Water Quality Modelling of Te Waihora/Lake Ellesmere

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Cover: View of the monitoring platform in the centre of the lake on 10 August 2015 (Moritz Lehmann)

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PREFACE

This project forms part of a sub-contract to the University of Otago for its project supported by Whakaora Te Waihora to investigate the mechanisms that drive in-lake nutrient processing in Lake Ellesmere/Te Waihora (Investigation Brief D4). The project has data provided from a variety of sources and other projects, including:

- The report by Schallenberg and Cranshaw on *In-lake nutrient processing in Te Waihora/Lake Ellesmere.* This report was provided to Environment Canterbury on 11 July 2016. The data contained in the report provide parameter inputs for the lake model application described in the present report (denitrification rates, oxygen consumption rates, etc.). Calibration of the model could not be undertaken in full until the report by Schallenberg and Cranshaw had been made available.

- Two lake monitoring stations that provide high frequency (15 minute) data transmitted to Environment Canterbury. These stations were installed by University of Waikato, in conjunction with Environment Canterbury, in May 2015. The stations have been maintained in good condition by Environment Canterbury and have been used as a part of the calibration of the lake model.

- Miscellaneous information from a variety of sources including meteorological data, tidal heights, water level elevations, lake water quality monitoring data, etc.

Obtaining the latter data proved challenging within the time constraints of this project. We were only able to undertake the last phase of the modelling once *all* of the data were available, i.e., validating quality of the data, formatting the data for model input, calibrating and validating the model, updating relationships of opening and closing regimes to physical variables, and running preliminary scenarios.

The focus of this project was to advance the technical performance of the lake model. A significant milestone in the present report is achieving a simultaneous water and salinity balance for the lake. The latter was not undertaken in detail in the previous modelling studies (see Trolle et al. (2010) and Appendix B in Norton et al. (2014)). The updated model application is used in this report to present a number of scenarios related to changes to catchment nutrient loads and water level management regimes. The scenarios presented in this report are indicative only, and not necessarily representative of real-world solutions or engineering designs targeted to lake restoration. Rather, they are intended specifically as a starting point to stimulate discussion with stakeholders and interested parties (e.g., through the Whakaora Te Waihora Joint Cultural and Ecological Restoration Plan and hui in partnership with Taumutu). The expectation is that scenarios will be refined in response to the needs of stakeholders.

ACKNOWLEDGMENTS

We are extremely thankful to Alex Ring (Environment Canterbury) for maintaining the in-lake sensor data from the two monitoring stations and for timely provision of data. We are grateful to Environment Canterbury and NIWA for making data available for this project. The modelling project was funded as part of a subcontract to the University of Waikato from the University of Otago for the modelling component related to mechanisms that drive in-lake nutrient processing in Lake Ellesmere/Te Waihora. Funding was from Whakaora Te Waihora and the Central Government Freshwater Cleanup Fund. We also acknowledge funding support from the New Zealand Ministry of Business, Innovation and Employment (UOWX1503; Enhancing the health and resilience of New Zealand lakes) which enabled additional support to be provided to meet the modelling deadlines.

We thank Marc Schallenberg (university of Waikato) for sharing data and provided valuable direction with the model calibration. Eunju Cho (University of Waikato) assisted with formatting data for the model and quality assuring data inputs to the lake model, Conrad Pilditch (University of Waikato) was involved with the development of this project and provided insights into the dynamics of the lake, and Moritz Lehmann (University of Waikato) collated data and established relationships to enable data to be obtained.

