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Lake Benmore Water Quality

Evidence (21 April 2010)

Jose R. Romero

Scope

- Assessment of Existing Environment
- Assessment of Nutrient Load Estimates
- Assessment of NIWA Modelling
- Simple Prediction of TP Response of Reservoir
- Review of NIWA (2009) Modelling
- Assessment of Proposed Additional Nutrient Loads
- Comments on Other Issues
- Conclusions

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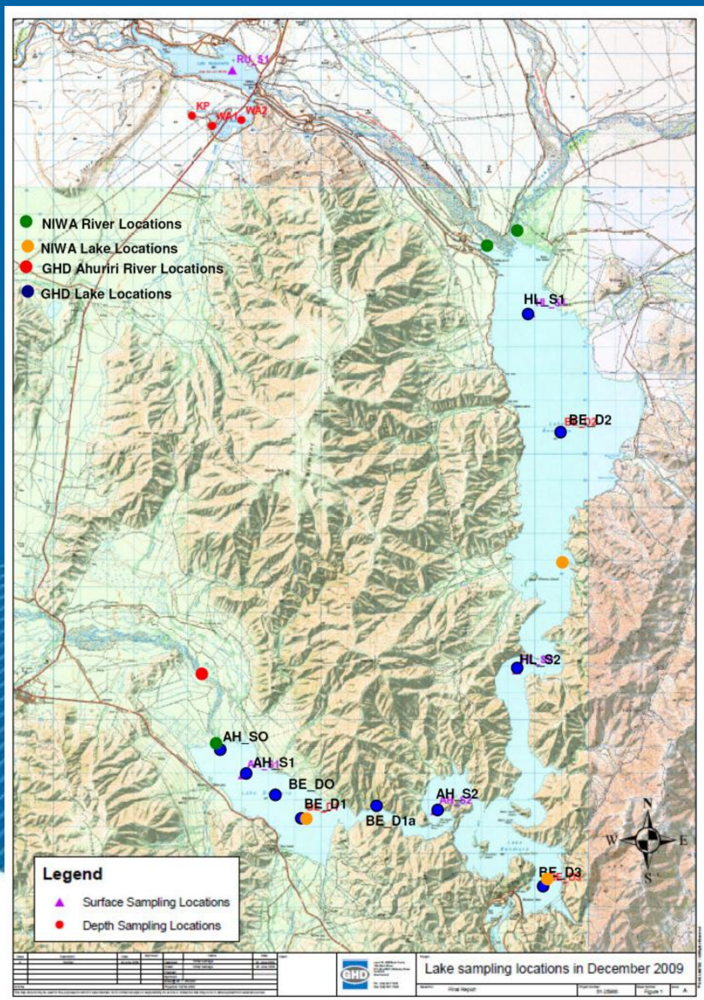
Assessment of Existing Environment

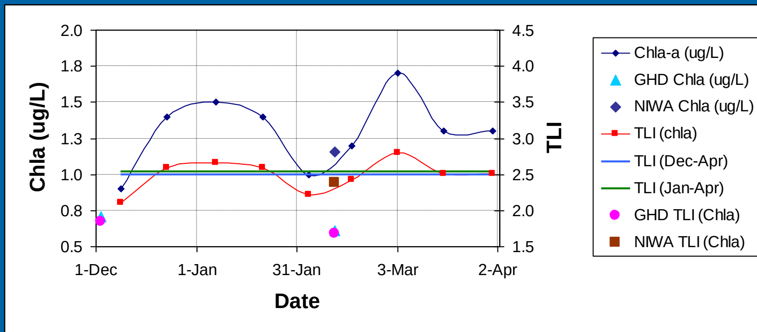
1 - Data Sources, Past Evidence, New Findings

