obtained from the water quality survey that was carried out by ECan staff on June 19th 2014 of the small ungauged streams entering the Ahuriri Arm (see Section 2.2.4 and Appendix B) indicated that concentrations measured in the main channel of the Ahuriri River mouth underestimated nutrient concentrations in the small ungauged streams entering the Ahuriri Arm, especially for NO_3-N but also for DON, DRP and DOP. In our opinion the results from this survey provide a more realistic representation of concentrations in ungauged flows entering the Ahuriri Arm than do the concentrations measured in the Ahuriri River. In the present (2011-13) study, we have assigned average concentrations from the 19 June 2014 samples to the Ahuriri Arm ungauged inflows for the entire 633-day duration of the baseline (i.e., validation of current conditions) model run. The concentrations measured in the 19 June 2014 samples are shown as dashed green lines in Figures 2-4 – 2-7, and can be compared with the symbols showing concentrations from samples collected in the Ahuriri River.

No quantitative information was available to us concerning either the quantity or quality of existing groundwater inputs to Lake Benmore. Neither was any information available regarding how such inputs are likely to change with intensifying land-use and irrigation. In the model all net groundwater inputs are incorporated in the ungauged inflows, and the water quality of groundwater is assumed to be that of the ungauged inflow for each basin.

Temperatures in the inflows have been modelled by sinusoids with a period of one year fitted to earlier data recorded by loggers for the 2008-09 work, and to temperatures measured intermittently during flow gaugings conducted by hydrologic survey field teams.

As noted above, since completion of the model study further review of the water balance compared with CLUES predictions suggests that the figures for partitioning the total positive residual of the lake water balance is closer to 17% for the Ahuriri Arm and 83% for the Haldon Arm, rather than the 24% - 76% partition used in the input for the present study. This corresponds to an overestimation of mean annual flow to the Ahuriri Arm in the current study of 9.5% and an underestimation of mean annual flow to the Haldon Arm of 1.1%; there is no change to the total lake inflow. In terms of nutrients, the change implies an overestimation of annual TN load to the Ahuriri Arm in the current study of 15.6% and of TP of 3.5%. For the Haldon Arm the change implies an underestimation in the current study of TN load to the Haldon Arm of 2.34% and of TP of 1.14%. The net result for the whole lake is an underestimation in the current study of 2.6% in annual TN load and 0.23% in annual TP load. Further details for the values of flows and loads are given in the accompanying supplementary spreadsheet. However, concentrations in Figures 2-4 – 2-7 for inflows remain unchanged.

Discovery of the suggested revisions has come too late for them to be incorporated in the model runs for the present study. With the exception of the 15.6% overestimation of TN load to the Ahuriri Arm, the errors in load implied by the suggested changes to ungauged inflow ratios are all well within the range of errors to be expected for model inputs and predictions. If the same percentage error for annual TN load were to be carried forward to in-lake predictions of summer mean TN concentrations in the Ahuriri Arm (and there is no way of knowing if this would be the case without rerunning the model), then the TLI-TN predicted for the current scenario in the Ahuriri Arm (Table 3-1) would be reduced from 2.78 to 2.59 (a decrease of 6.8%), and the mean TLI from 2.85 to 2.78 (a decrease of 2.2%). This would give a better match to the measured TLI-TN (2.63) and the measured mean TLI

(2.76) for the Ahuriri Arm during 2011-12 (see Table 3-1). Similar results would likely be applicable to scenario predictions.

2.2.2 Efforts to incorporate time variability in inflow concentrations

In the 2009 model study, concentrations in the inflows had been assigned constant values for the duration of the model run that were equal to averages of values from six sets of samples collected between 8 December 2008 – 17 February 2009. As explained in Norton et al. (2009; Section 3.2) we had been constrained to use averages because of the small number of samples available – only four sets had been analysed when the model calibration process started. A similar averaging approach was implemented for the present study for the initial model run in order to be consistent with the methods used for the 2008-09 study. For the initial run the nutrient concentrations used in the input files were averages over three periods: from 1 July 2011 – 30 April 2012, averages of concentrations from the nine fortnightly samples collected from 20 December 2011 – 17 April 2012 were used; from 1 June 2012 – 25 March 2013, averages of concentrations from the nine monthly samples collected from 12 June 2012 – 27 Feb 2013 were used; and a transition period for 1 – 31 May 2012 used averages of the two averages for the fortnightly and monthly samples.

As noted in Section 1.2.1, unsatisfactory model predictions for some variables from the initial model run led us to try and improve the representation of input data. We felt that one way to do this was to incorporate the time variability of the data into the input data files, rather than simply using averages over time. This had not been possible in the 2009 study, as discussed in the paragraph above. In the present study, however, values for all 18 sets of samples for the entire duration of the model run were available prior to starting the modelling work.

We examined possible correlations between river nutrient concentrations and discharge to see if “nutrient rating curves” could be developed to provide daily variation in concentrations. Scatter plots of the various nitrogen and phosphorus components measured in samples collected from the Ahuriri River, the Ohau C Canal and the Tekapo River versus flow in those rivers are shown in Figures A2 - A6 of Appendix A. The most promising results were for some particulate species, but most dissolved fractions showed little if any correlation between concentration and discharge.

Our only other option for incorporating time variability was to interpolate linearly over time between sample concentrations, in spite of the long gaps between samples. This is shown for both nitrogen and phosphorus species in the Ahuriri and Haldon Arms in Figures 2-4 to 2-11. This resulted in some improvement, most notably in NO_3-N predictions, but overall the improvements in model results were small.

At a meeting in July 2014, ECan suggested that we re-examine correlations between P concentrations and flow in the Ahuriri River as these included the most promising results from the scatter plots. As a result the regressions were developed for TP versus flow, DOP versus flow, and PP and PIP versus TP (from the TP regression against flow). The regressions, together with regression performance statistics, are shown in Figure A-1 (Appendix A). The regressions were used to assemble input files incorporating daily variability for all phosphorus components required by the model. The regressions of TP and DOP against flow were used to generate daily time series for TP and DOP. Then the regressions for PP and PIP against TP were used to generate time series for PP and POP (as PP – PIP). Finally, a daily time series for DRP was calculated as a residual of TP – PP – DOP.

Table A-1 (Appendix A) shows a comparison of nutrient loads in the Ahuriri River calculated using the regressions of phosphorus against flow vs. those calculated using linear interpolation between sample concentrations on consecutive sampling occasions; the loads for all phosphorus fractions calculated using the regressions show a substantial increase over those calculated from linear interpolation.

The remaining input files for nitrogen and carbon for the Ahuriri River, and for all inputs for the Ohau C Canal and the Tekapo River, were assembled using linear interpolation between sample concentrations. The incorporation of the results from correlation of phosphorus with flow in the Ahuriri River resulted in an improvement in the model predictions for Chl-*a* in the Ahuriri Arm.

2.2.3 Inter-laboratory quality assurance

In order to address potential errors in laboratory analytical methodology a one-off inter-laboratory comparison was undertaken at four laboratories that routinely undertake both Chl-*a* and TN analyses. Details of the laboratories used, methodology and results are presented in Appendix B. The results gave us no cause for concern that laboratory analytical results were a significant issue that would affect the model interpretations.

2.2.4 Input data not accounting for all of the important nutrient loads

This led us to more detailed analysis of the river inflow data when compared with in-lake data. There were two main aspects to this part of the investigation. Firstly, we identified ungauged flows in the Ahuriri Basin as potential high nutrient sources. ECan staff conducted a water quality survey of the small ungauged streams entering the Ahuriuri Arm on 19 June 2014. The results are included in Appendix B and showed relatively high concentrations of several species, particularly of NO_3-N, and these concentrations were used in the load calculations for ungauged flows to the Ahuriri Arm. We recognise the problem of using a single measurement in these load calculations but believed this was preferable to using the concentration values from the Ahuriri River for ungauged stream load estimates.

Secondly, we also identified an unaccounted-for source of nutrients from a major weed-kill event (spraying of 74 ha of *Lagarosiphon major* with Diquat) in the upper Ahuriri Arm in March 2012, and incorporated the effects of large-scale nutrient release from *L. major* decay in the model input over an 84-day period from 12 March – 3 June 2012. Loads from this release are included in the mean annual TN and TP loads shown in Tables 2-1 and 2-2, and in Table A-1 of Appendix A. The loads are not included in the graphs in Figures 2-4 – 2-7. Note also that the loads were not subject to the load multipliers used for scenarios, but remained at the same levels as those used for the validation (baseline) run. The loads from *L. major* decay were calculated in the following steps:

- A total nutrient store of 6,660 kg N and 760 kg P were calculated from the 75 ha of *L. major* bed in the Ahuriri Arm (Dr John Clayton, NIWA, Unpublished) and from N and P concentrations measured in *L. major* under oligotrophic conditions (C. Howard-Williams – NIWA, Unpublished). Release rates of nutrients over time were obtained from decomposition experiments on *L. major* tissue that showed an 84 day decomposition time at 15 ^{o}C (C. Howard-Williams – NIWA, Unpublished).
- Nutrient release rates were applied to the total nutrient store in the weed bed as it decomposed over time to arrive at the load per day entering the water of the Ahuriri Arm over the 84 days from 12 March – 3 June 2012.
- For modelling purposes the daily addition of nutrients from the decomposing *L. major* were added to the inflows from the Ahuriri River.

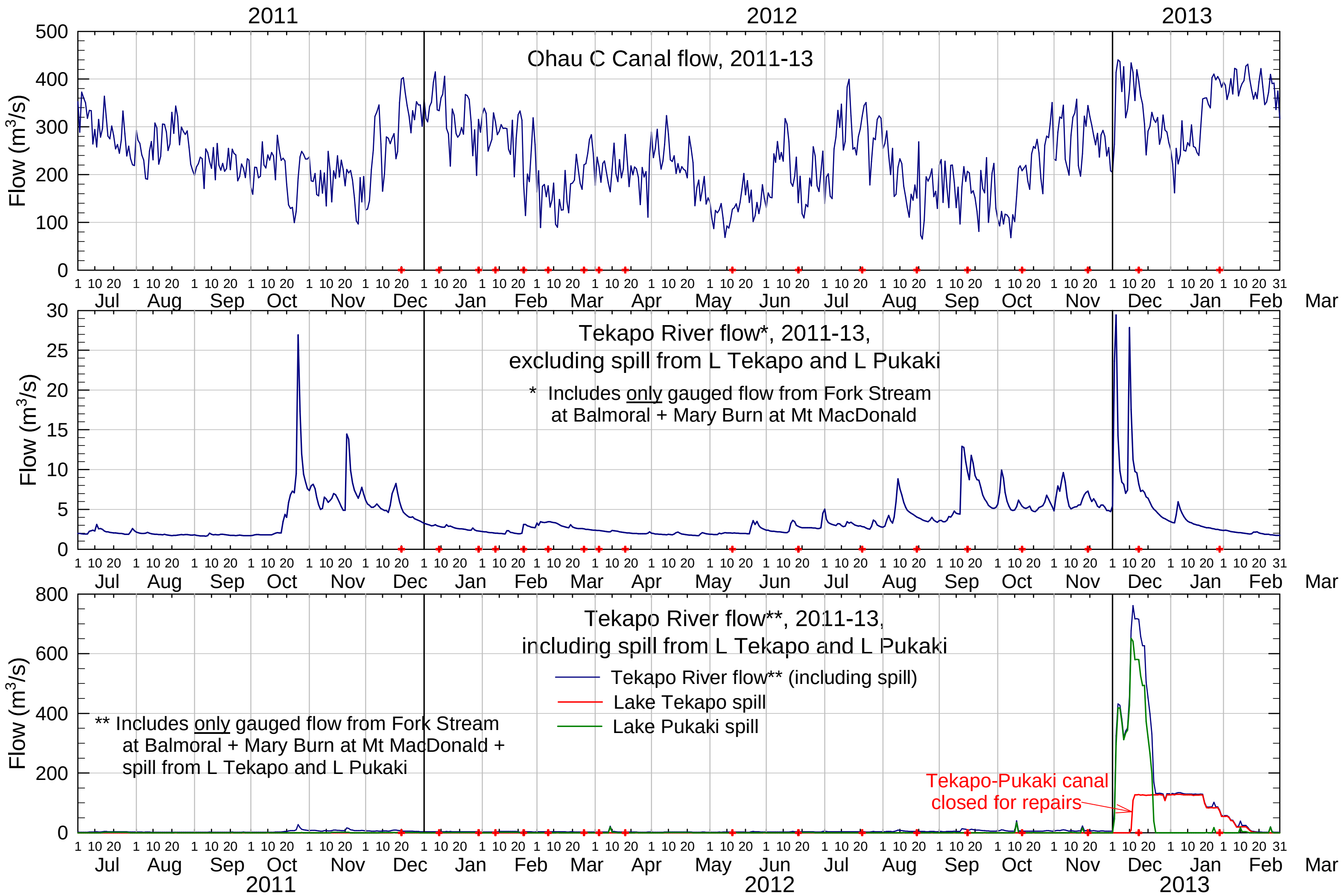

Figure 2-2: Inflows into the Haldon Arm from 2011 to 2013. Top = Ohau C Canal, Middle = Tekapo-Pukaki excluding spill events, Bottom = Tekapo-Pukaki including spill events. Water quality sampling occasions indicated by red dots.

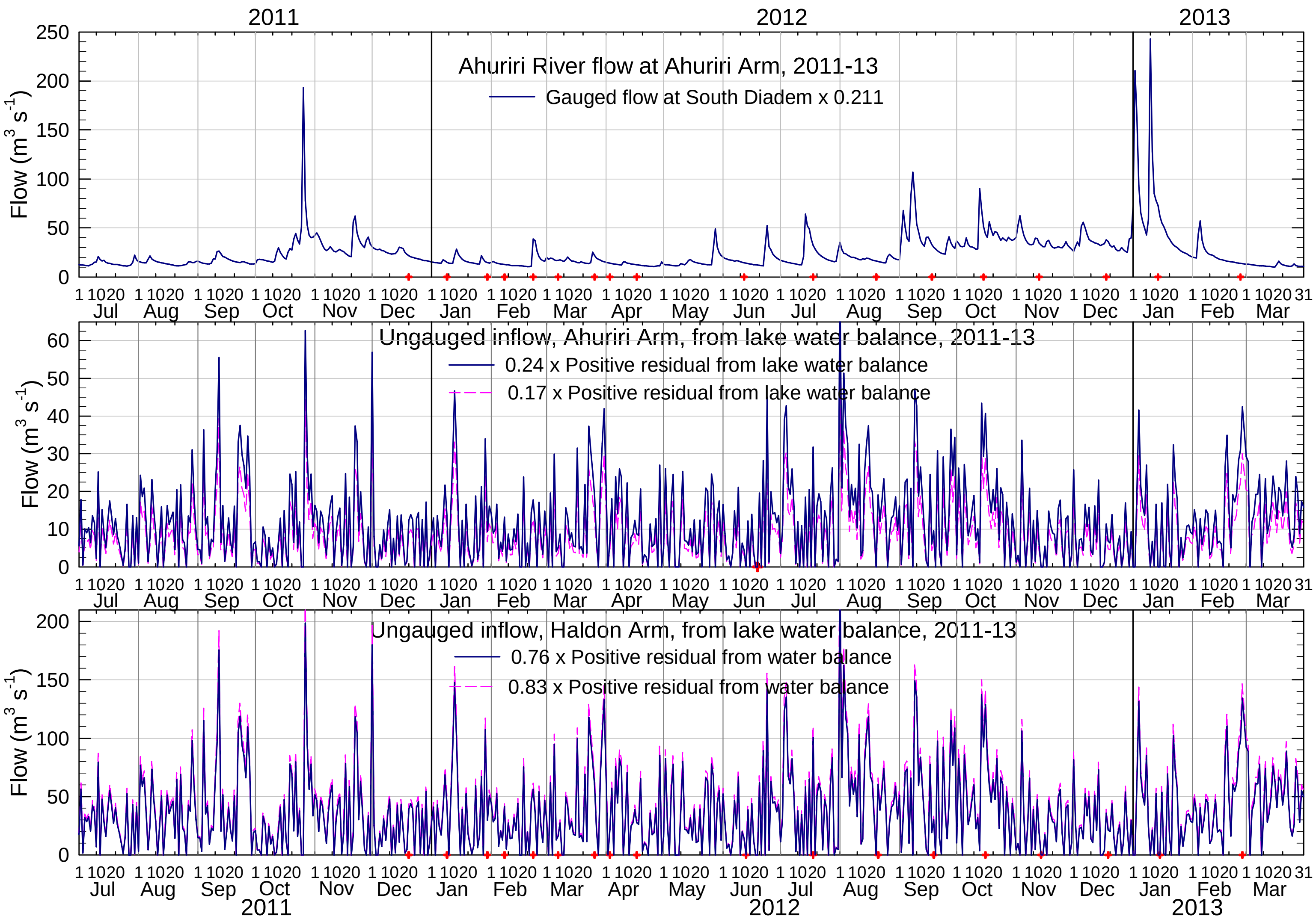

Figure 2-3: Gauged inflow into the Ahuriri Arm and ungauged inflow into the Ahuriri and Haldon Arms from 2011 to 2013. Top = Ahuriri River flow at South Diadem, Middle = ungauged inflow into Ahuriri Arm (from water balance), Bottom = ungauged inflow in Haldon Arm (from water balance). Water quality sampling occasions indicated by red dots.