EXECUTIVE SUMMARY

As a component of work to contribute towards the management of water quality of Te Waihora/Lake Ellesmere, the University of Waikato was subcontracted by University of Otago to apply a coupled hydrodynamic-water quality model to the lake. The primary funder for this work was Environment Canterbury (ECAN), Whakaora Te Waihora and the Central Government Freshwater Cleanup Fund. The main modelling tool used in the study to simulate the dynamics of Te Waihora/Lake Ellesmere was the one-dimensional (1-D) hydrodynamic-water quality model DYRESM-CAEDYM. The model was used to reproduce observed water column data for a mid-lake station over the period 2011 to 2015. Once a satisfactory level of reproduction of these data had been achieved, an assessment was carried out with the model to examine the impact of various management scenarios on lake water quality. These scenarios involved: (i) projected changes to external nutrient loads to the lake that could be associated with future land management in the catchment and (ii) different lake water level management regimes based around opening of the barrier separating the lake from the ocean. The scenarios are intended here to be a catalyst for further hui and consultations that may adapt and refine additional scenarios, some of which may involve testing of multiple management options. The quantitative output from the model provides a component of the input required to inform strategies for lake management, alongside historical and expert knowledge, as well as analysis of measured data.

Te Waihora/Lake Ellesmere is a shallow, coastal ICOLL (intermittently closing and opening lagoon-lake). Depth and area of the lake vary widely according to stage of filling of the lake following periods when the barrier separating the lagoon from the ocean closes naturally following artificial opening; on average, depth is around 1.8 m in the middle of the lake and area is 190 km^2. The lake water has high turbidity associated with persistently high levels of fine sediment that is periodically resuspended by strong winds characteristic of the coastal climate. The lake is also highly eutrophic, with high levels of nutrients and chlorophyll *a.* The model provides a tool to test management strategies designed to mitigate the high levels of suspended solids, nutrients and chlorophyll *a,* as well as the low water clarity, as these variables are all directly output from the model or can be derived from it (in the case of water clarity).

Updates and advances to technical aspects of the Lake Ellesmere DYRESM-CAEDYM model

The lake model application required collation of a large volume of data from disparate sources and included inputs related to hydrology, meteorology and lake morphology, as well as in-lake measurements for calibration and validation of the model. A water and salinity mass balance was constructed for the lake, and was considered highly satisfactory in reproducing the observed lake water level and salinity. It provided confidence that the inflows and outflows were adequately quantified, including those associated with periods when the barrier was open. In order to complete the water and salinity mass balance, and for the purpose of testing different water level management regimes as well as predicting when barrier closure might occur, a barrier opening and closing model was developed. The resulting accurate water and salinity mass balance revealed that around 30-40% of freshwater inflows are not accounted for through gaugings; a figure that is somewhat larger than those found in previous studies.

The base model setup for the lake was derived from measured data for the period 2011 to 2015. The middle of this period had a prolonged period of barrier opening when salinity in the middle of the lake was as high as two-thirds of seawater. This period was characterised by unusually clear water (low Secchi depth), low levels of nutrients (total phosphorus and total nitrogen) and low phytoplankton biomass (chlorophyll *a*). The period following the opening, however, notably when the lake water was weakly brackish from mid-2014 to late 2015, was characterised by strongly elevated levels of nutrients and chlorophyll *a.*

The lake model was calibrated against measurements at the mid-lake station for 2014 to 2015. It provided a good fit to most variables: temperature, dissolved oxygen, chlorophyll *a*, nutrients (total nitrogen, nitrate, ammonium, total phosphorus, dissolved reactive phosphorus, suspended solids and Secchi depth), including the dynamics associated with barrier openings and closings, sediment resuspension and seasonal changes in inorganic nutrient concentrations. The output from the model is on a daily time scale and therefore it provides limited insight into the potential role of temporary stratification (i.e., a few hours) and oxygen depletion in bottom waters that could lead to release of dissolved nutrients from anoxic bottom sediments of Te Waihora/Lake Ellesmere.