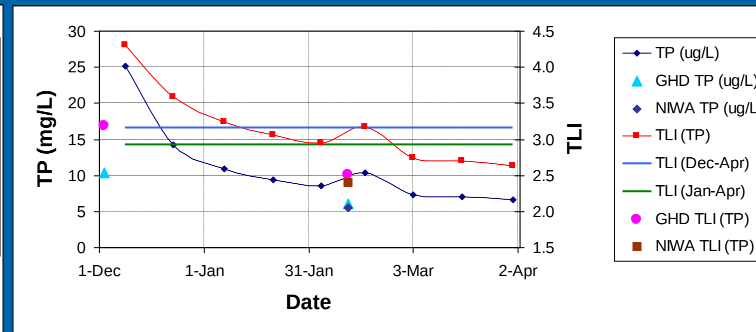


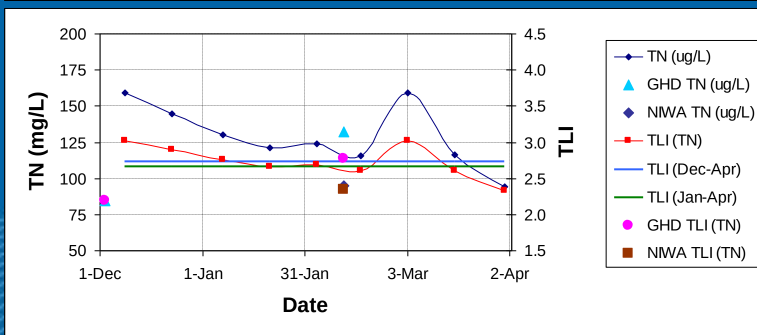
- Reservoir TN, TP and Chla Measurements
  - GHD Jan. 08 & Apr. 08
  - NIWA Dec. 08 – Apr. 09 (3 stations)
  - Recent GHD Dec. 09 & Feb. 10 (>3 stations)
- NIWA (2009) Modelling for average water balance year (2003-2004)
- Threshold measure = summer epilimnetic TLI
- Past Evidence
  - GHD (2009): Ahuriri Arm oligotrophic, Northern Arm microtrophic
  - NIWA (2009) Modelling: Ahuriri Arm TLI = 2.4, Northern Arm TLI = 2.05
  - Sutherland Evidence (2009): Ahuriri Arm TLI = 2.9, Northern Arm = 2.4
- New Findings
  - Lognormal averages of Sutherland Data: Ahuriri Arm TLI = 2.8
  - Lognormal averages of Jan.-Apr. Sutherland Data: Ahuriri Arm = 2.7
  - Recent GHD: Ahuriri Arm = 2.3-2.5, Northern Arm = 2.0-2.7*

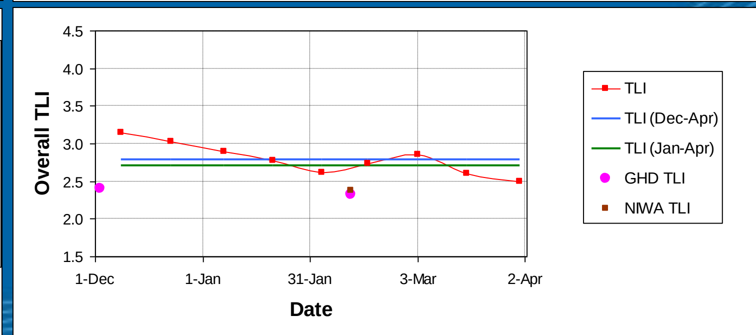
*Based on data at site BE_D2 well upstream of NIWA sampling location

Assessment of Existing Environment
2 – Ahuriri Arm TLI: Seasonal and Inter-annual