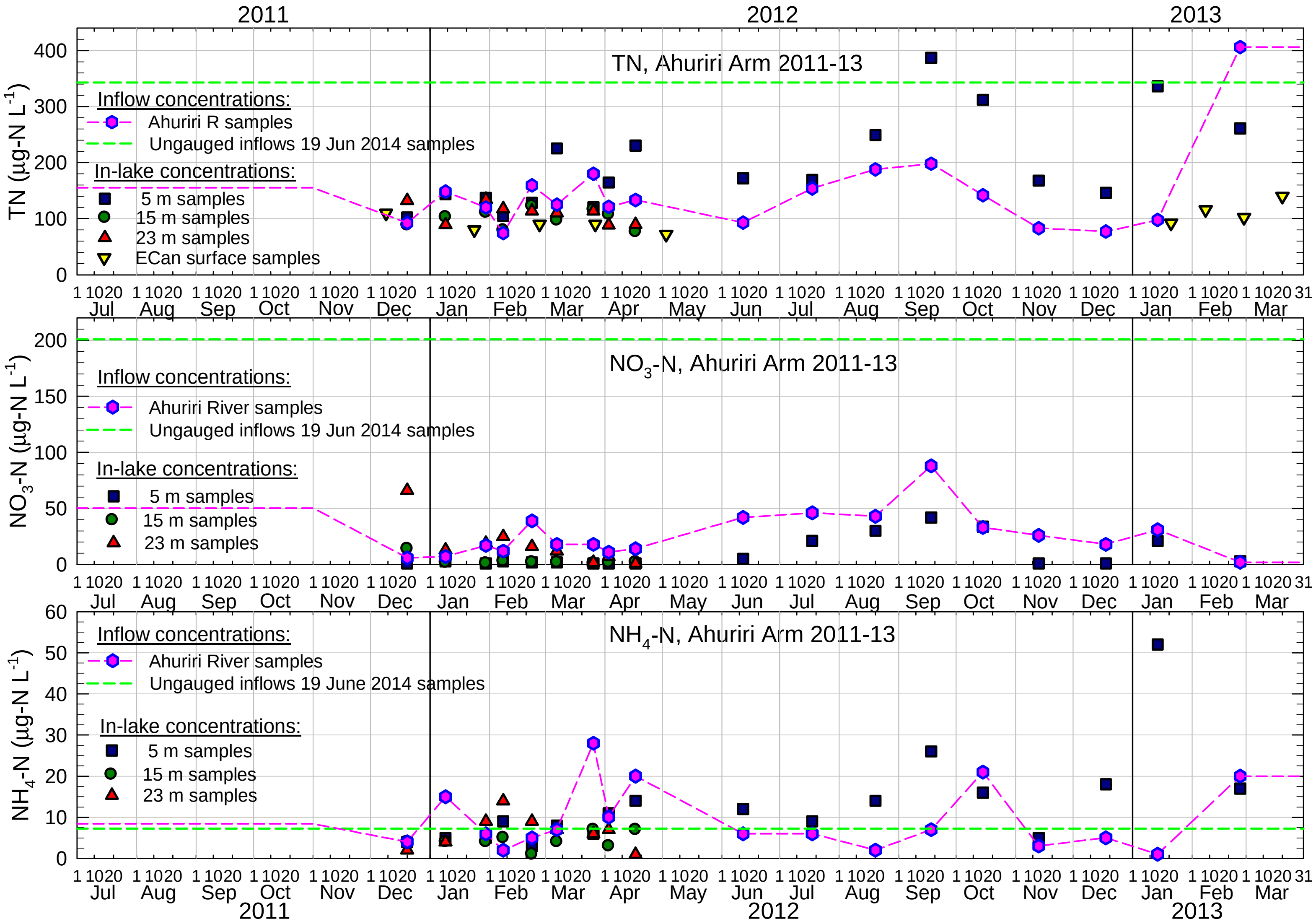

Figure 2-4: Nitrogen species concentrations in the inflow and lake sites for the Ahuriri Arm from 2011-2013. TN = total nitrogen, NO_3-N = nitrate nitrogen, NH_4-N = ammonium nitrogen.

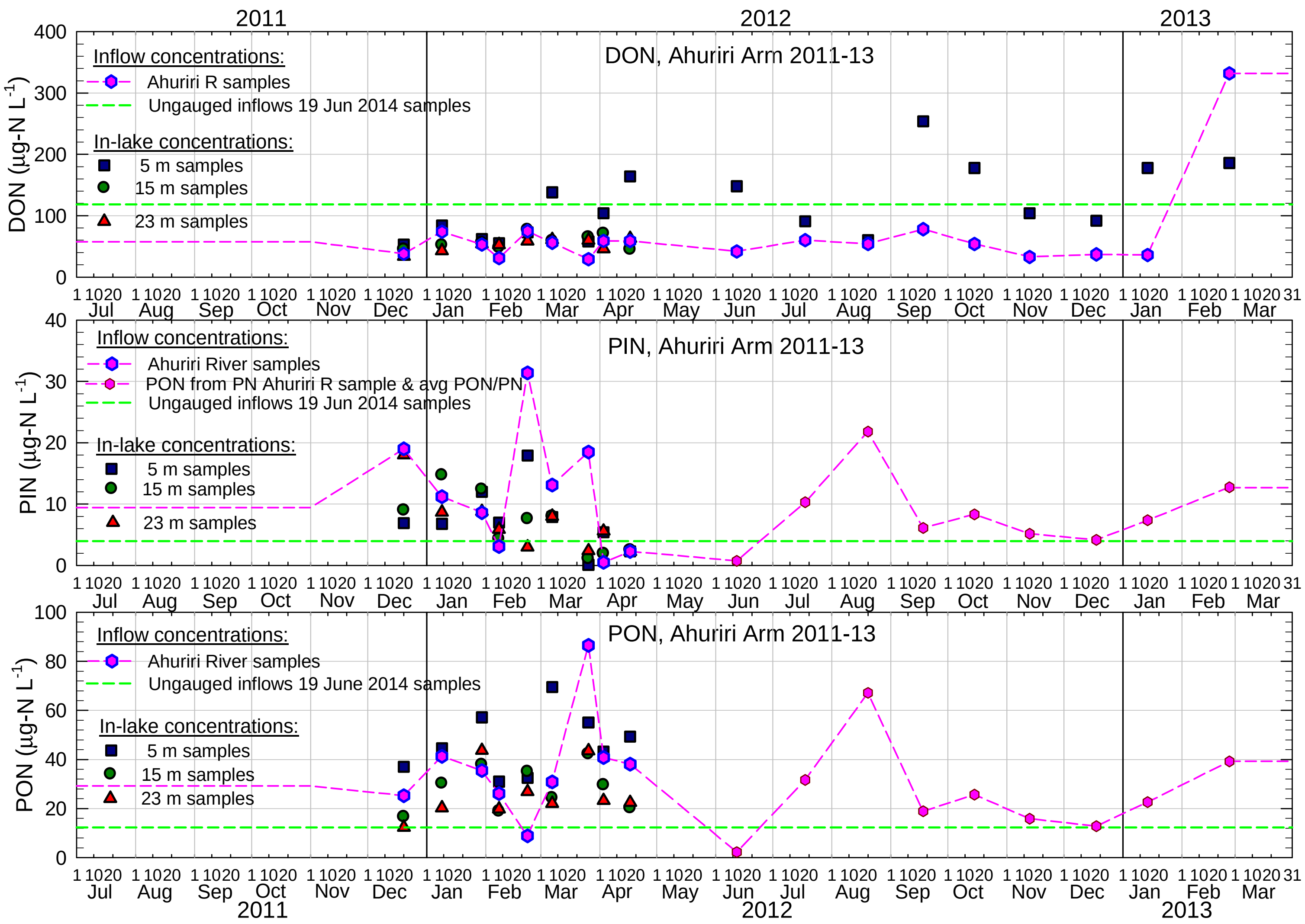

Figure 2-5: Nitrogen species concentrations in the inflow and lake sites for the Ahuriri Arm from 2011-2013. DON = dissolved organic nitrogen, PON= particulate organic nitrogen, PIN = particulate inorganic nitrogen.

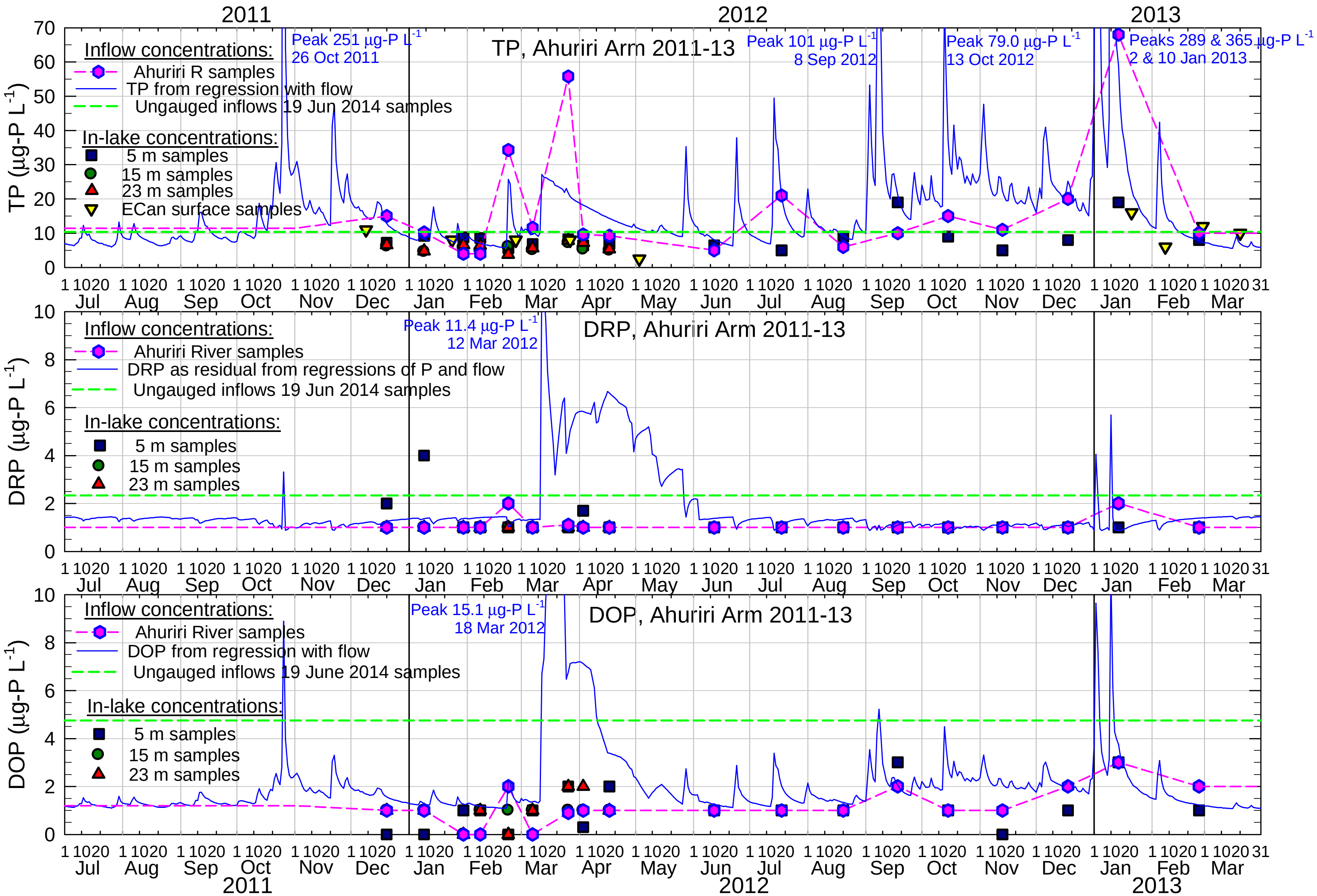

Figure 2-6: Phosphorus species concentrations in the inflow and lake sites for the Ahuriri Arm from 2011-2013. TP = total phosphorus, DRP = dissolved reactive phosphorus, DOP= dissolved organic phosphorus.

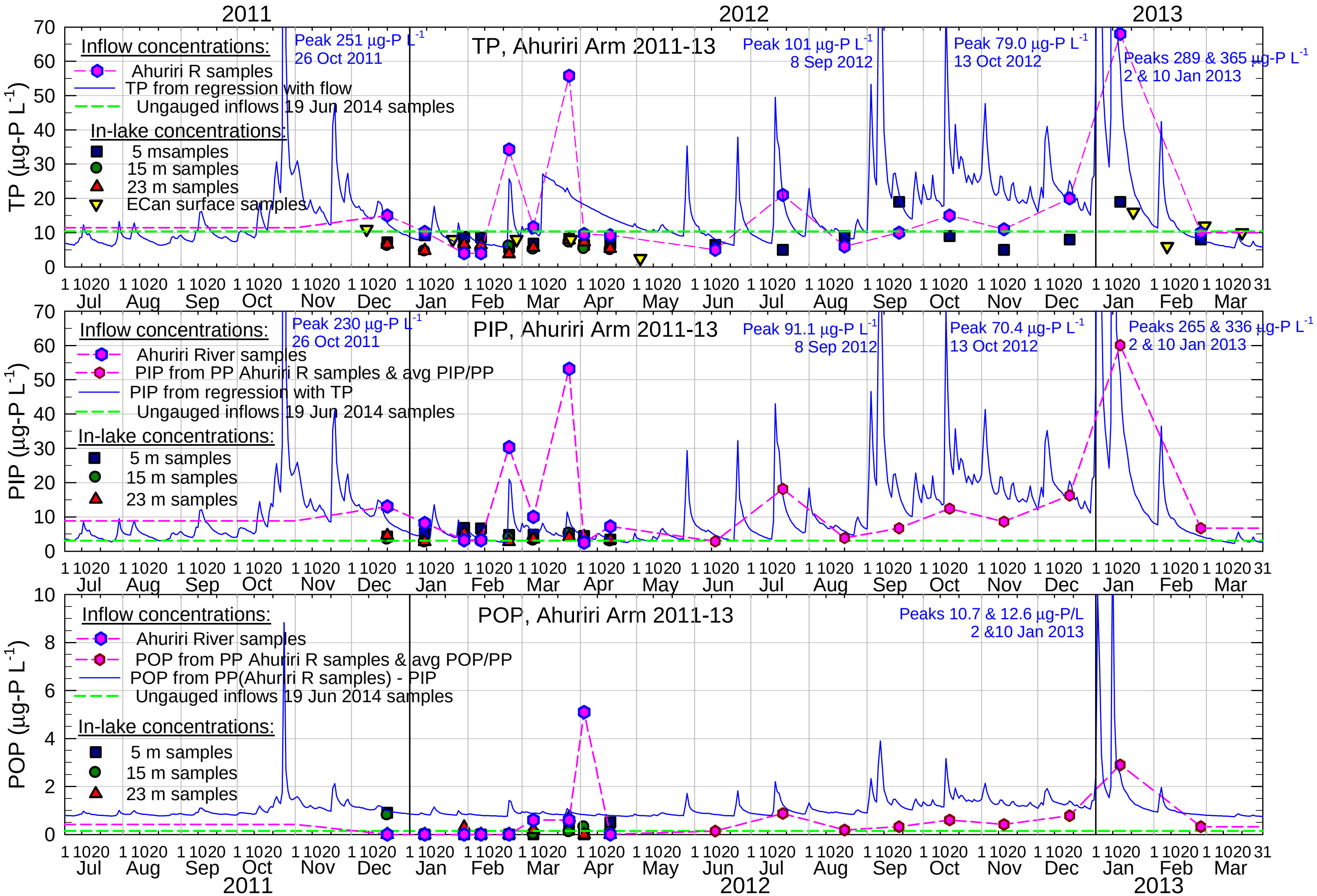

Figure 2-7: Phosphorus species concentrations in the inflow and lake sites for the Ahuriri Arm from 2011-2013. TP = total phosphorus, PIP = particulate inorganic phosphorus, POP= particulate organic phosphorus.

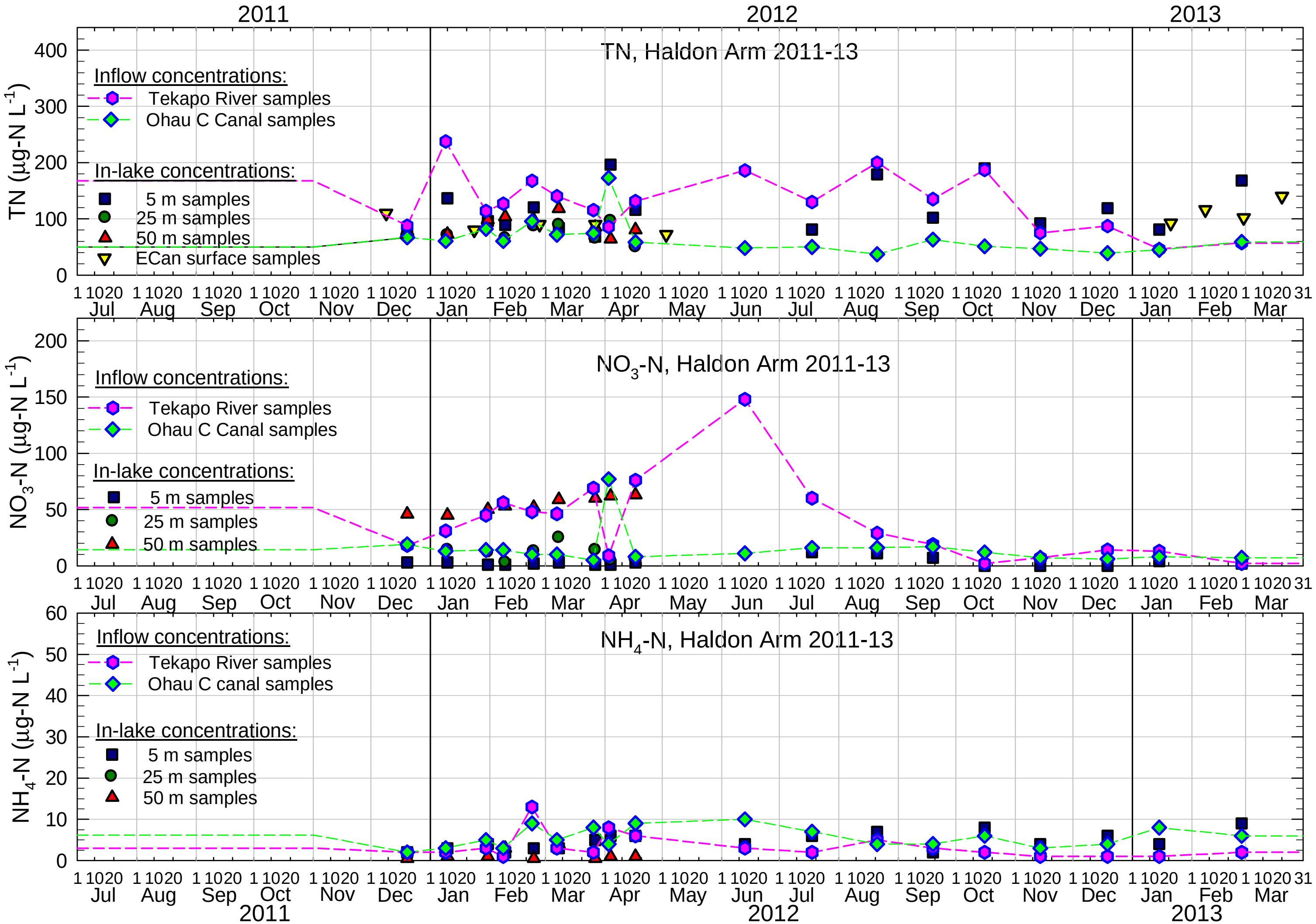

Figure 2-8: Nitrogen species concentrations in the inflow and lake sites for the Haldon Arm from 2011-2013. TN = total nitrogen, NO_3-N = nitrate nitrogen, NH_4-N = ammonium nitrogen.