The aggregated Trophic Level Index (TLI) derived from model output closely matched the observed TLI for the 2011-2015 study period, and the constituent TLI values (for total nitrogen, total phosphorus, chlorophyll *a* and Secchi depth) were also well matched. The model did not capture some of the dynamics of the saline intrusion, however, and this was attributed to specific process representations that were absent or only weakly represented in model algorithms. We hypothesise that flocculation likely played an important role in the high clarity and low levels of total phosphorus during the major marine water incursion from a prolonged barrier opening in 2013, and that benthic infauna nutrient processing may have largely been 'shut down' in 2014-15 as a result of the earlier salinity stress, which ultimately resulted in elevated levels of chlorophyll *a* and nutrients (an outcome that was poorly represented in the model). For example, enhanced denitrification from the activities of benthic infauna may be an important ecosystem-level process for dealing with the elevated tributary nitrogen loads to Te Waihora/Lake Ellesmere. The departures between observations and model results represent valuable learning opportunities and, when complemented by measurements and anecdotal information (i.e., related to absence of benthic infauna following the 2013 marine incursion), suggest that exceptional incursions of marine water into the lake could increase trophic status as the lake water returns to fresh or weakly brackish status.

Indicative model scenario simulations

The scenarios presented in this report are indicative only, and not necessarily representative of real-world solutions or engineering designs targeted to lake restoration. Rather, they are intended as a starting point to stimulate discussion with stakeholders and interested parties (e.g., through the Whakaora Te Waihora Joint Cultural and Ecological Restoration Plan and hui in partnership with Taumutu). The expectation is that scenarios will be refined in response to the needs of stakeholders.

The barrier opening/closing model coupled with the lake model was also used to predict water quality outcomes for a number of scenarios relating to changes in nutrient loads and lake opening regimes. Increases in nitrate loads of 20%, 40% and 60% had only a small impact on TLI values and a 20% increase in total phosphorus loads also produced only a small change in the chlorophyll constituent of the TLI. The results of these scenarios reflect the dominant nature of the internal loads over external loads in the short term (e.g. up to several years). The model does not explicitly account for expected long-term changes in the composition of bottom sediments with sustained changes to external nutrient loads, however, which might be expected to occur over time scales of decades.

A series of scenarios were run with the trigger limit for the lake opening altered from the present 1.05 m (1 Aug – 31 Mar) and 1.13 m (1 Apr – 31 Jul) to 1.4 m, 2 m, 3 m ('pre-European') and 4 m ('pre-human'), as well as for two cases with a flow-controlled outlet structure. As expected, the increased depths of the pre-European and pre-human scenarios decreased sediment resuspension and reduced the TLI slightly more than any of the other water level and nutrient load reduction scenarios. The pre-European and pre-human scenarios are designed only to reflect historical water levels, however, whilst nutrient loads used in the simulations are contemporary (i.e., 2011 to 2015). Refinements of these scenarios, including concurrently simulating multiple management options, could be investigated following dissemination and evaluation of the current set of model simulation results.

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GLOSSARY

ECAN	Environment Canterbury
CAEDYM	Computational Aquatic Ecosystem Dynamics Model. An aquatic ecology and water quality model.
DONL	Dissolved organic nitrogen (labile)
DRP	Dissolved reactive phosphorus
DYRESM	Dynamic Reservoir Simulation Model. A 1–D hydrodynamic model.
N	Nitrogen. An essential nutrient for plants.
NH_4–N	Ammonium nitrogen
NO_3–N	Nitrate nitrogen
P	Phosphorus. An essential nutrient for plants.
PO_4–P	Phosphate phosphorus
PONL	Particulate organic nitrogen (labile)
Tāonga	[Māori] Treasure (often used in the context of a natural resource)
TLI	Trophic Level Index, used in New Zealand as a measure of lake nutrient status
TN	Total nitrogen
TP	Total phosphorus