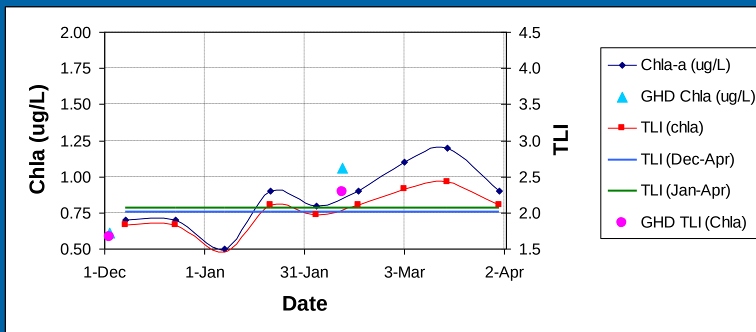


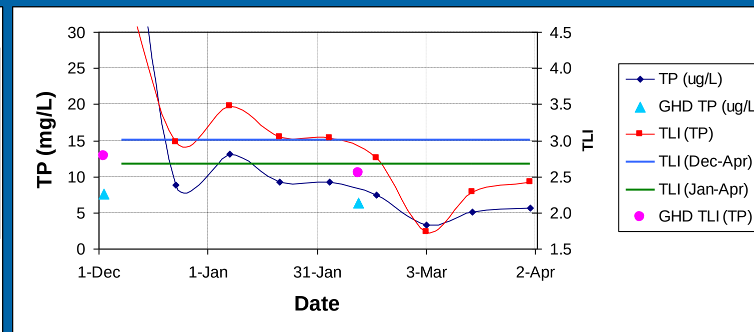


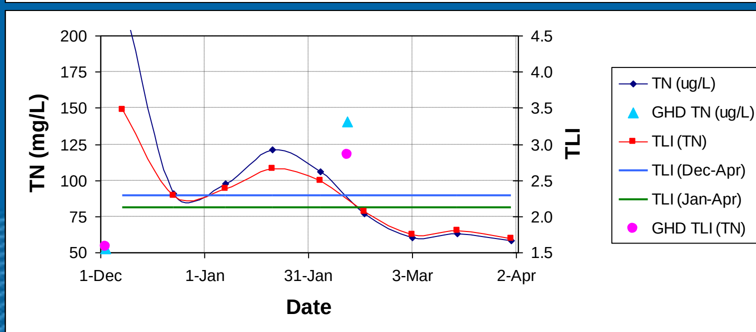


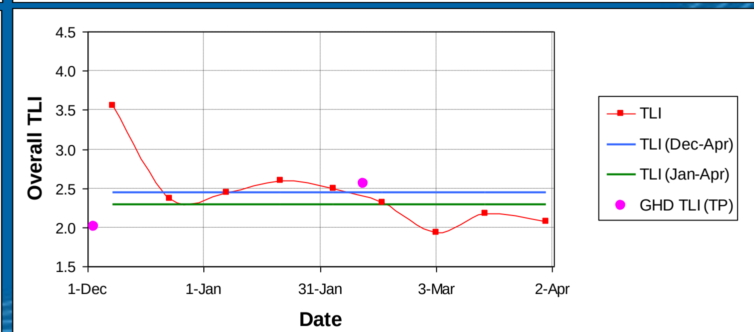
- **Chlorophyll a reasonably constant**
- **TN: 2008-2009 data slight downward trend, 2009-2010 data suggests constant**
- **TP: In December both 2008-2009 and 2009-2010 TLI elevated**
- **Overall TLI: 2008-2009 data less than 3.0 except for December, 2009-2010 data less than 3.0**
- **Inter-annual differences in TLI - WHY?**

Assessment of Existing Environment
3 – Haldon Arm TLI: Seasonal and Inter-annual









- **Chlorophyll a: Upward seasonal trend in both years**
- **TN: 2008-2009 data seasonal downward trend, 2009-2010 data suggests increase**
- **TP: In December both 2008-2009 and 2009-2010 data downward trend**
- **Overall TLI: 2008-2009 data less than 3.0 except for December, 2009-2010 data less than 2.6**
- **Inter-annual differences in TLI - WHY?**

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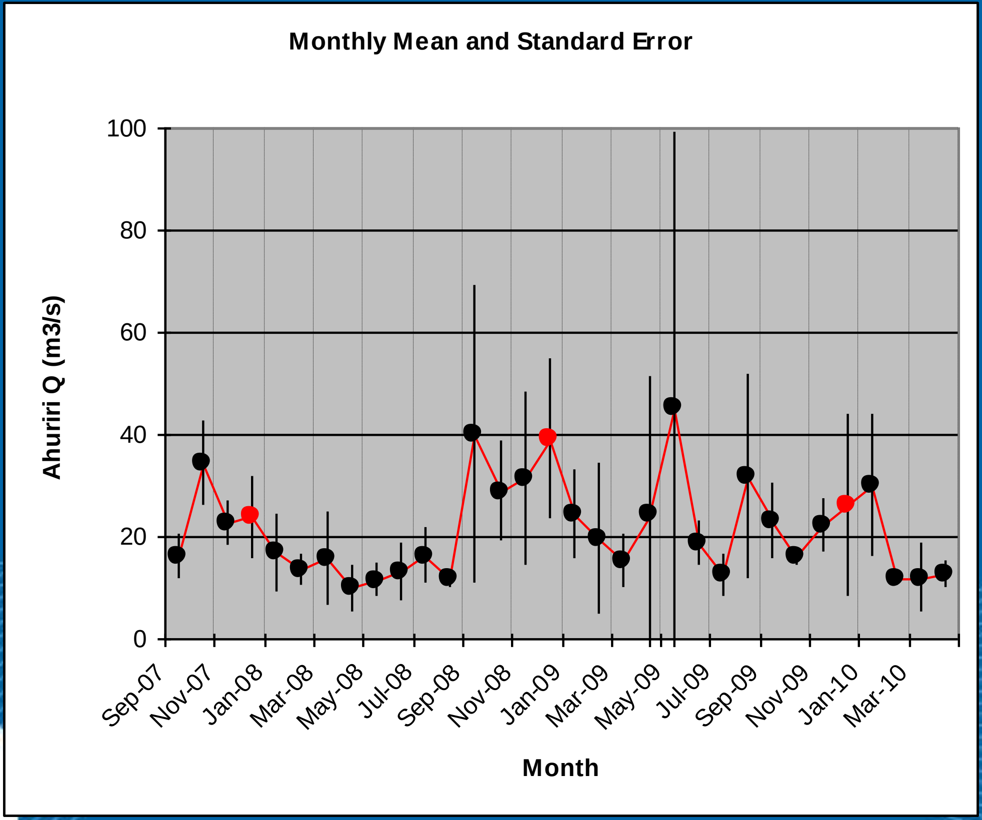
Assessment of Existing Environment
4 – Ahuriri River Discharge