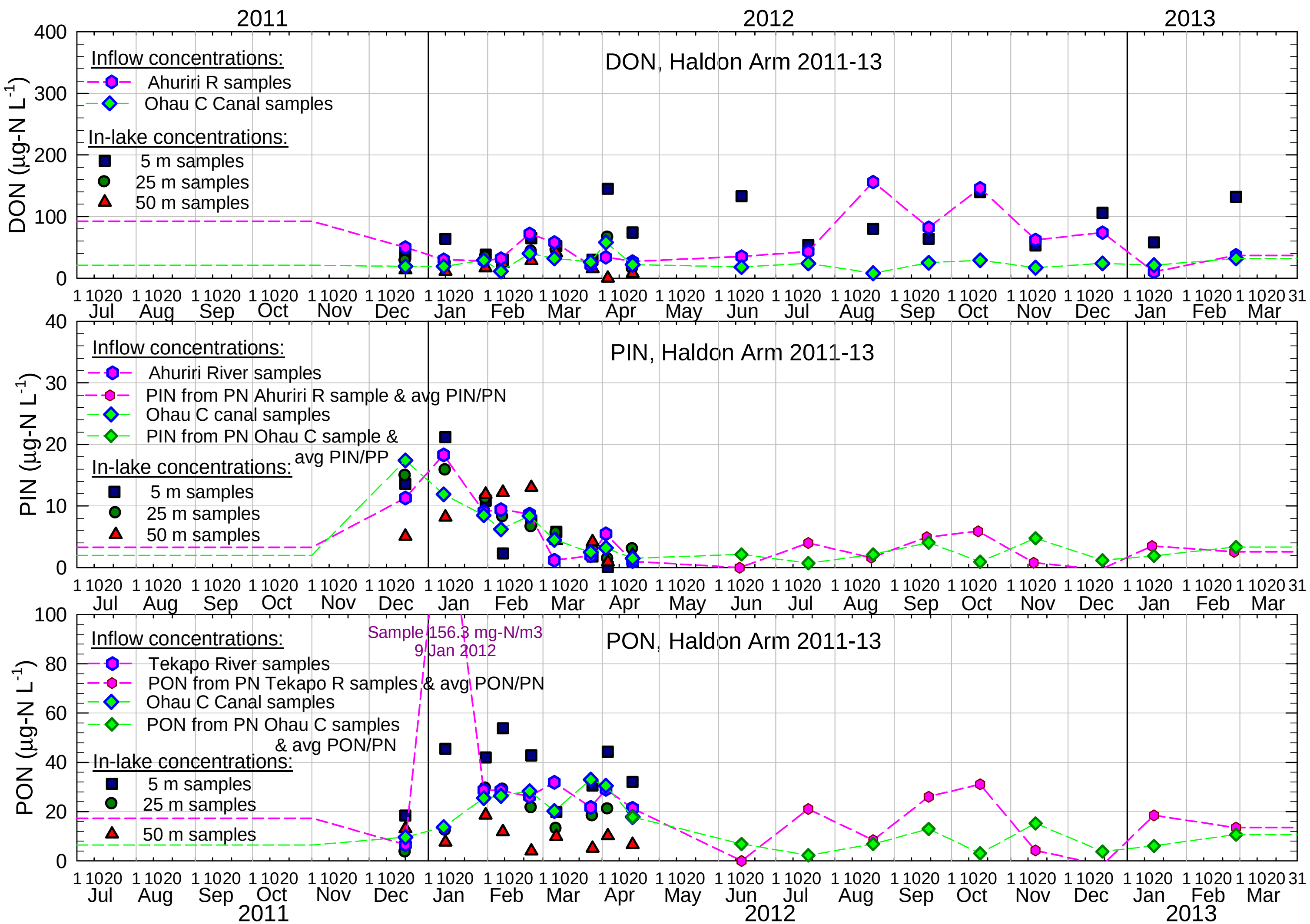

Figure 2-9: Nitrogen species concentrations in the inflow and lake sites for the Haldon Arm from 2011-2013. DON = dissolved organic nitrogen, PON= particulate organic nitrogen, PIN = particulate inorganic nitrogen.

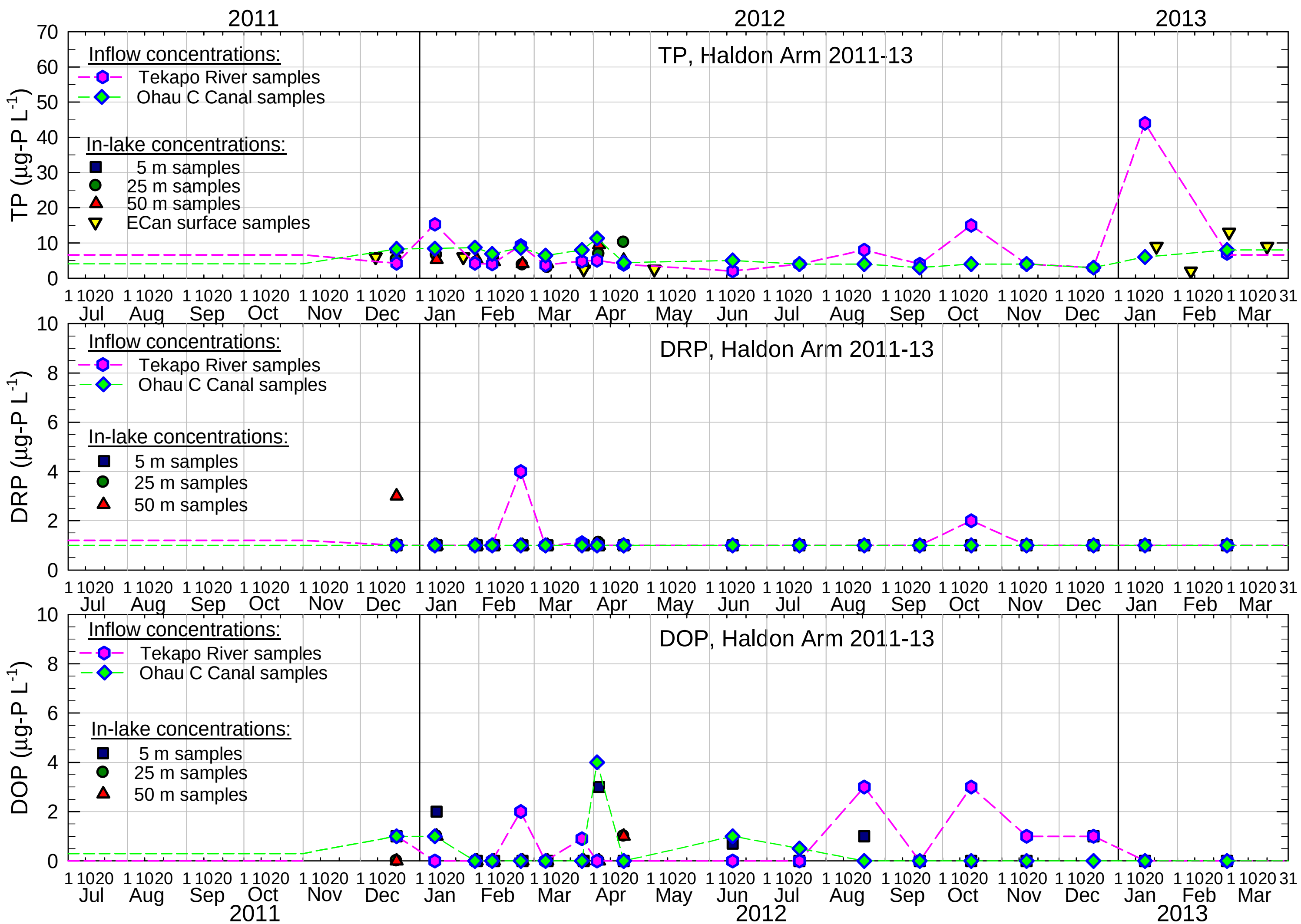

Figure 2-10: Phosphorus species concentrations in the inflow and lake sites for the Haldon Arm from 2011-2013. TP = total phosphorus, DRP = dissolved reactive phosphorus, DOP= dissolved organic phosphorus.

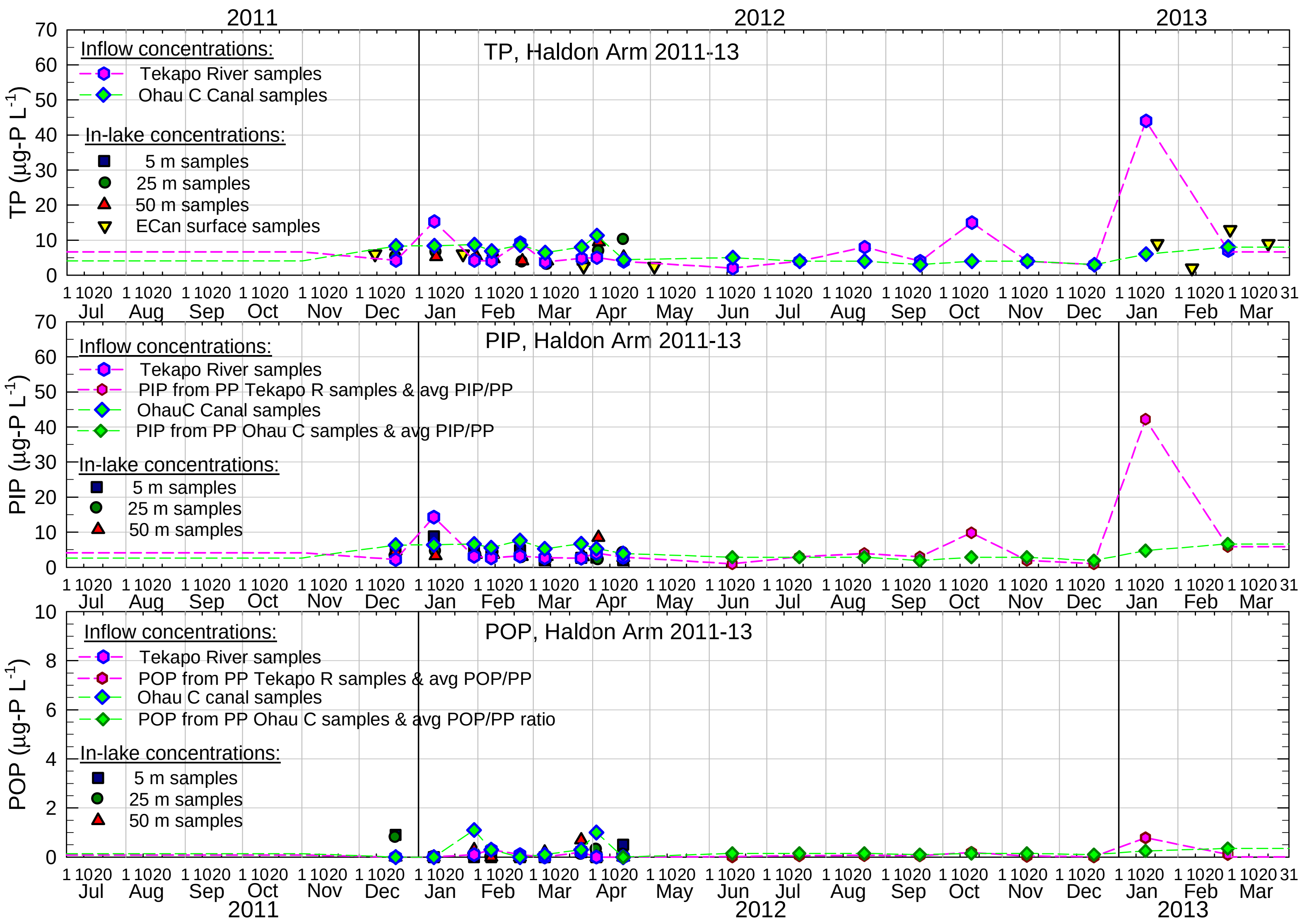

Figure 2-11: Phosphorus species concentrations in the inflow and lake sites for the Haldon Arm from 2011-2013. TP = total phosphorus, PIP = particulate inorganic phosphorus, POP= particulate organic phosphorus.

2.3 Model configuration and calibration

2.3.1 Model configuration and calibration overview

The 2011-13 model runs used the 2008-09 model setup (see Norton et al. 2009, Section 3.4) – the same model versions (ELCOM v 2.2, CAEDYM v 2.3), bathymetry, model grid, inflow sites, in-lake sampling sites; the same CAEDYM model parameters (in the file Benmore.dat) and model configuration (in the file Benmore.con). The model configuration included: two phytoplankton groups, freshwater diatoms and cyanobacteria, both with internal N and P storage; two suspended solids groups, one representative of fine-grained glacial flour (used for inflows to the Haldon Arm) and one of coarser silt (used for inflows to the Ahuriri Arm); no zooplankton, fish or benthic algal communities were modelled. Some minor changes have also been made to model parameters as detailed in Section 2.3.2, but the basic model configuration has not changed.

As noted in Section 2.1, the model runs for the present study all start at noon on 1 July 2011, and end at noon on 25 March 2013 (633 days); this covers the period during which water quality samples were collected from river and lake sampling sites (20 December 2011 – 27 February 2013), with a lead-in period starting with uniformly mixed conditions in winter. This allows for a period in which the model adjusts to initial conditions before comparisons are made between model predictions and observed values (first set of samples were collected 20 December 2011). It also allows for specification of initial conditions at a time when it can be safely assumed that the lake is well-mixed vertically, thereby minimising the assumptions about initial profiles for nutrients. The lead-in values of concentrations for the period 1 July – 1 November 2011 for the Ahuriri River, Tekapo River and Ohau C Canal were set equal to the averages of concentrations measured in those inflows during the winter of 2012 (five samples, collected 12 June – 16 October 2012), with a linear transition from these constant values to the values measured for the first samples on 20 December 2011. No lead-in period was necessary for phosphorus components in the Ahuriri River because daily values were available from regressions based on flow (Section 2.2.2). The lead-in periods for linearly interpolated inflow data can be seen in Figures 2.4 – 2.11 as the dashed lines preceeding the sampling point symbols for the inflow time series.

2.3.2 Detailed re-examination of model parameters

Professor David Hamilton made a detailed re-examination of model parameters that revealed two parameters that he felt were unrealistic: the diameter of particulate organic matter, which affects settling rates, was too large (specified as 20 µm, when it fact diameters were probably less than 4 µm); and a release rate of nitrate from sediments specified with a negative value (-0.04 g-N/m2/day, so sediments were acting as a sink for NO_3-N, which is inappropriate for an oligotrophic lake). These parameter values were changed. Changes were made to some other model parameters in an effort to improve model performance (all changes are detailed below), but parameters relating to phytoplankton growth were not modified. We contend that major recalibration was not justified, given uncertainties that remained in specifying input data for nutrient concentrations as discussed in Sections 1.2.2, 2.2.2 and 2.2.4.

Parameter value changes were as follows:

- Diameter of POM (particulate organic matter) decreased from 20 µm to 3.5 µm;
- Release rate from sediments of nitrate-nitrogen changed from -0.04 g m^{-2} day^{-1} to +0.04 g m^{-2} day^{-1} and subsequently to +0.044 g m^{-2} day^{-1};

- Maximum mineralisation rate of dissolved organic nitrogen to ammonium-nitrogen decreased from 0.015 day^{-1} to 0.010 day^{-1};
- Nitrification rate coefficient decreased from 0.16 day^{-1} to 0.10 day^{-1};
- Release rate from sediments of dissolved reactive phosphorus decreased by 25% from 0.00260 g-P m^{-2} day^{-1} to 0.00195 g-P m^{-2} day^{-1}.
- The initial conditions for internal storages for nitrogen and phosphorus (as concentrations, g-N m^{-3} , g-P m^{-3}) in algal cells as specified for the 2008-09 model runs were too large; these were corrected to more realistic levels to match average values calculated during the main part of the model run. This had very little effect on model performance.

These changes resulted in further small improvements in model performance. Further improvements may still be possible; see, for example the discussion of DRP in the hypolimnion of the Haldon Arm (Section 3.1.1).

Finally, the model was rerun with the revised parameter values and the 2008-09 input data-set. Although there were some small changes in model results, we do not think that these would alter any of the conclusions in the 2009 report (Norton et al. 2009).

2.4 Scenario nutrient loads

2.4.1 Load development

As discussed in Section 2.2, ECan provided us with the catchment development scenarios in September 2014. These scenarios consisted of sets of mean annual loads for TN and TP at sites generated by the CLUES model (see Figure 2-12 for CLUES model site locations). Considerable effort was required to make them compatible with the daily time-step input used to run the model. TN and TP loads had to be partitioned into their component species. For TP the species were DRP, DOP, PIP and POP and for TN the species were NO_3-N, NH_4-N, DON, PIN, PON (further detail is provided in Section 2.5). In addition, the sites for which the CLUES data were generated were not the same as the sites for which we had hydrological and water sampling information, as explained in Section 2.4.2.

The annual loads supplied by ECan and the corresponding loads generated for the model input are summarised in Tables 2-1 and 2-2. As discussed in more detail below in Section 2.5, ten different load factors are necessary to specify the load scenario for model input (one for TN and one for TP for each of the five main inflows for the model). There is no simple way to describe the overall variation in loads among the different scenarios, but Fig. 3-9, which is used later to illustrate TLI for different scenarios, does show how annual loads of TP and TN vary among the four scenarios modelled for the two arms of the lake. It will be seen in Tables 2-1 and 2-2 that while the annual loads for CLUES and the lake model are of similar magnitudes, they are not identical. We matched the relative increases in CLUES loads at the model input sites (denoted by an asterisk in the Tables 2-1 and 2-2) rather than their magnitudes. The reasons for the differences between CLUES and lake-model loads are explained in more detail following Tables 2-1 and 2-2.