INTRODUCTION

1.1. Background

Te Waihora/Lake Ellesmere is associated with a large and increasingly intensively farmed agricultural catchment, with complex water management issues. Due to changing land use practices in the catchment area, Te Waihora/Lake Ellesmere has undergone significant ecological transformations in recent years, highlighting its sensitivity to catchment processes such as hydrology, erosion and contaminant transport. Irrigation is a major driver for further intensification of agriculture in the catchment. The lake is New Zealand's fourth largest (190 km^2 in area) and was considered the food basket of Rākaihautū (the legendary ancestor who helped form the landscape of the area). The lake is of high cultural value to Te Runanga o Ngai Tahu and is described by them as a tribal tāonga. From an economic income viewpoint, its commercial fishing output is $0.64M p.a. and lake-associated fishery quota is worth $3.3M p.a., while farming production around the lake contributes $34M p.a. (Hughey and Taylor 2009). Te Waihora/Lake Ellesmere catchment has extensive wetlands and its wildlife values are of national and international importance (Hughey and Taylor 2009). Although it is thought that the lake is managed to support intensive agriculture in its lowland catchment, it has a legacy of past devastation, for instance, the 'Wahine storm' (1968), which resulted in a regime shift to the current resilient, turbid, eutrophic state. There is however little published detail related to the lake's internal nutrient dynamics or sedimentation regimes. Notwithstanding, studies that monitored trophic status based on a Trophic Level Index (TLI) (Burns et al., 1999, 2000) which integrates annual mean measurements of Secchi depth and concentrations of total nitrogen, total phosphorus and chlorophyll *a,* have indicated that Lake Ellesmere/Te Waihora is hyper-eutrophic (Burns et al., 2000; Burns et al., 1999; Verburg et al., 2010).

A regional accord of co-governance, the first of its kind in New Zealand, was established between Te Runanga o Ngai Tahu and Environment Canterbury in 2012, for the purpose of restoring Te Waihora/Lake Ellesmere to full ecological and cultural health. Additional commitments include $21M through the DOC/Fonterra Partnership on *Community Investment in Water* (2013-2023) and $11M from government and Ngai Tahu for the Fresh Start for Freshwater Clean-up Fund (Government Freshwater Reforms 2011).

The interacting stressors of land use intensification, raising lake levels to improve water quality but flooding surrounding farmland, legacy effects, cumulative impacts, and 'load to come' from contaminated groundwater represent a major challenge for regulatory goals for the lake water quality and ecosystem function to be met. Solutions are required to the challenges of land use intensification, lake and groundwater legacies, resilience associated with the current degraded lake state and the impending in-lake restoration targets (i.e., Variation 1 of the Canterbury Regional Land and Water Plan).

Te Waihora/Lake Ellesmere represents a model in its infancy of understanding how science, economics, policy and co-governance can effectively interact to produce desired societal outcomes. This model is of national interest to evaluate the balance of land use and economic benefits, and the relative costs of different restoration approaches, including the balance of short-term engineering options versus long-term catchment restoration actions. Critical underpinning research is required to verify models to support effective and holistic decision support tools that integrate legal, social and policy contexts. Application of such a lake model is the subject of this report. It is designed to generate knowledge to support rehabilitation where irrigation and changing land use are imminent and where objectives and limits specified in the Canterbury Regional Land and Water Plan will be applied for lake ecosystem health. The modelling is designed to improve policy and management decisions relevant to the time frames for remediating legacy effects.

From a general perspective, the restoration of eutrophic shallow lakes is difficult, especially when they are in a devegetated (with respect to submerged aquatic plants), turbid state which is well recognised to be resilient to imposed management actions (Scheffer, 1993). Gibbs & Norton (2013) identified improved lake level control as an essential part of managing and restoring Te Waihora/Lake Ellesmere, and described a range of options including construction of an outfall control structure at the present opening site, an engineered connection to the seaward end of neighbouring Wairewa/Lake Forsyth, or some combination of these two approaches. Nevertheless, the degree of external nutrient loading from diffuse sources within the catchment, the legacy of nutrients contained within lake sediments, frequent resuspension of bottom sediments into the water column, the desire of landholders to actively manage water levels in the lake (Horrell, 2011), and the hysteresis of the turbid and productive waters to management actions to reverse eutrophication, represent major challenges.