- Mean Ahuriri River discharge of 40 $m^3 s^{-1}$ yielded elevated TLI of 2.8-2.9
- Mean Ahuriri River discharge of 25 $m^3 s^{-1}$ yielded lower TLI of 2.3-2.5
- Indicates inter-annual variability linked to precedent hydrology
- Recommendations:
  - Reduce variability by using January to April as the compliance period
  - Collect at least 3 integrated samples at 3 locations in near proximity to reduce ‘outlier’ debate and utilise lognormal average to reduce outlier effect

Assessment of Nutrient Loads
1 – Sub-Scope

- Overview the available river water quality datasets and establish ‘characteristic’ annual river concentrations for TN and TP (not shown in evidence presentation)
- Adopt either the GHD (2009) or NIWA (2009) Lake Benmore water balance
- Summarise and compare previous (GHD 2009; NIWA 2009) and my nutrient loading estimates to the lake
- Assess the veracity of the nutrient load estimates

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Assessment of Nutrient Loads
2 – Water Balance

Source	NIWA (2009) Combined (GLY Aug 03-Jul 04)	GHD (2009) (GLY) – from Table 7
Ahuriri River	1066.5	1227.2
Ungauged Ahuriri Arm		
Ohau C Canal	8483.2	8223.4
Northern Arm rivers excluding spill	1453.5	1582.1
Spill, Lake Tekapo and Pukaki		
Ungauged Northern Arm		

- There are some discrepancies between the GHD (2009) and NIWA (2009) water balances:
  - Higher GHD (2009) estimates for the Ahuriri River (RPD = 14%)
  - Higher GHD (2009) estimates of the Tekapo-Pukaki system (RPD = 8%)
  - Slightly lower GHD (2009) estimates of the Ohau C Canal discharge (RPD = -3%).
- However, good agreement between GHD (2009) and NIWA (2009) lake-wide water balance sufficient (RPD = 1%)
- NIWA (2009) water balance adopted to maintain consistency with subsequent evidence on basis of 3D simulations

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Assessment of Nutrient Loads 3 – TN Load Estimates

Description	GHD (2009)	NIWA (2009) Average Dec 08 - Feb 09	NIWA (2009) Average Dec 08 - Apr 09	Average Pooled Dataset
Ahuriri River + Ungauged West Arm Flows (1066.6 GLY)	133.3	173.3	146.2	141.2
Tekapo-Pukaki River + Ungauged North Arm Flows (1453.5 GLY)	403.5	123.2	112.3	172.0
Ohau C Canal (8483.2 GLY)	62.0	523.0	540.7	670.0
Lakewide Loading	598.9	819.6	799.1	983.1

- All TN loads estimates with characteristic annual TN concentrations on the basis of the NIWA (2009) water balance (2003-2004)
- GHD (2009) TN load estimates for:
  - The Ahuriri Arm comparable to the other estimates.
  - The Tekapo River higher by factor of 2-4.
  - The Ohau C Canal TN is lower by a factor of 8-10.
- Arithmetic averages of the 'pooled' and NIWA (2009) datasets were comparable, partially an artefact of the NIWA (2009) dataset comprising approximately half the 'pooled' dataset.