Map – CLUES and Lake model flow sites used for assembling input files

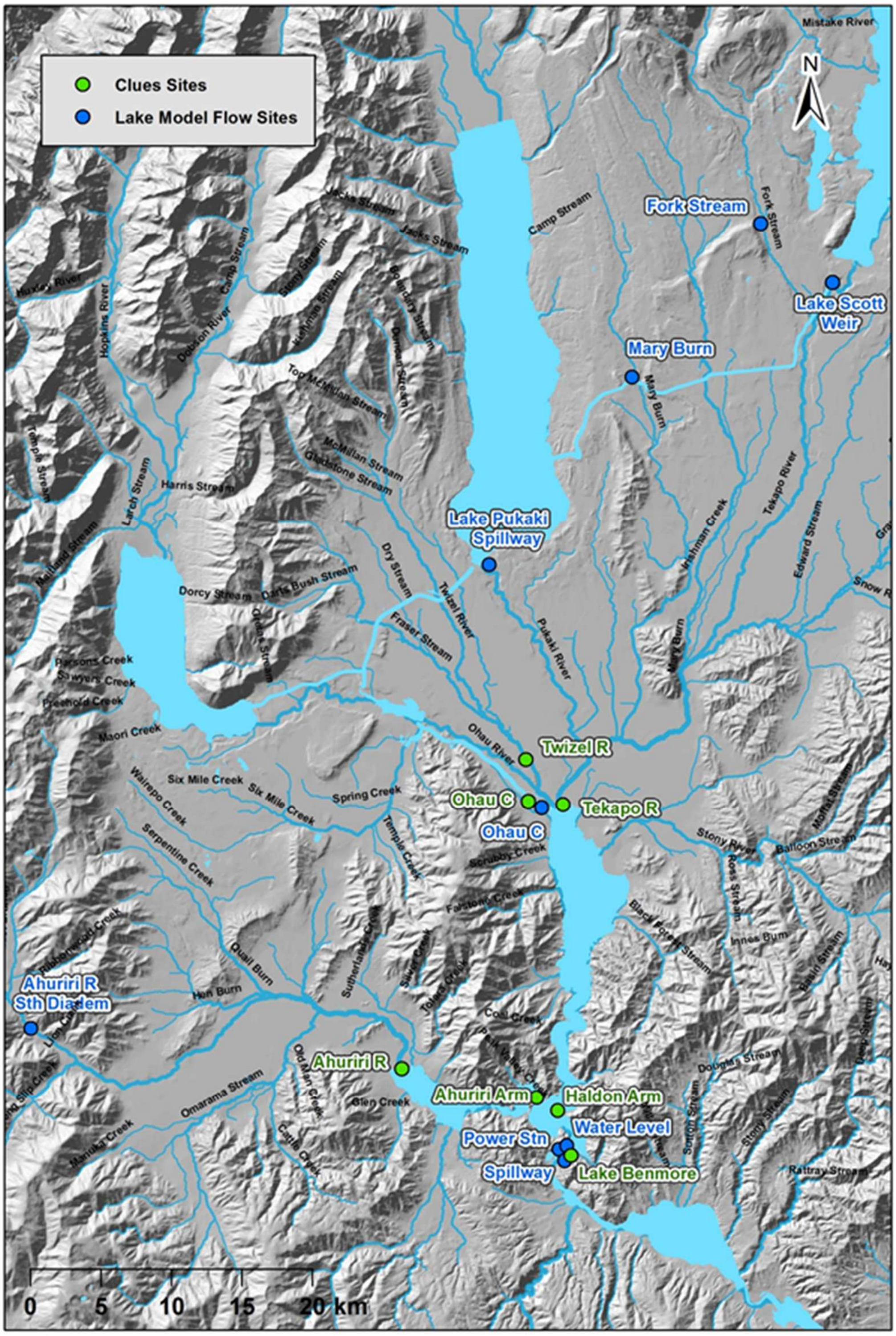

Figure 2-12: Locations of water quality flows and loads used in the CLUES model (green circles). Locations of hydrological gauging sites used for the lake model are also shown (blue circles).

Table 2-1: Nitrogen loads calculated for the model. For these sites the % increase in TP for the model should be the same as that for CLUES. Sites prefixed by * correspond to model input sites. Cells shaded green derived from Upper Waitaki CLUES - loads Lake Model_Pcorrected.xlsx. Supplementary information in the form of comments and formulas can be found in an accompanying spreadsheet sent separately.

Table key:	Scenario:			Current	Current	Scenario 1 V3 CLUES		Scenario 1 V3 Lake model	
v7c_niwa = calibrated LUT	Loads; % changes:	Flows	Flows	*t N/yr*	*t N/yr*	*t N/yr*	*% change*	*t N/yr*	*% change*
p/s = salmon farm point sources	Look-up table:	CLUES	Lake model	v7c_niwa	Lake model	v7c_niwa	(incl p/s)		
Name	**NZReach**	**MeanQ ($m^3 s^{-1}$)**	**MeanQ ($m^3 s^{-1}$)**	**CLUES N loads**	**Model N loads**	**CLUES N loads**	*% change*	**Model N loads**	*% change*
Haldon Arm	13517851	290.20	307.88	564.01	649.47	670.7	18.92%	757.67	16.66%
Ahuriri Arm (excl plants)	13517829	33.67	37.13	204.21	243.99	208.7	2.20%	253.36	3.84%
Haldon Arm + Ahuriri Arm		323.87	345.01	768.21	893.46	879.44	14.48%	1011.03	13.16%
Benmore Total (incl lower Benmore basin)	13518596	324.00	345.01	770.2	893.46	881.4	28.27%	1011.03	13.16%
*Ohau C Canal	13513540	260.00	242.24	375.35	430.09	457.0	21.76%	523.67	21.76%
Twizel River	13513349	7.19	No data	51.58		52.1	0.95%		
*Tekapo River at Haldon Arm	13513240	23.35	27.51	99.17	54.69	123.6	24.63%	68.16	24.63%
*Ahuriri River at Ahuriri Arm (excl plants)	13516923	30.59	25.09	167.70	113.75	169.9	1.34%	115.27	1.34%
Ahuriri River, load from plants only		N/A for flow	N/A for flow	N/A for CLUES	3.62	N/A for CLUES		3.62	0.00%
Ahuriri River, including load from plants		N/A for flow	N/A for flow	N/A for CLUES	117.37	N/A for CLUES		118.89	1.29%
Tekapo R from Fork Stm at Balmoral and Mary Burn at Mt MacDonald			3.861						
Upper Tekapo River from L Scott Weir	13507315	5.00		5.61		5.68	1.19%		
Tekapo to Pukaki Canal	13600000	95.00		121.51		157.63	29.73%		
Upper Pukaki River from L Pukaki Spillway	13510553	8.66		8.89		9.85	10.77%		
Pukaki to Ohau Canal	13600001	176.00		168.50		186.54	10.70%		
Ahuriri ungauged ECan = Ahuriri Arm -Ahuriri River		3.083		36.50		38.764	6.19%		
Haldon ungauged Ecan = Haldon Arm - (Ohau C + Tekapo R + Twizel R)		-0.340		37.91		38.051	0.37%		
Benmore ungauged Ecan = Benmore Total - (Haldon Arm + AhuririArm)		0.127	N/A for model	1.974	N/A for model	1.974	0.03%	N/A for model	
*Ahuriri ungauged for model = Ahuriri ungauged Ecan + 0.5 x Benmore ungauged Ecan		3.146	12.04	37.49	130.23	39.751	6.03%	138.08	6.03%
*Haldon ungauged for model = Haldon ungauged Ecan + Twizel R + 0.5 x Benmore ungauged Ecan		6.909	38.13	90.48	164.70	91.109	0.70%	165.84	0.70%
*Lake Benmore rain			1.349		5.278			5.278	0.00%
*Lake Benmore dryfall					5.210			5.210	0.00%

Table 2-1 continued

Table key:	Scenario 2a 15 Sep, CLUES		Scenario 2a, Lake model		Scenario 2b 15 Sep, CLUES		Scenario 2b, Lake model		Scenario 1a-2a, CLUES		Scenario 1a-2a, Lake model	
v7c_niwa = calibrated LUT	*t N/yr*	*% change*	*t N/yr*	*% change*	*t N/yr*	*% change*	*t N/yr*	*% change*	*t N/yr*	*% change*	*t N/yr*	*% change*
p/s = salmon farm point sources	v7c_niwa	(incl p/s)			v7c_niwa	(incl p/s)			v7c_niwa	(incl p/s)		
Name	**CLUES N loads**	*% change*	**Model N loads**	*% change*	**CLUES N loads**	*% change*	**Model N loads**	*% change*	**CLUES N loads**	*% change*	**Model N loads**	*% change*
Haldon Arm	736.40	30.57%	839.82	29.31%	745.33	32.15%	849.75	30.84%	736.40	0.00%	839.82	29.31%
Ahuriri Arm (excl plants)	249.61	22.24%	286.63	17.48%	245.73	20.34%	279.28	14.47%	208.71	0.00%	253.36	3.84%
Haldon Arm + Ahuriri Arm	986.01	28.35%	1126.45	26.08%	991.06	29.01%	1129.03	26.37%	945.11	23.03%	1093.17	22.35%
Benmore Total (incl lower Benmore basin)	987.90	28.27%	1126.45	26.08%	992.95	28.92%	1129.03	26.37%	947.04	22.96%	1093.17	22.35%
*Ohau C Canal	507.23	35.14%	581.20	35.14%	503.06	34.02%	576.42	34.02%	507.23	35.14%	581.20	35.14%
Twizel River	61.86	19.92%			69.76	35.25%			61.86	19.92%		
*Tekapo River at Haldon Arm	126.31	27.37%	69.66	27.37%	133.51	34.63%	73.63	34.63%	126.31	27.37%	69.66	27.37%
*Ahuriri River at Ahuriri Arm (excl plants)	208.82	24.52%	141.64	24.52%	206.63	23.21%	140.16	23.21%	169.94	1.34%	115.27	1.34%
Ahuriri River, load from plants only	N/A for CLUES		3.62	0.00%	N/A for CLUES		3.62	0.00%	N/A for CLUES		3.62	0.00%
Ahuriri River, including load from plants	N/A for CLUES		145.26	23.76%	N/A for CLUES		143.78	22.50%	N/A for CLUES		118.89	1.29%
Upper Tekapo River from L Scott Weir	5.86	4.46%			5.71	1.76%			5.86	4.46%		
Tekapo to Pukaki Canal	160.85	32.38%			157.98	30.01%			160.85	32.38%		
Upper Pukaki River from L Pukaki Spillway	10.12	13.85%			9.84	10.65%			10.12	13.85%		
Pukaki to Ohau Canal	191.74	13.79%			186.33	10.59%			191.74	13.79%		
Ahuriri ungauged ECan = Ahuriri Arm -Ahuriri River	40.795	11.75%			39.106	7.13%			38.764	6.19%		
Haldon ungauged Ecan = Haldon Arm - (Ohau C + Tekapo R + Twizel R)	41.010	8.18%			39.005	2.89%			41.010	8.18%		
Benmore ungauged Ecan = Benmore Total - (Haldon Arm + AhuririArm)	1.888	-4.35%	N/A for model		1.888	-4.35%	N/A for model		1.931	-2.16%	N/A for model	
*Ahuriri ungauged for model = Ahuriri ungauged Ecan + 0.5 x Benmore ungauged Ecan	41.739	11.33%	144.99	11.33%	40.050	6.83%	139.12	6.83%	39.730	5.97%	138.08	6.03%
*Haldon ungauged for model = Haldon ungauged Ecan + Twizel R + 0.5 x Benmore ungauged Ecan	103.808	14.73%	188.96	14.73%	109.712	21.26%	199.70	21.26%	103.830	14.76%	188.96	14.73%
*Lake Benmore rain			5.278	0.00%			5.278	0.00%			5.278	0.00%
*Lake Benmore dryfall			5.210	0.00%			5.210	0.00%			5.210	0.00%

Table 2-2: Phosphorus loads calculated for the model. For these sites the % increase in TP for the model should be the same as that for CLUES. Sites prefixed by * correspond to model input sites. Cells shaded green derived from Upper Waitaki CLUES - loads Lake Model_Pcorrected.xlsx. Supplementary information in the form of comments and formulas can be found in an accompanying spreadsheet sent separately.

Table key:	Scenario:			Current	Current	Scenario 1 V3		Scenario 1 V3 Lake model	
v7c_niwa = calibrated LUT	Loads; % changes:	Flows	Flows	*t P/yr*	*t P/yr*	*t P/yr*	*% change*	*t P/yr*	*% change*
p/s = salmon farm point sources	Look-up table:	CLUES	Lake model	v7c_niwa	Lake model	v7c_niwa	(incl p/s)		
Name	**NZReach**	**MeanQ ($m^3 s^{-1}$)**	**MeanQ ($m^3 s^{-1}$)**	**CLUES P loads**	**Model P loads**	**CLUES P loads**	*% change*	**Model P loads**	*% change*
Haldon Arm	13517851	290.20	307.88	87.79	77.73	102.79	17.08%	90.90	16.94%
Ahuriri Arm (excl plants)	13517829	33.67	37.13	30.37	32.51	30.42	0.16%	32.56	0.15%
Haldon Arm + Ahuriri Arm		323.87	345.01	118.16	110.24	133.20	12.73%	123.46	11.99%
Benmore Total (incl lower Benmore basin)	13518596	324.00	345.01	118.3	110.24	133.35	12.72%	123.46	11.99%
*Ohau C Canal	13513540	260.00	242.24	64.68	42.70	76.98	19.01%	50.82	19.01%
Twizel River	13513349	7.19	No data	5.71		6.02	5.36%		
*Tekapo River at Haldon Arm	13513240	23.35	27.51	12.72	25.37	15.10	18.74%	30.13	18.74%
*Ahuriri River at Ahuriri Arm (excl plants)	13516923	30.59	25.09	26.52	28.59	26.52	0.01%	28.59	0.01%
Ahuriri River, load from plants only		N/A for flow	N/A for flow	N/A for CLUES	0.43	N/A for CLUES		0.43	0.00%
Ahuriri River, including load from plants		N/A for flow	N/A for flow	N/A for CLUES	29.02	N/A for CLUES		29.02	0.01%
Tekapo R from Fork Stm at Balmoral and Mary Burn at Mt MacDonald			3.861						
Upper Tekapo River from L Scott Weir	13507315	5.00		0.9085		0.9133	0.23%		
Tekapo to Pukaki Canal	13600000	95.00		21.0352		28.2586	34.15%		
Upper Pukaki River from L Pukaki Spillway	13510553	8.66		1.9113		1.9968	4.31%		
Pukaki to Ohau Canal	13600001	176.00		36.3119		37.9332	4.31%		
Ahuriri ungauged ECan = Ahuriri Arm -Ahuriri River		3.083		3.847		3.894	1.21%		
Haldon ungauged Ecan = Haldon Arm - (Ohau C + Tekapo R + Twizel R)		-0.340		4.677		4.687	0.21%		
Benmore ungauged Ecan = Benmore Total - (Haldon Arm + AhuririArm)		0.127	N/A for model	0.149	N/A for model	0.151	0.93%	N/A for model	
*Ahuriri ungauged for model = Ahuriri ungauged Ecan + 0.5 x Benmore ungauged Ecan		3.146	12.04	3.922	3.926	3.969	1.20%	3.973	1.20%
*Haldon ungauged for model = Haldon ungauged Ecan + Twizel R + 0.5 x Benmore ungauged Ecan		6.909	38.13	10.467	9.660	10.783	3.03%	9.95	3.03%
*Lake Benmore rain			1.349		0.413			0.413	0.00%
*Lake Benmore dryfall					0.744			0.744	0.00%

Table 2-2 continued

Table key: v7c_niwa = calibrated LUT p/s = salmon farm point sources	Scenario 2a 15 Sep, CLUES		Scenario 2a, Lake model		Scenario 2b 15 Sep, CLUES		Scenario 2b, Lake model		Scenario 1a-2a, CLUES		Scenario 1a-2a, Lake model	
	t P/yr	*% change*	*t P/yr*	*% change*	*t P/yr*	*% change*	*t P/yr*	*% change*	*t P/yr*	*% change*	*t P/yr*	*% change*
	v7c_niwa	(incl p/s)			v7c_niwa	(incl p/s)			v7c_niwa	(incl p/s)		
Name	**CLUES P loads**	*% change*	**Model P loads**	*% change*	**CLUES P loads**	*% change*	**Model P loads**	*% change*	**CLUES P loads**	*% change*	**Model P loads**	*% change*
Haldon Arm	111.22	26.69%	96.90	24.67%	113.15	28.88%	99.90	28.53%	111.22	28.88%	96.90	24.67%
Ahuriri Arm (excl plants)	32.26	6.22%	34.54	6.23%	32.84	8.13%	35.17	8.17%	30.42	8.13%	32.56	0.15%
Haldon Arm + Ahuriri Arm	143.5	21.43%	131.44	19.23%	145.98	23.55%	135.07	22.52%	141.63	19.87%	129.47	17.44%
Benmore Total (incl lower Benmore basin)	143.62	21.40%	131.44	19.23%	146.13	23.52%	135.07	22.52%	141.78	19.84%	129.47	17.44%
*Ohau C Canal	84.74	31.01%	55.94	31.01%	84.99	31.40%	56.11	31.40%	84.74	31.01%	55.94	31.01%
Twizel River	6.36	11.32%			6.70	17.16%			6.36	11.32%		
*Tekapo River at Haldon Arm	15.35	20.69%	30.62	20.69%	16.55	30.13%	33.02	30.13%	15.35	20.69%	30.62	20.69%
*Ahuriri River at Ahuriri Arm (excl plants)	28.29	6.67%	30.49	6.67%	28.91	9.02%	31.17	9.02%	26.52	0.01%	28.59	0.01%
Ahuriri River, load from plants only	N/A for CLUES		0.43	0.00%	N/A for CLUES		0.43	0.00%	N/A for CLUES		0.43	0.00%
Ahuriri River, including load from plants	N/A for CLUES		30.93	6.57%	N/A for CLUES		31.60	8.88%	N/A for CLUES		29.02	0.01%
Tekapo R from Fork Stm at Balmoral and Mary Burn at Mt MacDonald												
Upper Tekapo River from L Scott Weir	0.9133	0.52%			0.9140	0.60%			0.91	0.52%		
Tekapo to Pukaki Canal	28.2586	34.34%			28.2724	34.41%			28.26	34.34%		
Upper Pukaki River from L Pukaki Spillway	1.9968	4.47%			1.9965	4.46%			2.00	4.47%		
Pukaki to Ohau Canal	37.9332	4.46%			37.9274	4.45%			37.93	4.46%		
Ahuriri ungauged ECan = Ahuriri Arm -Ahuriri River	3.966	3.08%			3.925	2.01%			3.894	1.21%		
Haldon ungauged Ecan = Haldon Arm - (Ohau C + Tekapo R + Twizel R)	4.769	1.96%			4.911	4.99%			4.769	1.96%		
Benmore ungauged Ecan = Benmore Total - (Haldon Arm + AhuririArm)	0.149	-0.41%	N/A for model		0.149	-0.41%	N/A for model		0.150	0.26%	N/A for model	
*Ahuriri ungauged for model = Ahuriri ungauged Ecan + 0.5 x Benmore ungauged Ecan	4.040	3.01%	4.045	3.01%	3.999	1.96%	4.003	1.96%	3.969	1.19%	3.973	1.20%
*Haldon ungauged for model = Haldon ungauged Ecan + Twizel R + 0.5 x Benmore ungauged Ecan	11.205	7.05%	10.34	7.05%	11.680	11.60%	10.78	11.60%	11.205	7.06%	10.34	7.05%
*Lake Benmore rain			0.413	0.00%			0.413	0.00%			0.413	0.00%
*Lake Benmore dryfall			0.744	0.00%			0.744	0.00%			0.744	0.00%

2.4.2 Lake model loads vs CLUES loads

There are fundamental differences between the way the lake model and CLUES operate, the time scales they focus on, and the level of detail they produce. The nutrient loads used as input for the lake model depend on measured values of both flows and concentrations. The description below has been divided into sections that treat differences between the way the models operate, differences in the way river flows are calculated, and differences in the way concentrations are specified.