1.2. General aspects of modelling Te Waihora/Lake Ellesmere

This study builds upon previous modelling of Te Waihora/Lake Ellesmere (Trolle et al. 2010; Allan 2014; Norton et al. 2014) to provide a contemporary (2011-2015) calibration of the simulation model (DYRESM-CAEDYM) used in the earlier studies. In this report, we provide a quantitative assessment of the impact of changes in nutrient loads and water level operating regimes on water quality in the lake. These scenarios have been designed to provide a basis for stakeholder engagement and discussion of more detailed and specific management actions that could be tested as scenarios in additional model runs. The advantage of a strategic use of the model in this fashion is that it might help to avoid potentially costly and ineffective management actions that could have flaws not easily identifiable in empirical evaluations or expert opinion, particularly in a system as complex as Te Waihora/Lake Ellesmere. In this study we examine (i) changes to external nutrient loads (nitrogen and phosphorus separately) that may represent various increases in nitrogen loads from 'load to come' and intensification of irrigated pasture in the lake catchment, as well as a decrease in nutrients related to improved management practices, and (ii) changes in water level operating regimes that represent varying levels of inundation of the catchment adjacent to the lake and are connected to different degrees to historical water levels or those levels thought to be beneficial to the re-establishment of plants.

A significant advance of this study from previous modelling work is the successful simulation and closure of both water and salinity mass balances. This component of the modelling was necessitated by an extended period of lake opening in the mid-period of 2011-2015. Previous modelling studies had either not accounted for salinity entering during openings (although accounting for lake water losses from opening events) or had not presented evidence of a mass balance closure for both water and salinity.

Over the years, water quality at Te Waihora/Lake Ellesmere has continued to deteriorate owing to land-use changes and clearing of wetlands (MfE, 2016). Among 140 lakes captured in a New Zealand-wide study conducted by The National Institute of Water and Atmosphere (NIWA 2010), Te Waihora/Lake Ellesmere was the most nutrient enriched. Environment Canterbury (ECAN), Ngai Tahu and local rununga, in a co-governance arrangement, assisted with funding from the Ministry for the Environment, have thus devoted time and resources to help in restoration of the lake, including establishing native plants, spraying grey willow, completing large numbers of farm environmental plans, erosion control works on the Kaituna River and fencing of significant lengths of the Kaituna and Huritini/Halswell catchments to keep out stock (Lomax, 2015; OAG, 2016), nutrient limits for farming activities in the Selwyn-Waihora watershed and the commissioning of a number of science investigations (MfE, 2016).

As part of these efforts to manage water quality at Te Waihora/Lake Ellesmere, the University of Waikato was contracted to develop hydrodynamic-water quality models for the lake. The one-dimensional (1-D) model of lake water quality described here is intended to provide a basis for future modelling efforts, to increase understanding of the nutrient dynamics in the lake, including the conditions that drive the loss of dissolved oxygen from bottom waters, and to set a basis for refinement of modelling scenarios relevant to iwi, other stakeholders, ECAN and the Ministry for the Environment.

1.3. Hydrology and ecology of Te Waihora/Lake Ellesmere

Te Waihora/Lake Ellesmere (Fig. 1) is a large (~ 190 km^2), shallow (contemporary maximum depth 2.1 m) ICOLL (Intermittently Closed and Open Lake or Lagoon). It has high cultural importance to Ngāi Tahu Whānui. It has been recognised as an internationally important wildlife area (DOC, 2016). The lake holds high natural, recreational, commercial, historical and cultural significance to the indigenous Māori population and the lake bed was vested with the iwi in their 1998 Treaty of Waitangi Deed of Settlement. The Kaitorete Spit separates the lake from the Pacific Ocean, and is regularly artificially breached. The Spit is occasionally overtopped in marine storm surges. It is also somewhat permeable, allowing some exchange between lake water and ocean water. Water levels in a pre-human state may have been around 4 m a.s.l (maximum depth 5.7 m), with infrequent and irregular openings on the order of several years. Artificial openings were first practiced by Ngai Tahu in association with tuna (eel) migration, and after European colonisation to manage water level in the lake and prevent excessive inundation of adjacent farmland (Hemmingsen, 1997).