Assessment of Nutrient Loads
4 – TP Load Estimates

Description	GHD (2009)	NIWA (2009) Average Dec 08 - Feb 09	NIWA (2009) Average Dec 08 - Apr 09	Average Pooled Dataset
Ahuriri River + Ungauged West Arm Flows (1066.6 GLY)	8.5	23.9	18.0	16.7
Tekapo-Pukaki River + Ungauged North Arm Flows (1453.5 GLY)	19.2	14.3	11.5	15.3
Ohau C Canal (8483.2 GLY)	20.2	53.3	53.6	45.6
Lakewide Loading	48.0	91.6	83.1	77.6

- All of the TP loads estimated with characteristic annual TN concentrations on the basis of the NIWA (2009) water balance (i.e. year 2003-2004).
- GHD (2009) TP load estimates for:
  - The Ahuriri River is lower by a factor 2-3.
  - The Ohau C Canal is lower by a factor 2-3.
  - The Tekapo River is higher.
  - Lakewide lower because of Ohau C Canal underestimate.
- The arithmetic averages of the ‘pooled’ and NIWA (2009) dataset were comparable, which is partially an artefact of the NIWA (2009) dataset comprising approximately half the ‘pooled’ dataset.

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Assessment of Nutrient Loads 5 – Conservative Criteria Test

Case	GHD (2009) River	NIWA (2009) Average Dec 08 - Feb 09 River	NIWA (2009) Average Dec 08 - Apr 09 River	Average Pooled Dataset River	Lognormal Average of Reservoir Data for Comparison
Lakewide TN (ug/L)	54.4	74.5	72.6	89.4	89.2
Lakewide TP (ug/L)	4.4	8.3	7.6	7.1	6.0
Ahuriri Arm TN (ug/L)	125.0	162.5	***137.1***	132.4	125.7
Ahuriri Arm TP (ug/L)	8.0	22.4	***16.9***	15.6	10.1
Northern Arm TN (ug/l)	46.9	65.0	65.7	**84.7**	83.0
Northern Arm TP (ug/l)	4.0	6.8	**6.6**	6.1	5.7

- Simplest test of the validity of nutrient loading estimates is to assume inputs of TN and TP are conservative with no net loss or gain in the reservoir and that the outflow discharge is the same as the inflows.
- Comparison of load estimates with the lognormal averages of the three 'lake' stations from the NIWA (2009) 2008-2009 dataset. Is indicative because simulated water balance (2003-2004) does not correspond to the hydrology of the monitoring year (2008-2009). Shading indicates where TN and TP characteristic river concentrations meet criteria (i.e. greater than the lake).
- The average 'pooled' dataset meets all the criteria. The average of all NIWA (2009) data is also considered a reasonable estimate as it uses all of the available river water quality data with a low LoR. Recommend that the maximum TN and TP nutrient loads from Table 9 that correspond to the concentrations in bold italic adopted as interim nutrient load estimates.

Simple TP Model Predictive Tool
1 – Motivation

- Next, a simple steady-state model is used to investigate variations in inter-annual river discharge and nutrient loading on reservoir TP concentrations. Motivations to briefly consider a steady-state model include:
  - The 2008-2009 NIWA (2009) data collected during elevated Ahuriri River discharge in December 2008;
  - Recent lake sampling by GHD in December 2009 and February 2010 was after several months of lower discharge than the previous NIWA (2009) year;
  - TP is generally the largest component (greater than Chlorophyll a and TN) of TLI; and
  - Floods may cause considerable variation in nutrient loads, and hence trophic response of the reservoir, which has not been addressed. So I also consider the following 2 cases:
    - A 'wet' year with a 15% increase in the water balance of the Northern Arm and Ahuriri Arm water balances (but not the Ohau C Canal) and a 30% increase in TP load*; and
    - A 'dry year' was evaluated with a 15% decrease in water inputs and 30% decrease in TP loads except for the Ohau C Canal.

* Note if both a 15% increase in discharge and nutrient loads occurred there would be no change in the resultant TP levels in the reservoir. The assumption here is that higher annual average flows result from a greater frequency of floods with higher concentrations of TP relative to average flow conditions.