Models

CLUES is a GIS-based model that can be used to predict mean annual values of flow ($m^3\ s^{-1}$), TN load (tonnes-N y^{-1}) and median annual concentration (mg-N m^{-3}); and TP load (tonnes-P y^{-1}) and median annual concentration (mg-P m^{-3}) in the reaches of the national stream and sub-catchment network of the NIWA River Environment Classification (REC) system. The original model was described by Woods et al. (2006b) and more recently by Semadeni-Davies et al. (2011). CLUES links a number of models and geo-spatial databases together into one software package. The hydrological model to estimate flow is described by Woods et al. (2006a) and is based on catchment water balance calculations that utilize measurements of precipitation and estimates of potential evapotranspiration. The model flow predictions used in the Waitaki implementation of CLUES for this study have been adjusted by U. Shankar (NIWA Christchurch) to achieve a good match between measured flows and predicted mean annual flows at gauging sites, and to account for flow diversions of the Waitaki hydroelectricity power scheme. CLUES can use several models to estimate TN and TP runoff, including SPARROW, SPASMO, and OVERSEER (Semadeni-Davies et al. 2011; Palliser et al. 2015).

TN and TP concentrations predicted by CLUES have been calibrated against median annual concentrations measured at sites in the New Zealand National River Water Quality Network. For the purposes of the CLUES model application to the Waitaki catchment, the calibration was extensively revised using additional data for both flows and concentrations from sites set up recently in the Waitaki catchment by ECan and NIWA, including the three water quality sampling sites used in the lake model application (the entrance of the Ohau C canal into the Haldon Arm, the Tekapo River mouth and the Ahuriri River mouth). The recalibration incorporated statistical techniques and is described in Palliser et al. (2015).

The model that was used to simulate water quality in the lake has been described in Section 2.1. The model relies on an extensive input data-set of daily data for inflow discharges and nutrient concentrations. These are specified at the Ahuriri River mouth, the Tekapo River mouth, the Ohau C canal entrance to the lake, and for ungauged inflows into the Ahuriri Arm, and into the Haldon Arm. The data are all specified as daily mean values for the 633-day duration of the model runs (1 July 2011 – 25 March 2013). The calibration procedure applies only to the in-lake water quality variables, not to the inflows. It has been described for the 2008-09 model runs in Norton et al. (2009), and the basic calibration has not been altered for the 2011-13 model runs.

Inflow discharges

The lake model uses daily flows that were measured at Meridian and NIWA gauging sites during the 633-day period of the model simulation (1 July 2011 – 25 March 2013). The locations of the gauging sites are shown in Figure 3 of Norton et al. (2009) and in Figures 2-1 and 2-12 above. The flows predicted by the CLUES model are long-term mean annual flows; the CLUES sites are shown with green circles and green typeface in Figure 2-12. The only inflow site that coincides with a gauging site is that at Meridian's Ohau C power station. Even at this site, however, the mean lake model discharge is not exactly the same as that from CLUES because of the different time periods over which the average is calculated.

Gauging stations for flows in the Ahuriri River and the Tekapo River are at some distance upstream from the lake, so these measurements underestimate the actual flow into the lake. A correction for the Ahuriri River was made using CLUES predictions in 2008, which showed that mean annual flow at the lake entrance was approximately 1.2 times that at the gauging site at South Diadem. No similar corrections were available in 2008 for the Tekapo River because the CLUES model did not incorporate the power canal network and associated flow diversions at that time. CLUES has now been revised to account for the diversions, but a corresponding correction like that for the Ahuriri River has not been made for flows input to the lake model from the Tekapo River. In the lake model, the discrepancy is accounted for by including flow that enters the river downstream of the gauging sites in the ungauged flow input to the Haldon Arm. The ungauged flow is computed as a residual from a daily water balance that accounts for all gauged inflows and outflows, changes in lake level and evaporation and rainfall. The calculated residual therefore includes net groundwater inflow as well as surface runoff. Ungauged inflows to the Ahuriri Arm also were calculated as a residual from a water balance, and therefore also implicitly include any net groundwater inflow. Partition of the water balance residual for the whole lake into amounts assigned to the Ahuriri Arm and the Haldon Arm has been discussed above in Section 2.2.1. While groundwater transfers between surface sub-catchments was accounted for in some locations in the Waitaki CLUES model, it was still assumed in the CLUES modelling that all flows enter the lake through surface streams.

A further difference between Tekapo River flows in the lake model and in CLUES arises from the way that the two models treat flood flows that are discharged over the spillways of Lake Tekapo and Lake Pukaki to the Tekapo and Pukaki Rivers. It is necessary to partition these flows from the river flows derived only from the local catchment because the nutrient load increases that are specified for the scenarios are assumed not to apply to the flood flows from the two upstream lakes. The lake model uses daily measured spillway flows for this purpose, and these can vary greatly not just from day to day and week to week but also from year to year. The corresponding CLUES mean annual flood flows are assumed to be approximately 5% of the total mean annual outflow from the lakes.

Yet another difference in inflows to the Haldon Arm is associated with the Twizel River. Although flows have been gauged in the Twizel River, gauging sites did not operate during the periods of the model simulations for either 2008-09 or 2011-13, and Twizel River flow therefore could not be specified explicitly in the lake model input. Instead, it is incorporated in the ungauged inflow from the water balance residual. In contrast, CLUES specifies flows and loads separately for the Twizel River.

Inflow concentrations

Concentrations specified for the lake model are based on samples collected at the three main inflow sites (Ahuriri River mouth, Tekapo River mouth, Ohau C Canal entrance to the lake) on 18 occasions from 20 December 2011 – 27 February 2013. As explained in Section 2.2.2, these samples were used to specify daily concentrations of nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_4-N), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), particulate inorganic nitrogen (PIN), dissolved reactive phosphorus (DRP), dissolved organic phosphorus (DOP), particulate organic phosphorus (POP), and particulate inorganic phosphorus (PIP) for the three major inflows (Ahuriri River, Ohau C Canal and Tekapo River), by interpolating linearly over time between consecutive sample values. The exception was for the phosphorus components (DRP, DOP, POP, PIP) in the

Ahuriri River, for which a reasonable correlation was found between TP, particulate phosphorus (PP) and discharge (see Appendix A; rating curves used for this study are shown in Figure A-1). No reasonable correlations with flow were found for N at any inflow site, or for P at any of the sites other than the Ahuriri River. Ungauged inflows in the Haldon Arm were assigned concentrations equal to those measured in the Tekapo River, as in the 2008-09 study.

Concentrations for ungauged inflows in the Ahuriri Arm were assigned constant values over the model run equal to averages of those measured in a single set of samples collected at the mouths of small ungauged streams around the perimeter of the Ahuriri Arm on 19 June 2014. Results from this survey are described in Appendix B, and the values of the resulting concentrations used for model input can be compared with concentrations measured in the Ahuriri River in Figures 2-4 – 2-7, as well as in Tables 2-1 and 2-2. It can be seen that the survey results indicated substantially higher concentrations for dissolved species NO_3-N, DON, DRP and DOP than those measured in the Ahuriri River, most notably for NO3-N; concentrations of particulate fractions of both nitrogen and phosphorus were lower in the 19 June 2014 samples than those measured in the Ahuriri River.

In addition, an extra pulse of dissolved N and P was added to the Ahuriri River input for the 84-day period 12 Mar – 3 Jun 2012 to account for decay of *L. major* over 74 hectares in the Ahuriri River delta following spraying with herbicide, as described in Section 2.2.4. (This pulse was not subject to nutrient load increases in the scenarios). Finally, it may be worth noting that TN and TP are not used anywhere in model calculations; only the individual components listed above are used.

CLUES concentrations for mean annual TP and TN are calculated using methods based on the SPARROW model and calibration against measured data at specified calibration sites. For the Lake Benmore application these sites include the three lake inflow monitoring sites, in addition to others throughout the Lake Benmore catchment. The details of the methods have been documented in Palliser et al. (2015). While the loads calculated by CLUES therefore depend on the concentrations measured for the lake model, they are also influenced by the other processes incorporated in the CLUES methodology, and cannot be expected to be the same as those used for the lake model.

Mean annual loads for all scenarios as predicted by CLUES and as adapted for input to the lake model are shown in Tables 2-1 and 2-2 (the "Current" scenario is the same as the baseline or final validation run). While the CLUES and lake model loads are of similar magnitudes, they are not identical, for the reasons discussed above. Percent increases in loads for the scenarios, as predicted by CLUES, have been used to calculate loads for the lake model, rather than the actual CLUES loads. Note that the percent increases in loads are identical for CLUES and lake model loads only for the actual inflow sites used in the model (sites prefixed by an asterisk * in the first column): Ahuriri River (excluding contribution from plant decay), Ohau C Canal, Tekapo River and the ungauged inflows for the Ahuriri Arm and the Haldon Arm. Lake model loads for the remaining sites that have been included in the tables to show comparisons with CLUES flows and loads are calculated in the "Lake model" columns from these five inflows as follows:

- "Haldon Arm" flows and loads for the lake model are the sum of flows and loads for the "Ohau C Canal", the "Tekapo River at Haldon Arm" and "Haldon ungauged for model";
- "Ahuriri Arm (excluding plants)" flows and loads are the sum of flows and loads from the "Ahuriri River at Ahuriri Arm (excluding plants)" and "Ahuriri ungauged for model";

- Entries for “Benmore for model” and “Benmore total including Lower Benmore Basin” are the same for the lake model, because inflows for the lake model do not account for the very small contribution of ungauged flows and loads predicted by CLUES for the Lower Benmore Basin; for the error involved in neglecting these inflows see the entry for “Benmore ungauged ECan = Benmore Total - (Haldon Arm + Ahuriri Arm)”

2.5 Modelling strategy

In Norton et al. (2009; see Section 3.7) we noted that although the time available for project completion did not allow us to run long-term simulations with ELCOM, it was necessary to run scenarios for a full year in order to calculate statistics for trophic level index (TLI, Burns et al. 1999, Burns and Bryers 2000). In the 2009 study it was decided to model a representative year that best typified climate, inflow and outflow variables for the Upper Waitaki Basin, and August 2003- July 2004 was chosen, based on examination of annual means for climate variables, inflows and outflows. The initial contract (Section 1.2.1) specified that the same strategy was to be followed for scenario testing in the present study. However, by the time that a satisfactory model validation had been achieved that would allow the scenarios to be run, the 2009 approach was no longer appropriate, mainly for two reasons:

- In the 2009 study, values for inflow nutrient concentrations were set at constant average values for the duration of the model runs, and did not reflect seasonal variability or the influence of flow and climate variability. In contrast, the introduction of time variation in the input data for the present study (Section 2.2.2) means that input time series for nutrients now reflect 2011-13 seasonal, climate and flow variations, so it is not reasonable to combine them with 2003-04 weather and flow time series.

- Input load specifications for the present scenarios are much more complex than those of the 2009 application, where a single load multiplier was sufficient to completely characterise the increase in loading of both nitrogen and phosphorus for both arms of the lake. The relative complexity of the present scenarios (Section 2.4.1) means that ten load multipliers, rather than one, are necessary to characterise the loading configuration for a single scenario – one for nitrogen and one for phosphorus in each of the five main inflows (Ahuriri River, Tekapo River, Ohau C Canal, ungauged inflow to the Ahuriri Arm and ungauged inflow to the Haldon Arm).

In the present study, the input data for used in the final validation run for flows, climate and nutrients now serves as the baseline or ‘current’ scenario input, and the duration of the scenario runs is the same as that of the validation run (1 July 2011 – 26 March 2013). Influences of climate and flow variability on patterns of inflow concentrations are therefore preserved.

Inputs for rainfall and dryfall are not specified for CLUES and remain at baseline levels for all scenarios as in the 2009 study. Also as in 2009, load multipliers are not applied to concentrations in spillway overflows from Lake Tekapo and Lake Pukaki that are directed into the Tekapo River and Pukaki River, respectively, and eventually enter the lake in the Tekapo River.

As discussed in Section 2.4 the annual loads for TN and TP in each of the five main inflows as specified by output from the CLUES model are shown in Tables 2-1 and 2-2; the five main inflow names are prefixed with an asterisk in the tables. Corresponding annual TN and TP loads for the lake model are derived using the same percentage increase (i.e., load multiplier) from the baseline or 'current' scenario level. As in the 2009 study, annual TN and TP loads need to be partitioned into loads of individual nitrogen and phosphorus components required for model input, and these components adjusted to account for the increasing fraction of dissolved inorganic components as total nitrogen and phosphorus increase. The same approach used in 2009 and described in Norton et al. (2009, Section 3.6) was used for the present study. Figures E-3 and E-4 and associated regressions in Norton et al. (2009) were updated (not shown) to account for current (2011-13) concentrations of TN and TP in five main inflows. The load multipliers were then applied to the input concentration time series, ensuring that the values for total annual nitrogen and phosphorus loads specified for the scenario were preserved.

As in 2009 (Norton et al. 2009, Section 3.7), each scenario was run two times for the full 633-day run duration (1 July 2011 – 26 March 2013). For the first run the initial conditions for in-lake nutrient concentrations and sediment oxygen demand were as for the current baseline conditions. As would be expected, at the end of the first run for a scenario with nitrogen and phosphorus loads increased above existing levels, the in-lake nutrient and Chl-*a* concentrations were higher at the end of the year than at the start of the year. For the second run, the initial conditions for nutrient concentrations were reset to in-lake values averaged over the lake volume and over the last 5 days of the first run.

As in 2009 (Norton et al. 2009, Section 3.7), the sediment oxygen demand parameter for CAEDYM was recalculated after the first scenario run using the relationship given by Schallenberg and Burns (1999), which relates areal hypolimnetic oxygen demand (AHOD) to summer mean epilimnion Chl-*a* concentration, euphotic depth, and lake mean depth. Chl-*a* and euphotic depths from the first run were used to increase the sediment oxygen demand parameter by a factor based on the ratio of oxygen demands specified by the Schallenberg-Burns relationship. Ideally the iteration procedure of running the model for 633 days, revising the initial conditions and sediment oxygen demand, and rerunning the model could be repeated until end-of-run results either exhibited minimal further change or agreed with initial conditions within some specified tolerance. However, initial testing in the 2009 study indicated that convergence was rapid and one iteration was considered satisfactory. Modelled data output from the second run were used to extract the statistics and other results presented in Section 3.

3 Results

3.1 Validation of model

Time-series data showing concentrations of measured constituents and model simulations for each of the lake arms are shown in Figures 3-1 to 3-6. Recall (Section 2.3.1) that although model runs start on 1 July 2011, no measured data are available from field samples with which to compare model predictions until 20 December 2011. The period 1 July – 20 December 2011 is treated as a 'lead-in' period for the model run that allows initial conditions to be specified in the lake in winter when the water column is vertically mixed, and then time for the model to fully adjust to these conditions.

3.1.1 Haldon Arm

In the Haldon Arm the model simulated Chl-*a* concentrations at between 0.1 and 1.5 mg m^{-3} demonstrating oligotrophic water. However there were periods when observed concentrations at 5 and 25 m water depth (the lake epilimnion) were between 2 and 3 mg m^{-3} suggesting the Haldon Arm may be approaching mesotrophy. Of interest is the winter 2012 rise in Chl-*a* to a maximum that was not captured in the model. No winter sampling was conducted in 2008-09 to compare, but it is this winter maximum in Chl-*a* that contributes largely to the discrepancy between observed and simulated Chl-*a* at this time. Winter diatom blooms are a feature of several oligotrophic North Island lakes and result from nutrient mixing up from the hypolimnion. However, South Island oligotrophic lakes have not been studied to the same degree as North Island lakes and it is unclear if the winter bloom phenomenon is a feature of other oligotrophic lakes in the South Island. Certainly the southern lakes Wanaka and Wakatipu do not have winter maxima. A further point to note was that ECan's surface water samples show lower Chl-*a* values than the 5m samples in this study. The reasons for this are being evaluated in a separate study.

While the model was able to adequately simulate surface NO_3-N and NH_4-N (Figure 3-1) the simulations for TN were, on occasion, only half the observed values in the epilimnion at 5 and 25 m depth. In this regard it is noted that DON was also higher in the lake than was simulated (Figure 3-2) and the relatively high TN can be largely ascribed to the DON fraction. While the model simulated the annual pattern of increasing bottom water (50 m depth) NO_3-N concentration during the lake's summer stratified period, again the simulation concentrations were lower than observed. TP and DRP were adequately simulated by the model, with the exception of the accumulation of DRP in the hypolimnion predicted by the model (discussed in the next paragraph). The organic constituents of the Haldon Arm (Figure 3-2) were all adequately simulated in the model with the exception of DON.