The main inflows to Te Waihora/Lake Ellesmere are from the Selwyn, Halswell, Irwell and Kaituna Rivers. There are several smaller surface inflows and a small direct groundwater discharge to the lake which has been estimated to be between zero and 0.5 $m^3\ s^{-1}$ (see Horrell, 2009). Substantial denitrification occurs in the catchment groundwater system (Jacobs Group 2014) but tributary surface inflows mostly have high (> 1 mg L^{-1}) concentrations of nitrate-nitrogen. With no further land use intensification, it has been estimated that total nitrogen (TN) loads to the lake will increase by around 35% in the forthcoming 10-20 years, i.e., the nitrogen load to come due to the effects of storage time in the groundwater aquifer beneath areas where agricultural intensification has occurred (Norton et al. 2014).

Te Waihora is largely devoid submerged plant vegetation (i.e. 'devegetated') and has high levels of planktonic production, coupled a high-wind exposure and regular sediment resuspension, making it highly eutrophic (Gibbs & Norton, 2013). It has persisted in a devegetated state of low water clarity since the 1968 'Wahine' storm when submerged plant beds were uprooted. Prior to the Wahine storm, the lake was observed to undergo cycles of submerged plant (*Ruppia megacarpa* and *Potamogeton pectinatus)* dominance, with high spatial variability of plants when they were present (Hughes et al., 1974). High catchment nutrient loads have been identified as a hindrance to recovery of the lake, i.e., revegetation by submerged plants. The lack of recovery of macrophyte beds in the lake has been attributed to low water clarity and high nutrient loading from catchment sources (Gibbs & Norton, 2013), as well as desiccation of the lake margin during prolonged spells of barrier opening (Jellyman, 2009).

A water balance for Te Waihora has been carried out by Horrell (1992, 2011). This water balance incorporated discharge from gauged surface inflows, synthesised discharge from ungauged surface inflows, groundwater direct to the lake, precipitation, evaporation, inflows and outflows from the artificial openings, water exchange through the Kaitorete Spit and ocean wave overtopping on storm surges. Spigel (2009) extended the earlier work by Horrell to account for salinity in the lake. This model tended to over-predict salinity, which was attributed to uncertainty in the magnitude and timing of one or more of seawater intrusion, overtopping and evaporation fluxes. Salinity also varies spatially within the lake; briefly, there can be short to more prolonged periods of vertical stratification when there is an artificial opening, and there may be longitudinal gradients away from the opening, from near marine salinity (i.e., 35 ppt) to freshwater. The period used in the model simulations in this study (2011-2015) was characterised by one extended opening period when salinity was strongly elevated throughout the lake. The high levels of salinity observed during this time necessitated a far more detailed approach to the salinity mass balance and representation of artificial opening and closing regimes than that used in previous studies.

A number of possible restoration scenarios for Te Waihora/Lake Ellesmere are presented in the report by Norton et al. (2014). The DYRESM-CAEDYM model was also used in this instance to generate possible lake water quality responses to the scenarios. Most scenarios involved altered water discharge and nitrogen loads to the lake associated with intensified land-use under irrigation (~30,000 ha) in the Selwyn-Waihora catchment. A subset of these involved variations upon this central intensification scheme, some involving even greater levels of intensification, some involving assumed farmer behavior modifications (e.g., best practice in on-farm nutrient management) and others involving assumptions about the effectiveness of in-lake treatments (e.g., use of a flocculant such as aluminium sulphate) to increase sedimentation of phosphorus in the water column and reduce releases of phosphate from the lakebed sediments. The model simulations generally showed that under the intensified irrigation scheme scenarios, nutrients and Trophic Level Index (TLI) would increase further to above TLI 7.0 in unmitigated intensification scenarios, and would therefore continue to fail the regional plan target TLI3 of 6.0 (note that this is a modified, but very similar TLI (derived from TLI4). The simulations suggested that under the irrigation scheme the TLI target of 6.0 would only be attained in the lake margins after adoption of a comprehensive suite of best management practices in the catchment as well as in-lake treatment to reduce internal phosphorus loads by around 50%; under this heavily mitigated scenario a mid-lake TLI of only 6.6 would be achieved. The simulations suggested that TN and TP loads would need to be decreased by more than 50% to achieve a TLI of 6.0 or less mid lake; such a decrease in external nutrient loads was assessed as incompatible with current land use and the consented irrigation scheme.