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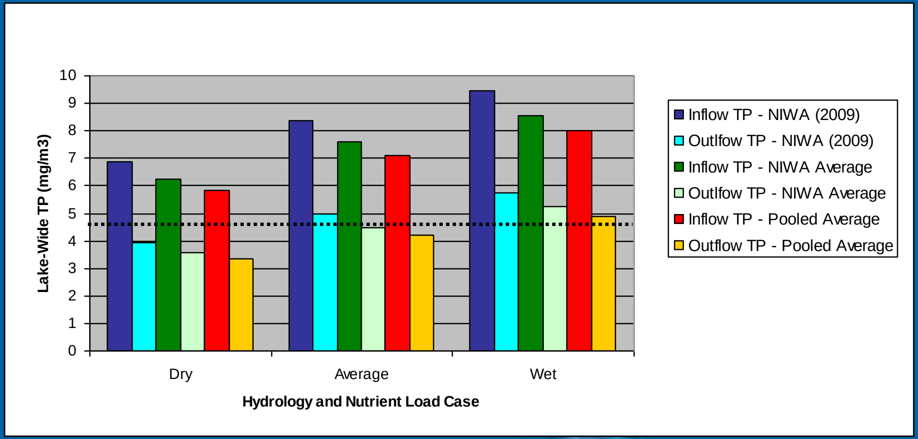
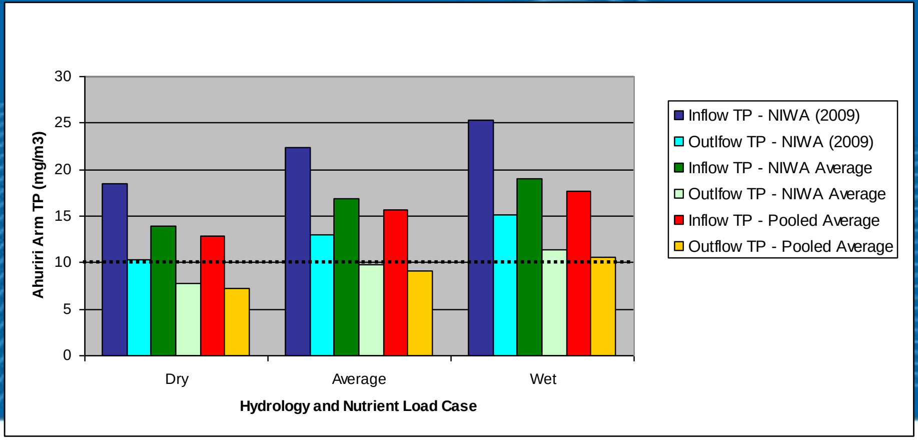
Simple TP Model Predictive Tool 2 – Model and Predictions





- **Model**: Phosphorus retention in reservoirs often characterised with steady-state models such as equation $S=L\tau(1-R)/z$ where S is the outlet concentration (g/m^3), L is the areal TP loading rate ($g/m^2/s$), τ is the reservoir residence time (years), R is the fraction of inflow TP retained in the reservoir, and z is the mean depth (m) of the reservoir. The relation of Hejzlar et al (2006) to define the retention coefficient as $R=1.84\tau^{0.5}(1+0.84\tau^{0.5})$.
- **Inputs**: The reservoir is at 5 m below full capacity with an area of 64.3 km^2 and a volume of 1516 GL, adopted NIWA's (2009) water balance for an average year (2003-2004), applied three plausible TP loading estimates (2 NIWA datasets and pooled dataset), and dry and wet cases.
- **Results**: Characteristic TP from NIWA (2009) gave good results, poor prediction in Northern Arm because did not have appropriate bathymetry data (not shown), inter-annual variations in river discharge and TP loads can have a substantive effect (particularly dry years).

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Review of NIWA (2009) 3D WQ Modelling

- **Parameter Uncertainty**: Reliance on David Hamilton's experience in setting parameter values is appropriate for this model and scope of application (of which Prof Hamilton is the original developer).
- **Trophic Range of Model Applicability**: The simulations up to a Nutrient Load Multiplier that first yields a mesotrophic state in terms of the biological variable of Chlorophyll a in a particular portion of the water body is considered reliable (i.e. Northern Arm, Ahuriri Arm, Lower Benmore, or Lakewide). This is because the model was calibrated for 2 oligotrophic 'type' phytoplankton groups.