The deep water (50 m) mismatch of observed NO_3-N and DRP is interesting as it shows NO_3-N accumulated in the hypolimnion but DRP did not accumulate. We cannot rule out that we might have set: (i) the bottom releases incorrectly in the model or (ii) mineralisation rates from organic nutrient constituents incorrectly. For the Haldon Arm we have less confidence in DRP than NO_3-N because while the trend in the simulated NO_3-N appears obvious during stratification, concentrations of DRP are still very close to detection limits. We point out that this mismatch of hypolimnetic values does not affect model predictions of summer TLIs, which are calculated only for the epilimnion.

3.1.2 Ahuriri Arm

In the Ahuriri Arm, Chl-*a* and nutrient levels were generally higher than in the Haldon Arm as reflected both in observed and simulated values (Figures 3-3 and 3-4). Again the model was not able to accurately reproduce the higher levels of observed Chl-*a*. Simulations of Chl-*a* in the top 15m varied between 1 and 3 mg m^{-3} while observed values varied between 1 and 4 mg m^{-3} (Figure 3-3) with samples from ECan (yellow diamonds) being lower. In the Ahuriri Arm the concentrations and annual patterns of NO_3-N, TP and DRP were well represented by the model (Figure 3-3). While NH_4-N values were generally low (<0.015 g-N m^{-3}), this variable showed high short-term variability from sample to sample. The model showed an annual mean, with low variability, around 0.005 g-N m^{-3} but did not adequately reflect the high spikes in NH_4-N. The model adequately simulated the organic components of the Ahuriri Arm (Figure 3-4) with the exception, of DON and POP. The latter concentrations were extremely low. The simulations of DON showed an annual variability of between 0.05 and 0.11 mg DON m^{-3} while observed values ranged from 0.03 to 0.25 mg DON m^{-3}. As in the Haldon Arm, DON made up the major portion of the TN concentration.

3.1.3 Lower Benmore Basin

In the Lower Benmore Basin (Figures 3-5 and 3-6) results of observed and simulated values for Chl-*a,* TN and DON followed the same patterns as those in the two lake Arms such that simulations of these three parameters were lower than the observed values. The model simulations of the other parameters closely matched observed values.

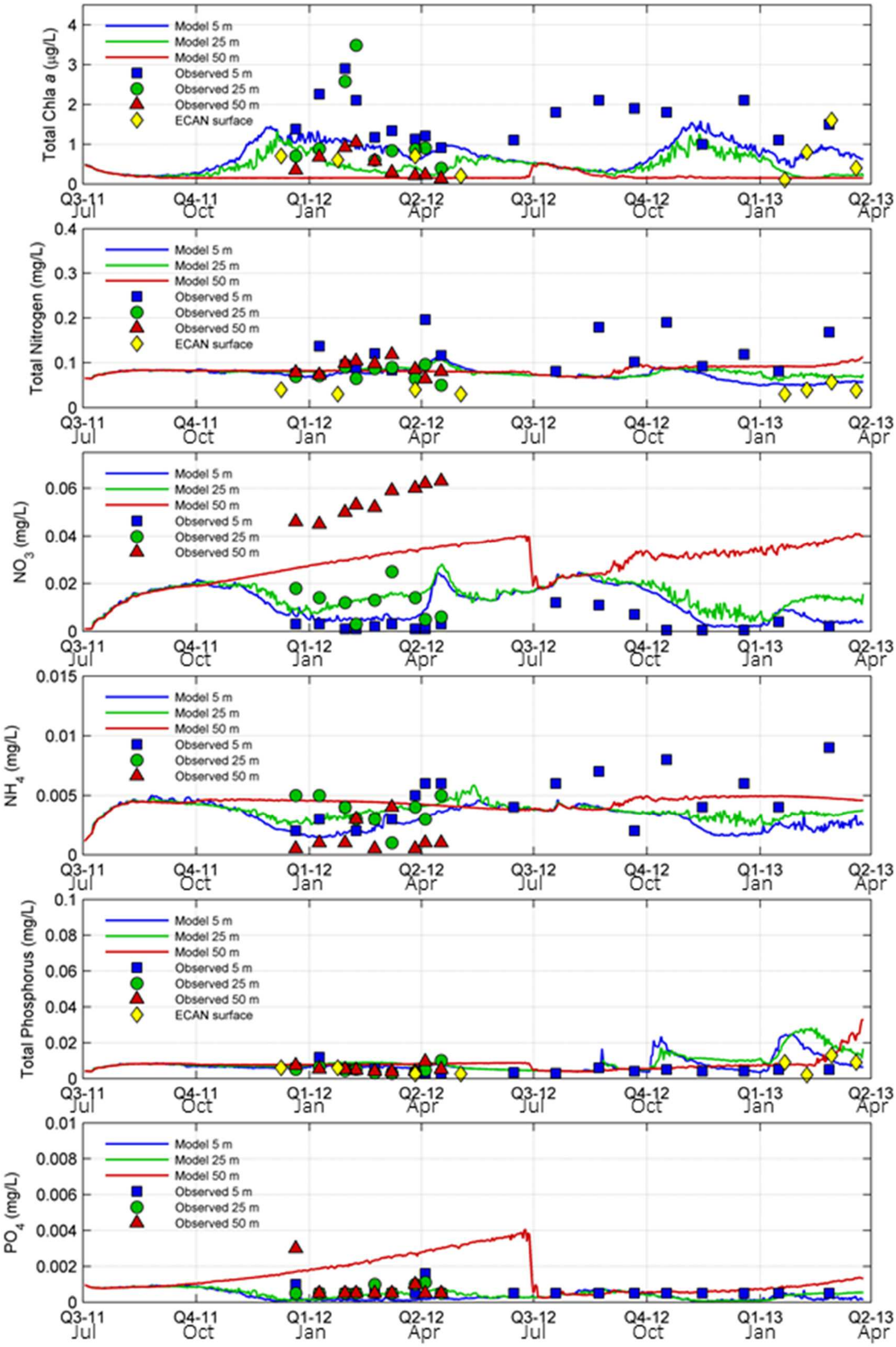

Figure 3-1: Simulated (lines) and observed (dots) values for Chlorophyll-*a*, TN, NO_3-N, NH_4-N, TP and PO_4 at three depths in the Haldon Arm. TN = total nitrogen, NO_3 = nitrate-N, NH_4 = ammonium-N, TP = total phosphorus and PO_4 = dissolved reactive phosphorus (DRP). Concentrations of NO_3 and NH_4 are mg-N L^{-1}.

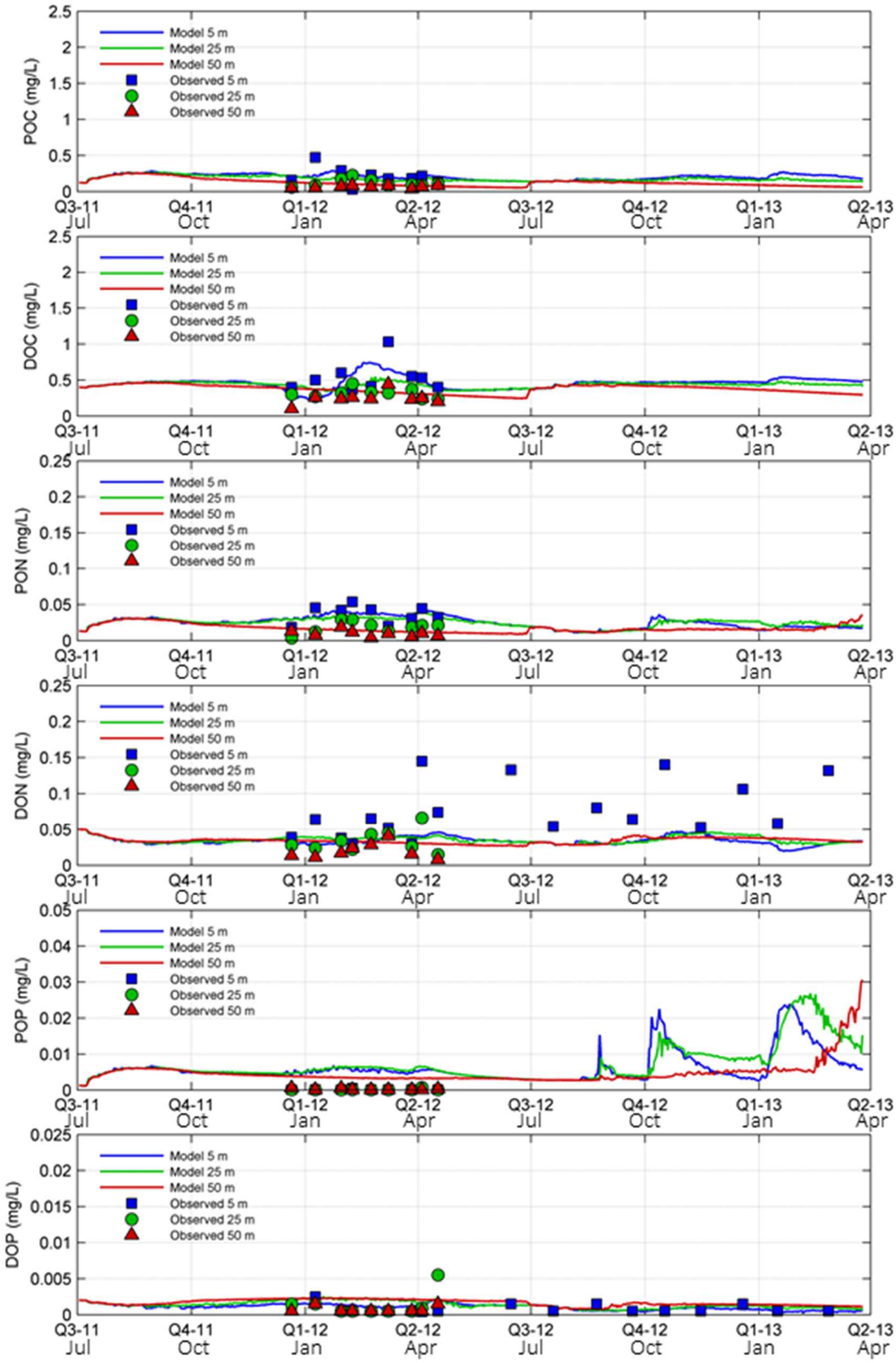

Figure 3-2: Simulated (lines) and observed (dots) values for POC, DOC, PON, DON, POP, DOP at three depths in the Haldon Arm. POC = particulate organic carbon, DOC = dissolved organic carbon, PON= particulate organic nitrogen, DON = dissolved organic nitrogen, POP = particulate organic phosphorus and DOP = dissolved organic phosphorus.

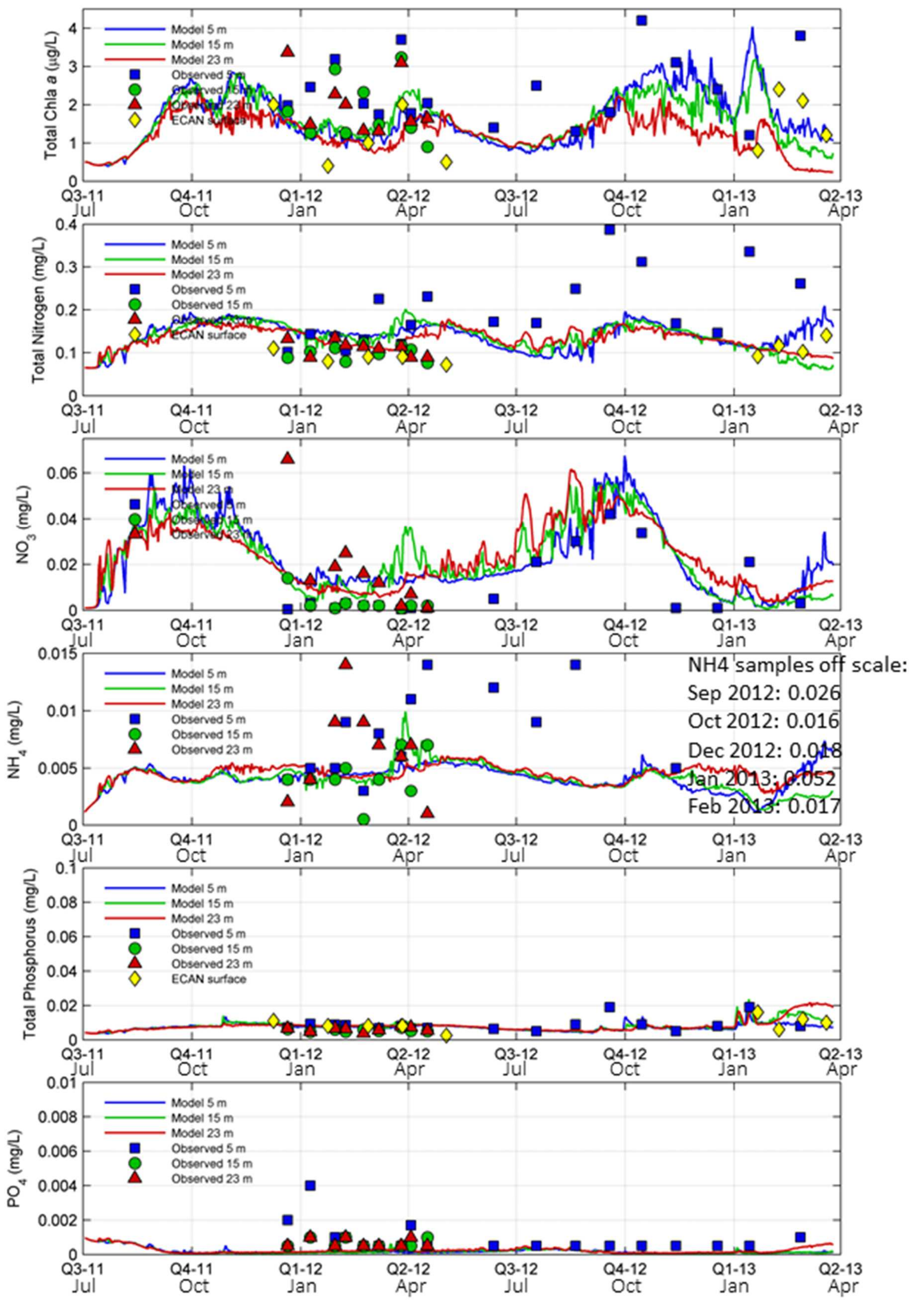

Figure 3-3: Simulated (lines) and observed (dots) values for Chlorophyll-*a*, TN, NO_3-N, NH_4-N, TP and PO_4 at three depths in the Ahuriri Arm. TN = total nitrogen, NO_3 = nitrate-N, NH_4 = ammonium-N, TP = total phosphorus and PO_4 = dissolved reactive phosphorus (DRP). Concentrations of NO_3 and NH_4 are mg-N L^{-1}.

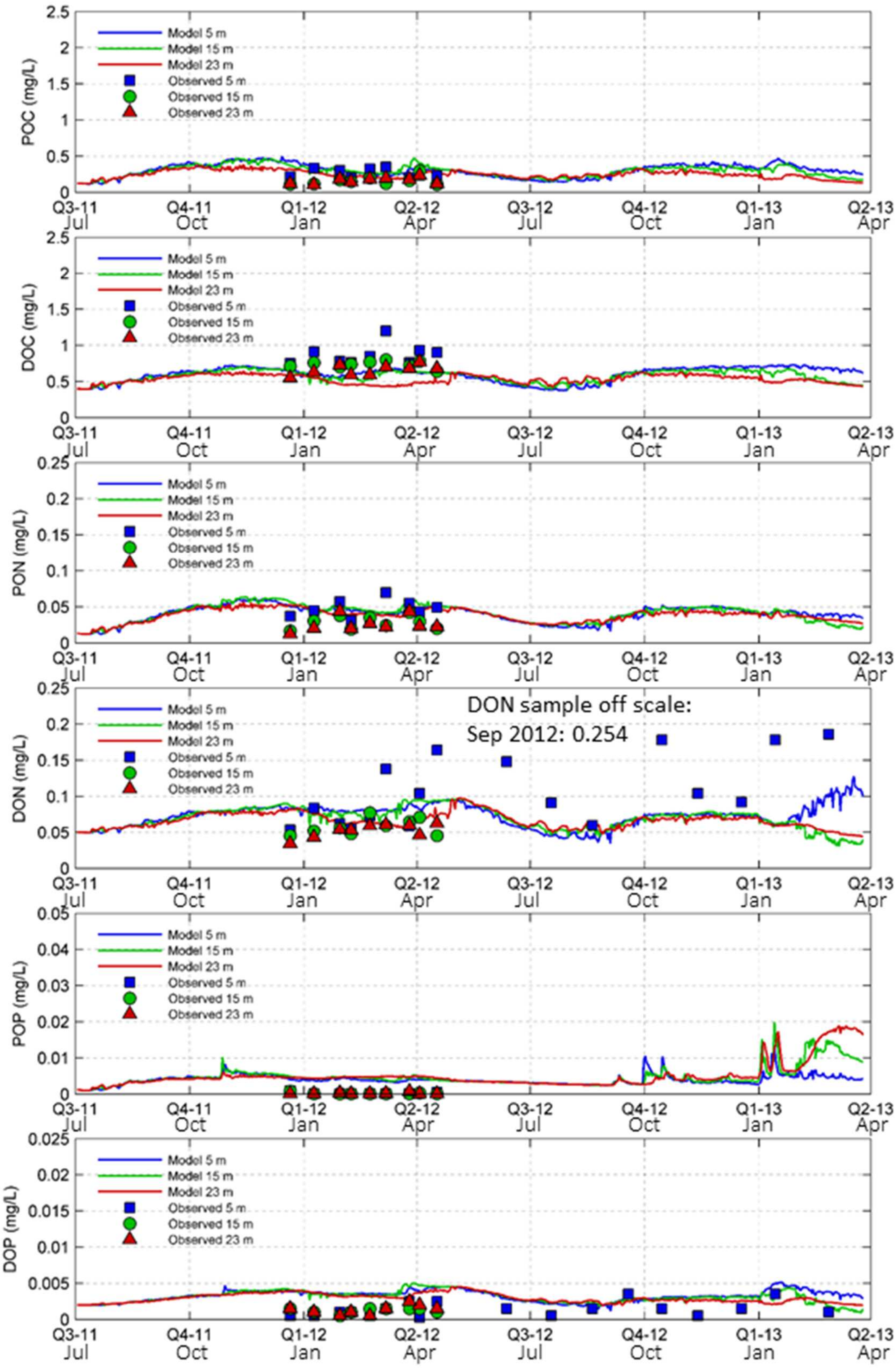

Figure 3-4: Simulated (lines) and observed (dots) values for POC, DOC, PON, DON, POP, DOP at three depths in the Ahuriri Arm. POC = particulate organic carbon, DOC = dissolved organic carbon, PON= particulate organic nitrogen, DON = dissolved organic nitrogen, POP = particulate organic phosphorus and DOP = dissolved organic phosphorus.