1.4. Selected previous monitoring and modelling studies of Te Waihora

Trolle et al. (2011) used the one-dimensional hydrodynamic-ecological model DYRESM-CAEDYM to assess effects of a future warmer climate on Te Waihora/Lake Ellesmere. Interestingly, the model predicted a decrease in concentrations of chlorophyll *a* under the climate warming scenario. They attributed this change to increased duration of low productivity through most of the year interspersed with a period of much higher productivity associated with a summer bloom of cyanobacteria. This model application largely ignored effects of salinity and did not attempt to simulate in any detail the artificial openings and closings in the future climate scenario. Similarly, Allan (2014) used the three-dimensional model ELCOM-CAEDYM to simulate sediment resuspension and transport within the lake. He validated model output of suspended sediment concentrations with concentrations derived from MODIS satellite spectral imagery. The satellite concentration data were ground-truthed with monitoring of suspended solids from Environment Canterbury. The CAEDYM model application by Allan (2014) included calibrated coefficients for critical shear stress (τ_c) of three sediment particle attribute classes with τ_c from 0.05 – 0.1 N m^{-2}. The numerical model (ELCOM-CAEDYM) simulated suspended sediment concentrations with modest success compared with grab sample data from a fixed station and the derived satellite data. A previous study by Hamilton and Mitchell (1996) used a calibrated τ_c of 0.49 N m^{-2} using a zero-dimensional model, and achieved a reasonable level of success for a mid-lake fixed station.

Two high-frequency monitoring stations were established in Te Waihora in May 2015. These stations measure a range of climate and water column variables at 15 minute intervals. These data include salinity, dissolved oxygen, clarity (i.e., using proxies of turbidity, beam transmission) and chlorophyll fluorescence from suspended microscopic algae (i.e., phytoplankton). Data for turbidity, beam transmission and dissolved oxygen from the monitoring station have been used in the present study to assist in model calibration. In the case of dissolved oxygen, transient periods of hypoxia can occur in bottom waters of the central station on a diurnal basis (e.g., in calm conditions early in the day). These events may stimulate internal loading of dissolved phosphorus and ammonium to the water column during calm conditions in summer and autumn, although quantifying the magnitude and impact of these events might require measurements of nutrient species and phytoplankton production at higher frequency than has been undertaken to date. Anoxic sediments may also drive microbial denitrification, which was found to be highly spatially and temporally variable in the lake (Schallenberg and Crawshaw 2016, Larned and Schallenberg 2006). A comprehensive calculation of the amount of inorganic nitrogen lost through denitrification has not been made at a whole lake scale but Schallenberg and Crawshaw (2016) suggested that uptake by phytoplankton may be relatively more important than denitrification in the observed decreases in nitrate in the lake with distance away from tributary inputs which are strongly enriched (> 1 mg L^{-1}) in nitrate-nitrogen.