Ahuriri Arm Summer Epilimnetic Mean	Northern Arm Summer Epilimnetic Mean
2.0	8.0-10.0

- **Different Calibration and Water Balance Years**: The calibration period is not coincident with the period of validation data collection. Hence, 1:1 correspondence cannot be expected, but rather are trends.
- **Nutrient Load Estimates**: TP loads used are considered reasonable on the basis of conservative criteria test and/or steady-state modelling. TN loads into the Ahuriri Arm in the modelling are large relative to other estimates. The TN loads into the Northern Arm are most suspect and require closer examination.
- **Utility**: I concur with the authors of the modelling study that the model currently provides the best option for a structured assessment of the current and future permissible loadings to maintain an oligotrophic reservoir.

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Assessment of Proposed Nutrient Loads

Description	TN (ton/yr)	TP (ton/yr)	TN (ton/yr)	TP (ton/yr)
Step 1 - Modelled Loads (GHD 2009)	Ahuriri Arm		Northern Arm	
Scenario 1 - Baseline	153.4	9.8	499.4	40.5
Scenario 2 - Mitigation (2m)	154	9.3	612.3	65.1
Step 2 - 2m Change in Nutrient Loads	0.6	-0.5	112.9	24.6
Step 3 - NIWA (2009) Baseline Loads				
Ahuriri and Other Northern Arm	173.3	23.9	110.4	12.8
Ohau C Canal (constant)			523.0	53.3
	TN Mult	TP Mult	TN Mult	TP Mult
Step 4 - Load Multiplier (Summer TLI = 2.75)	1.2	1.2	4.3	4.3
Step 5 - 2m Proposed Load Multiplier	1.0	1.0	2.0	2.9
	TN (ton/yr)	TP (ton/yr)	TN (ton/yr)	TP (ton/yr)
Step 6 - 2m Threshold Load (Summer TLI=2.75)	208	28.7	998	108.4
Step 7 - 2m Load	174	23.4	746	90.7
Step 8 - 2m Load Deficit to Attain Summer TLI=2.75	34	5	251	18

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Past Evidence Concerns

- **TLI Method** : Initially only TN and TP considered, appropriate to include Chlorophyll a, but not secchi depth.
- **Simple Model**: Originally, single uniform box and annual predictions. Now availability of three-dimensional water quality model that simulates temporal and spatial variability in the physics, nutrients and phytoplankton in the reservoir.
- **Nutrient Loading**: To date divergent estimates of nutrient loading. This audit has provided more clarity to the nutrient loading issue.
- **Utility of 3D Model**: Three-dimensional water quality model a ‘working hypothesis’. Mechanistic model that accounts explicitly for the physics, biogeochemistry and phytoplankton dynamics of the reservoir. Nutrient loads suggest that those used in the NIWA (2009) modelling are reasonable, albeit incorporation of flow-dependent concentrations may yield ‘some’ improvement. More than adequate tool to provide guidance on this issue (interactions between the arms and lower basin, response of lake nutrient concentrations to elevated nutrient loading). Model weakness is in its inability to predict phytoplankton shifts (accounts for 2 oligotrophic phytoplankton groups) so rely on expert opinion and possibly another modelling framework.
- **Climate change**: Current modelling framework can assess with appropriate inputs (i.e. changes to hydrology)
- **Ecological response**: Suggested risk of break of thresholds increases ‘exponentially’, whereas for the nutrient loads considered here my view is ‘linearly’.

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Conclusions

- The over-arching conclusion in my view is that the GHD (2009) threshold (TLI = 2.75) remains valid for most of the reservoir.
- I have not accepted the original GHD (2009) baseline nutrient load estimates, however those used in the modelling for the most appear reasonable and plausible.
- The second critical part is the nutrient load increase from the proposed development, in which I have taken the GHD (2009) as a credible estimate.
- Combining both of these analyses (i.e. establishment of baseline load and plausible nutrient load increases from development) is the basis for increased nutrient load assessment (Table 12).
- This analysis indicated that the proposed 'nutrient discharge allowances' remain valid for both the Ahuriri Arm and the Northern Arm, namely:
    - Adoption of the GHD (2009) TLI threshold of 2.75 as the summer epilimnetic threshold is appropriate for the Northern Arm and lower Lake Benmore (i.e. maintain oligotrophic).
    - This threshold value will possibly be exceeded in some high flow years in the Ahuriri Arm, in my view from 'natural' variability. Hence, it is recommended that the proposed development implement a strategy to not increase loads to the Ahuriri Arm as outlined in Scenario 2 with 'mitigation' in GHD (2009), which is appropriately conservative and precautionary.