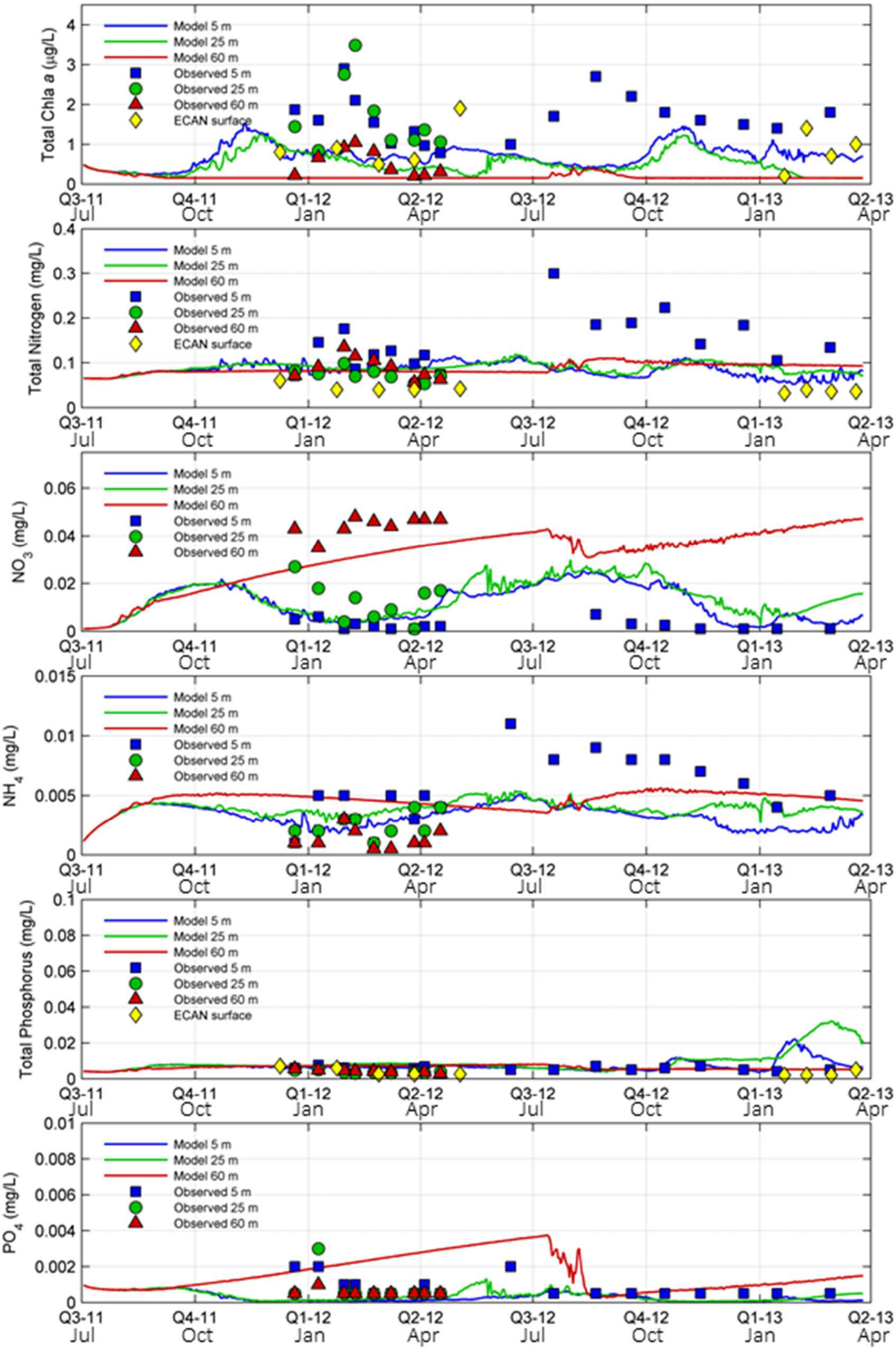

Figure 3-5: Simulated (lines) and observed (dots) values for Chlorophyll-*a*, TN, NO_3-N, NH_4-N, TP and PO_4 at three depths in the Lower Benmore Basin. TN = total nitrogen, NO_3 = nitrate-N, NH_4 = ammonium-N, TP = total phosphorus and PO_4 = dissolved reactive phosphorus (DRP). Concentrations of NO_3 and NH_4 are mg-N L^{-1}.

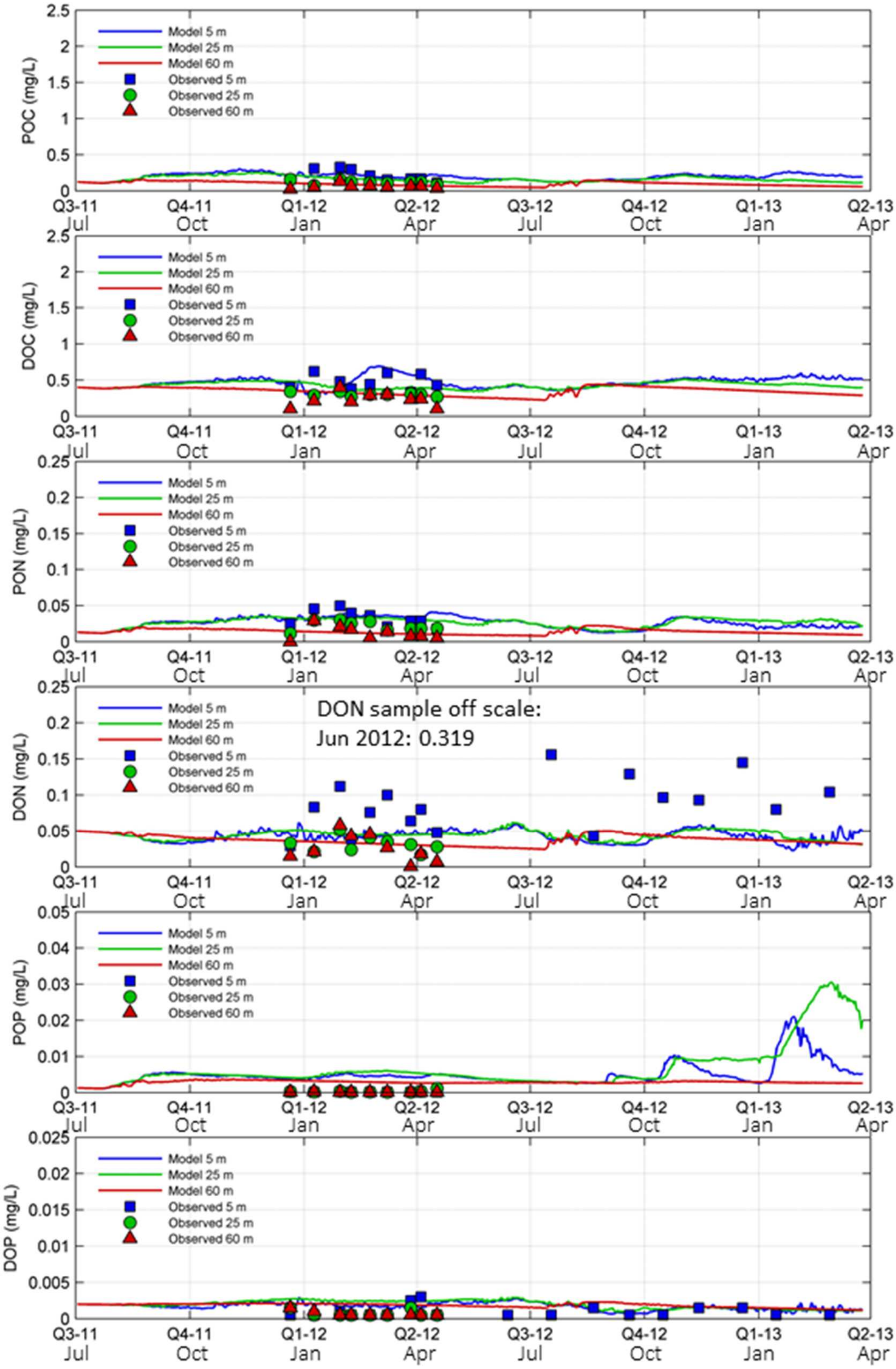

Figure 3-6: Simulated (lines) and observed (dots) values for POC, DOC, PON, DON, POP, DOP at three depths in the Lower Benmore Basin. POC = particulate organic carbon, DOC = dissolved organic carbon, PON= particulate organic nitrogen, DON = dissolved organic nitrogen, POP = particulate organic phosphorus and DOP = dissolved organic phosphorus.

3.2 Modelling TLI and its components – Chl-*a*, TN, TP

Modelling of the Trophic Level Index (TLI) was the primary mechanism for assessing effects of the changing land-use scenarios. The TLI provides a convenient and pragmatic numeric scale for measuring trophic status of New Zealand lakes. Choices for the desired trophic state of a lake can be equated with a numeric value on the TLI scale and thus TLI can be used for setting measurable regional plan objectives for lakes (Burns and Bryers 2000, Norton et al. 2009).

Figure 3-7 represents the 2011-13 period, where the nutrient, flow and climate data are all from 2011-13. The results of the 2008-09 study are presented for comparison in Appendix C. Figure 3-7 shows four sets, or groups, of bars – three groups for the Chl-*a*, TN and TP components of the TLI, and one for the mean TLI. The simulations ran over almost two years, and samples were collected differently in the two summers. In the first summer (2011-12) samples were collected approximately fortnightly at three depths at the lake sampling sites, so the calculations correspond exactly to those used in 2008-09. However, for the second summer (2012-13), samples were collected approximately monthly and only 10 m integrated tube samples were collected. Also, only three sets of samples were collected for the summer period of 2012-13 compared with seven sets for the summer of 2011-12.

Due to the different sampling protocols for the two summers, sample TLI values are presented separately for each summer. In Figure 3-7, 2012-13 summer TLI (blue bar) for both the Haldon and Ahuriri Arm, represents the TLI values calculated from the 0-10 m integrated tube samples, only. Whereas, 2011-12 summer TLI values are calculated from three different sampling depths in the Ahuriri Arm (5 m sample only; 5 m + 15 m samples only; and 5 m + 15 m + 23 m samples), and two different sampling depths in the Haldon Arm (5 m sample only; and 5 m + 25 m samples). We note that the method specified by Burns and Bryers (2000) for calculating TLI specifies that samples be collected throughout the depth of the epilimnion, and that there is an element of judgement involved in determining the extent of the epilimnion depth from temperature profiles. The multiple presentation of results for different depths in Figure 3-7 and in Tables 3-1 and 3-2 allows for differences among observations and sampling methods for TLI calculations. Figure 3-7 also shows that TLI values calculated from 5 m samples alone are larger than those that incorporate samples from deeper levels in the epilimnion.

In Lake Benmore, the maximum extent of the epilimnion in summer is usually 30 m; at the shallower Ahuriri Arm sampling site, the water column is frequently mixed to the bottom. When calculating TLI values from model output, averages have been taken over the top 30 m of the water column in the Haldon Arm and in the Lower Benmore Basin, and over the entire depth at the Ahuriri Arm sampling site. TLI values calculated from model output shown in Figure 3-7 and in Tables 3-1 and 3-2 therefore correspond most closely with sample TLI's based on averages from samples collected at all three depths (5 m, 15 m, 23 m) in the Ahuriri Arm, and at the top two depths (5 m, 25 m) in the Haldon Arm and Lower Benmore Basin. Values of TLI in the Lower Benmore Basin are not shown in Figure 3-7, but have been included in Tables 3-1 and 3-2.

As for TLI calculated from samples, the model simulation results are presented for summer-only conditions, but the TLI values are calculated from concentrations averaged over two summers (15 November 2011 – 15 March 2012, and 15 November 2012 – 15 March 2013). For the model calculations there are two bars, one for the sampling site and one for an average over several sites in each Arm. There was little difference between the two calculations indicating that the sampling sites were representative of wider Arm conditions.

Modelled mean TLI values in 2011-13 were similar to observed mean TLI values (*ca*. 2.76 vs 2.85 respectively in the Ahuriri Arm and 2.41 observed vs 2.38 modelled in the Haldon Arm). Of note in the Haldon Arm was the fact that TLI-TP was over-predicted and TLI- Chl-*a* was under-predicted (Figure 3-7). In the Ahuriri Arm TLI observed values were similar to those in 2008-09 (shown in Appendix C) with the exception of TLI-TP, but it is noteworthy that for the three samples collected in 2012-13 the TLI values were higher than in the previous years. Inspection of the inflow data in the Tekapo River showed that the model's over-prediction of TP in the Haldon Arm was associated with a flood that occurred in January 2013 (see Figure 2-10). A sample collected on 15 January 2013 contained very high concentration of TP, most of which was PIP (see Figure 2-10 and 2-11). As a result of the linear interpolation between sample collections, this would have almost certainly have overestimated TP inflow loads to the Haldon Arm. Correspondingly high concentrations were not recorded in samples from subsequent monitoring occasions at the Haldon Arm sampling point most likely as a result of sedimentation of particulate matter in the upper reaches of the Haldon Arm before the sediment could reach the sampling site approximately 13 km downstream. In the Haldon Arm, the model is calibrated for the very fine particle glacial flour rather than coarser sediment fractions associated with floods and therefore would not have simulated this sedimentation. The net result of linear interpolation and not predicting settling would have been the over-estimation of TLI-TP as seen in Figure 3-7.

Therefore, while there were discrepancies between measured vs. modelled TLIs for the individual Chl-*a*, TN and TP components, and there was greater variability amongst samples in 2011-13, the agreement between the mean modelled and measured TLIs was reasonable.

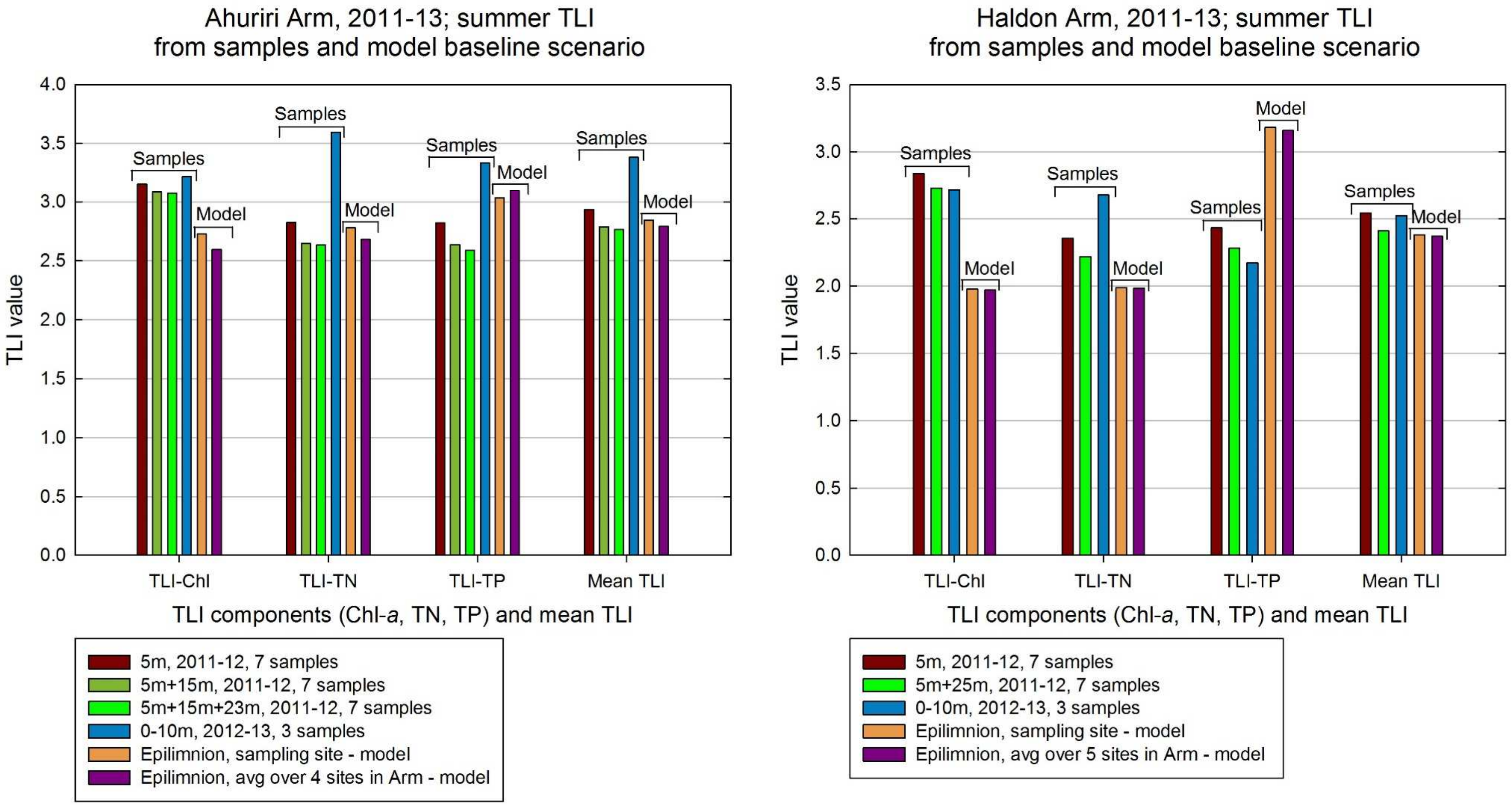

Figure 3-7: Trophic Lake Index (Mean TLI) in 2011-13 calculated for summer in the Ahuriri Arm (Left Panel) and the Haldon Arm (Right Panel). TLI for observed and modelled values are shown and these are further broken down into constituent values of the TLI (Chl-*a*, TN, TP) at different depth combinations.

Table 3-1: Lake Benmore - Baseline conditions. Measured and modelled concentrations, parameter-specific TLIs and mean TLIs for 2011-13 in the three arms of the lake. Observed = measured summer TLIs from fortnightly and monthly samples; averages over depths that correspond most closely to model. Modelled = Modelled summer TLIs from daily calculations at sampling sties; averages over "epilimnion" which is either 0-30 m or entire basin depth, whichever is smaller. 2011-13 7 samples from 20 December 2011 – 26 March 2012; 2012-13 = 3 samples from 18 December – 26 February 2013.

Site	Chl-*a* µg/L	TN µg-N/L	TP µg-P/L	TLI-Chl-*a*	TLI-TN	TLI-TP	Mean TLI
Ahuriri Arm 2011-12– observed	2.17	118.63	6.48	3.07	2.63	2.59	2.76
Ahuriri Arm 2012-13 – observed	2.47	247.67	11.67	3.22	3.60	3.33	3.38
Ahuriri Arm 2011-13 – modelled	1.58	132.60	9.20	2.73	2.78	3.03	2.85
Haldon Arm 2011-12 – observed	1.59	86.31	5.09	2.73	2.22	2.28	2.41
Haldon Arm 2012-13 – observed	1.57	122.67	4.67	2.72	2.68	2.17	2.52
Haldon Arm 2011-13 – modelled	0.80	72.34	10.34	1.98	1.99	3.18	2.38
Lower Benmore 2011-12 – observed	1.78	96.61	4.51	2.86	2.36	2.13	2.45
Lower Benmore 2012-13 – observed	1.57	141.00	4.67	2.72	2.86	2.17	2.58
Lower Benmore 2011-13 – modelled	0.68	82.94	10.62	1.80	2.17	3.21	2.39

3.3 Scenario testing

The model results for the current condition and the scenarios are presented in Table 3-2. In the Haldon Arm, the mean TLI increased from 2.59 to 2.71 from Scenario 1a to 2a and then increased slightly to 2.72 in Scenario 2b. Values were higher in the Ahuriri Arm, increasing continuously from 2.91 in Scenario 1a to 3.25 in Scenario 2b. Modelled TLIs for the Scenarios in the Lower Benmore Basin were slightly less that in the Haldon Arm.

The relative complexity of the scenarios with varying N and P levels depending on the types of agricultural activity make the graphical depiction of the TLI vs Scenario results more complex than the depictions in the 2008-09 report. The results are shown in Figure 3-8.

In the Ahuriri Arm, there was a large change in both N and P and hence the TLI between Scenario 1a-2a and Scenario 2a. The difference between Scenario 2a and 2b is largely due to an increase in P from 2a to 2b concurrent with a slight reduction in N in 2b. The result is a rise in TLI from 3.23 -3.25.

In the Haldon Arm the scenarios provided quite different combinations (Figure 3-8) so that from Current (baseline) to Scenario 2a, N and P increased almost in the same ratio up to relatively high levels (840 tonnes N and 97 tonnes P). However Scenario 2b then registered a small increase in P with little change in N. TLIs varied slightly between Scenarios 2a and 2b from 2.71 to 2.72.

Table 3-2: Lake Benmore modelled TLIs for Scenarios 2011-13. Model results for averages of Chl-*a*, TN and TP and TLIs over 2 summers for the epilimnion (0-30 m), or entire water column depth if that was less than 30 m.

Haldon Arm scenarios	Chl-*a* µg-/L	TN µg-N/L	TP µg-P/L	TLI-Chl-*a*	TLI-TN	TLI-TP	Mean TLI
Current	0.80	72.34	10.34	1.98	1.99	3.18	2.38
Scenario 1a	1.05	83.56	11.38	2.28	2.18	3.30	2.59
Scenario 1a-2a	1.23	92.19	12.11	2.45	2.30	3.38	2.71
Scenario 2a	1.23	92.50	12.15	2.45	2.31	3.38	2.71
Scenario 2b	1.24	92.95	12.26	2.46	2.31	3.40	2.72
Ahuriri Arm scenarios							
Current	1.58	132.60	9.20	2.73	2.78	3.03	2.85
Scenario 1a	1.66	141.03	9.60	2.78	2.86	3.09	2.91
Scenario 1a-2a	1.71	144.64	9.86	2.81	2.89	3.12	2.94
Scenario 2a	2.33	162.36	13.20	3.15	3.04	3.49	3.23
Scenario 2b	2.43	160.35	13.72	3.20	3.03	3.54	3.25
Lower Benmore scenarios							
Current	0.68	82.94	10.62	1.80	2.17	3.21	2.39
Scenario 1a	0.85	93.29	11.47	2.04	2.32	3.31	2.56
Scenario 1a-2a	0.95	101.13	12.08	2.17	2.42	3.38	2.66
Scenario 2a	1.00	103.59	12.51	2.22	2.46	3.42	2.70
Scenario 2b	1.02	103.75	12.68	2.24	2.46	3.44	2.71

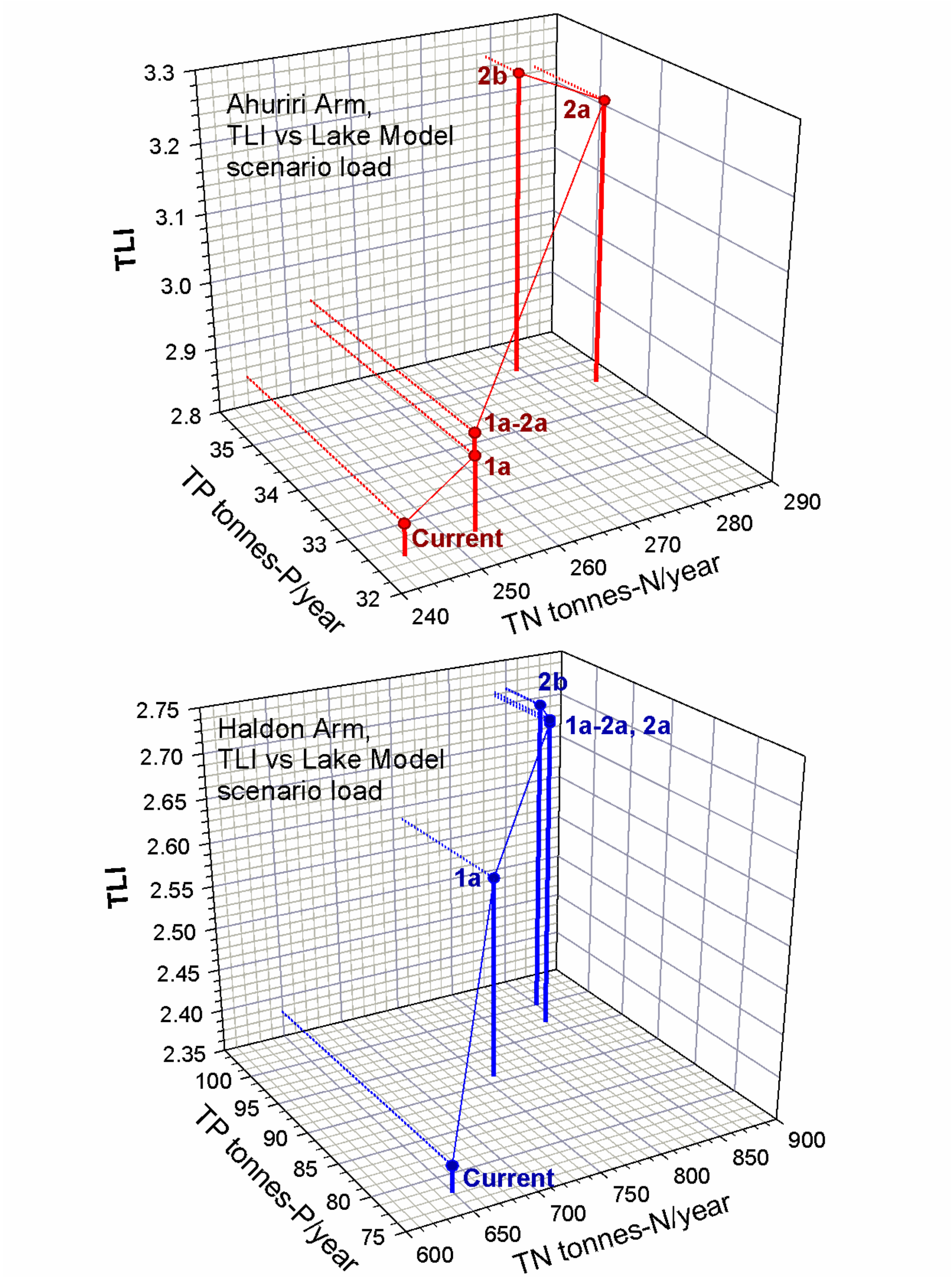

Figure 3-8: 3-D representations of the N and P loads in the different scenarios versus simulated TLI values.

4 Discussion

4.1 Model uncertainty

Model uncertainty was discussed in Section 5.1 of Norton et al. (2009). The qualitative aspects of that discussion are still relevant to this modelling study. However, the quantitative measures for root mean square errors between model predictions and observed values have not been calculated for this report. These can be calculated if required. Root-mean-square errors for temperature and DO cannot be calculated for this modelling study because these parameters were not measured in the 2011-13 study. However they should be similar to those given in Norton et al. (2009).

4.2 Concern over matching with in-lake parameters

In the 2008-09 study the observed TN and DON concentrations were reasonably well matched by the model (Norton et al. 2009) but these two parameters were significantly underestimated in the 2011-13 modelling runs. The relatively high TN values in 2011-13 can be attributed to the high contribution of DON. It appears from the input data (Section 2) that DON concentrations at 5 m in the lake were almost double those in the main river inflows (ca. 0.1 g m^{-3} DON in the Haldon Arm vs. ca. 0.05 g m^{-3} in Haldon inflows), and for the Ahuriri Arm, ca. 0.15 g m^{-3} DON in the lake vs. ca. 0.07 g m^{-3} in the inflows. This indicates either a transformation or a release pathway of DON in the lake waters at levels that we cannot currently account for in the model or that there was an unaccounted-for source of DON in the inflows. Apart from the potential for large-scale decay of *L. major* to directly release DON, or to contribute to DON increase via PON mineralisation, it is difficult to explain the variability in DON that was apparent in both Haldon and Ahuriri Arms, other than through DON loads to the lake via inflows and pathways not sampled. We note that large-scale weed kill and decay was only a feature of the Ahuriri Arm. However, DON in lake waters is generally regarded as refractory and unlikely to contribute directly to phytoplankton growth. The DON pathways in Lake Benmore are uncertain without further investigation.

In general the match of in-lake observations for Chl-*a*, TN and DON was not as good as it was in the 2008-09 modelling (see Norton et al. 2009, Trolle et al. 2014) and these three parameters, in particular, were underestimated. This suggests that the 2011-13 model results must be considered as underestimates when the effects on lake trophic state of scenarios for nutrient increases are discussed. Our understanding is that this could be due to incorrect estimation of nutrient input loads, deficiencies in model calibration/formulation, or a combination of both. Given that the model was well able to simulate the lake conditions for Chl-*a* in 2008-09 and that for all variables modelled in 2011-13 it was only DON and Chl-*a* that were consistently underestimated (note that the high TN values are accounted for by DON contribution). It is most likely that we have not correctly accounted for DON loads either in surface or groundwater, measured or unmeasured rather than the model formulation being at fault in this case. For instance, the 19 June 2014 sampling of ungauged inflows showed very high concentrations of DON in some small streams entering the Ahuriri Arm, most notably streams 3 and 7 (Appendix B)

4.3 Indications of nutrient limitation

Analysis of diagnostic model results (Appendix D) showed that Chl-*a* production for diatoms (the most abundant phytoplankton type) for 2011-13 in the Ahuriri Arm were limited in summer by P concentrations. The model showed P control on phytoplankton growth in 2011-13 that was in contrast to the situation in 2008-09 (lower three panels in Appendix D), when the phytoplankton growth in the model was frequently limited by availability of both N and P. Model predictions for the Haldon Arm indicated that in 2008-08 there were extended periods of both nitrogen limitation and N and P co-limitation. In 2011-13, there were alternate periods of P limitation and co-limitation of N and P.

The co-limitation predicted in 2008-09 modelling was consistent with bioassays carried out in the lake at that time to test for N and P limitation (Norton et al. 2009). No similar bioassays were carried out in 2011-13 but the model indications of P-limited conditions raise a question over the reasons for the high Chl-*a* concentrations observed in 2011-13 when both DRP and TP were so low (Figures 3-1, 3-3, 3-5). Nevertheless, model results clearly show that nutrient limitation varies with time that co-limitation of both N and P are common and therefore that over time-scales of months and years both nutrients are likely to affect phytoplankton growth in Lake Benmore. Both will need to be managed if the objective is to minimise phytoplankton growth and keep the TLI low.

The significant decline by almost a factor of two of the observed TP between 2008-09 (Appendix D) and 2011-12 in both the Ahuriri and Haldon Arms can be attributed to decrease in total inflows between the two monitoring periods. Floods and hydro-dam spill events have a major impact on the TP concentration and loads entering Lake Benmore. Inflows during 2008-09 were characterised by frequent, medium sized floods in both catchments, whereas in 2011-12 prevailing dry conditions in both catchments meant inflows were low (Sutherland et al. 2013). TP concentrations increased again in 2012-13 as both catchments experienced several large flood events (Sutherland et al. 2013). It is possible these events shifted the limitation away from phosphorus in 2014 but we do not have the information to support that. Land-use intensification can result in an increase in the ratio of TN/TP (Dr Sandy Elliott, pers. comm.), but in this case the hydrological variability may have outweighed effects of intensification between 2008-09 and 2011-2013.

4.4 TLI simulations

The time series data showed some discrepancies between observed and modelled individual values for some of the parameters (eg TN and Chl-*a,* which directly constitute components of the TLI, and DON which contributes to the TLI-N constituent). However, the close fit between modelled and observed mean TLI provides comfort that, at the general indicator level that TLI provides, we were able to model scenarios showing the effects on TLI (and overall lake quality) of nutrient additions.

The scenario testing on the lake TLI showed trends of rising TLIs with scenario load inputs in a pattern that was expected and explainable. The scenarios suggest the need for close management in the Ahuriri Arm catchment with Scenarios 2a and 2b potentially resulting in an exceedance of TLI 3.0 and lake mesotrophy even with the model apparently under-predicting observed Chl-*a*. The modelling indicated slightly reduced TLIs with the scenarios in the Lower Benmore Basin relative to Haldon Arm. This may require further investigation.

4.5 Land-use changes and nutrient input loads

During the course of the work reported here it became apparent that further land-use intensification had taken place in the Lake Benmore catchment since the 2009 work had been reported. This intensification is illustrated in an analysis of remote sensing data undertaken by Dr Mathew Allan and Professor David Hamilton, University of Waikato, included in Appendix E of this report. Any additional nutrient loading introduced by these recent developments would not have been adequately captured by the monitoring programme that was originally designed for the 2009 study and carried over to the 2011-13 work. The ability of the model to reflect known inflows in 2008-09 was demonstrated in the relative success of the model at that time (Norton et al. 2009). This was not the case for Chl-*a*, TN and DON in 2011-13 and there are at least two reasons for this potentially inadequate capture of additional inputs. Firstly, the post 2008 intensification is now starting to exhibit effects, secondly time lags in the system, including groundwater time lags, may be showing up. However, we still have a very little understanding of groundwater fluxes in the Waitaki basin.

Considerable effort was expended during the course of the present study to quantify these additional loads so that a satisfactory validation of the model predictions could be obtained before new nutrient loading scenarios could be run. Most of this effort focussed on the Ahuriri Arm, the basin that has been found to be most sensitive to increased nutrient loading (Norton et al. 2009). Despite these efforts we acknowledge that there is considerable uncertainty in extrapolating from a single day of measurements of nutrient concentrations to generate a complete time series of nutrient inputs for simulation purposes.

During the course of this study an inconsistency emerged between flows measured at the well-established gauging site on the Ahuriri River at South Diadem, and flows at the recently established gauging site at State Highway 8 Bridge, nearer the lake. To reduce uncertainty in load calculations for the Ahuriri basin, we recommend that this inconsistency be resolved and that more frequent monitoring of concentrations and flows be undertaken in the small streams entering the Ahuriri Arm, e.g., streams 3, 4, 5 and 7 in Appendix B.

Little is known of groundwater lag times in the Waitaki Basin and the high nutrient concentrations in the small streams of the lower Ahuriri Arm may well be a reflection of the last decade of land-use intensification there. It is clear from the investigations and modelling carried out in this and related projects (Norton et al. 2009, Palliser et al. 2015) that increased monitoring of water quality in the Waitaki Basin will be needed to better assess sources. In particular we recommend improved study of surface and groundwater interactions because increased leaching might be occurring in locations that tend to enter the lake through groundwater.

4.6 Final comments

- This study has confirmed the sensitivity of the Ahuriri Arm to nutrient additions relative to the other Arms of the lake that was first described in Norton et al. (2009).
- The study strongly suggests that nutrient loads have been underestimated in this basin and that increased monitoring of both surface water and groundwater is required to better assess change.
- Modelling in this and the previous study in 2009 (Norton et al. 2009) also suggest the need for dual nutrient control involving both N and P in the Waitaki catchments. The model predictions for lake change are conservative, but show that lake ecosystem health as defined by the Trophic Level Index (TLI) is likely to decline in the face of several of the scenarios for change that the model was asked to evaluate.
- This detailed modelling study has emphasised the need for precaution in the management of nutrients in the Upper Waitaki lake catchments and particularly the catchment leading to the Ahuriri Arm.

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7 Glossary of abbreviations and terms

Chl-*a*	Phytoplankton chlorophyll-*a*
DO	Dissolved oxygen
DOC	Dissolved organic carbon
POC	Particulate organic carbon
NH_4-N	Ammonium-nitrogen
NO_3-N	Nitrate-nitrogen
DIN	Dissolved inorganic nitrogen
DON	Dissolved organic nitrogen
TDN	Total dissolved nitrogen
PIN	Particulate inorganic nitrogen
PON	Particulate organic nitrogen
PN	Particulate nitrogen (total)
TN	Total nitrogen
DRP	Dissolved reactive phosphorus
DOP	Dissolved organic phosphorus
TDP	Total dissolved phosphorus
PIP	Particulate inorganic phosphorus
POP	Particulate organic phosphorus
PP	Particulate phosphorus
TP	Total phosphorus