METHODS

1.5. Te Waihora/Lake Ellesmere study site

The Te Waihora/Lake Ellesmere catchment extends from Banks Peninsula to the foothills of the Southern Alps, roughly between the Waimakiriri and Rakaia Rivers, and covers an area of 2,760 km^2 (Samad, 2007). The catchment is mostly flat to undulating and about 20% is described as highly productive (Taylor, 1996). There are about 40 tributary rivers, streams and drains which discharge directly into the lake. Among these are the Selwyn River, Harts Creek, LII River, Kaituna River, Doyleston Drain, Hanmer River, and Irwell River.

The average depth of Te Waihora/Lake Ellesmere is about 1.4 m and the maximum depth 2.7 m. The name Te Waihora means *spreading waters*, owing to its variability of surface area which historically expanded and contracted by up to 300 km^2 due to water-level variations (SDC, 2016). Prior to active water level management, the lake burst out through the sand and gravel spit separating it from the sea when a maximum surface elevation of approximately 4 m.a.s.l. was reached (SDC, 2016). Over recent decades the lake level has been artificially regulated by cutting a channel to the sea several times each year. This management action reduces variability of lake area, which is on average around 190 km^2; New Zealand's largest coastal lake (SDC, 2016).

Te Waihora/Lake Ellesmere belongs to a group of waterbodies referred to as intermittently closed and open lakes and lagoons (ICOLLs). ICOLLS are shallow barrier lakes which are intermittently connected to the sea and experience saline intrusions (Schallenberg et al., 2010). The current opening regime of the lake is based on water surface elevations as stated explicitly in the National Water Conservation (Lake Ellesmere) Order (1990), which prescribes that the lake can be opened when the water level near the barrier reaches seasonally-dependent elevations (NWCO, 2011). A summary of physical and hydrological characteristics of Lake Ellesmere based on ECAN data from 1987 to 1995, is presented in Table 1.

Table 1. Physical and hydrological characteristic of Te Waihora/Lake Ellesmere (Schallenberg et al 2010).

Lake attributes	Value
Trigger level opening (m above sea level (m.a.s.l.))	1.05 (1 Aug – 31 Mar) 1.13 (1 April – 31 July)
Maximum mean depth when open (m.a.s.l.)	1.9
Maximum (mean) depth at trigger level (m)	2.95
Area when open (km^2)	144.6
Area at trigger level (km^2)	213 (at 1.13 m a.s.l.)
Volume when open (m^3)	111.1×10^6
Volume at trigger level (m^3)	301.4×10^6
Catchment land area (km^2)	2500
Water residence time based on freshwater inflows (d)	104

1.6. Lake model description

In this study, the one-dimensional (1–D) hydrodynamic model DYRESM (version 3.1.0-03) was coupled with the aquatic ecological model CAEDYM (version 3.1.0-06), to simulate water quality in Lake Ellesmere. DYRESM (Figure 1) describes the vertical structure of density, temperature and salinity based on mixing processes driven by wind-forcing, heat flux and inflow at daily time scales (Hipsey et al., 2006; Imerito, 2013). CAEDYM (Figure 2) simulates time-varying fluxes that regulate biogeochemical variables. This includes comprehensive process representations for nutrients, dissolved oxygen (DO), and suspended particulate matter. These models were developed at the Centre for Water Research, University of Western Australia with a long track record in the scientific literature (Trolle et al., 2011) and have been applied to many lakes overseas (e.g., Gal et al., 2009) and in New Zealand (Özkundakci et al., 2011; Trolle et al., 2009), and for example, to Lake Rotorua for numerous years to understand in–lake processes and inform management decisions (Burger et al., 2008; Abell et al., 2015).

For the present study, Lake Ellesmere was conceptualised as a single vertical profile, i.e., vertical differences were modelled but horizontal variations were not accounted for. This 1–D assumption was made so that lake processes could be sufficiently simplified to enable simulation of potential changes in lake trophic status over time scales of multiple years, and so that simulation times were sufficiently short (i.e., several minutes) to allow a robust calibration process using multiple iterations. Details of the model conceptualisations and equations are available in the model science manuals (Hamilton & Schladow, 1997; Hipsey et al., 2006; Imerito, 2013).

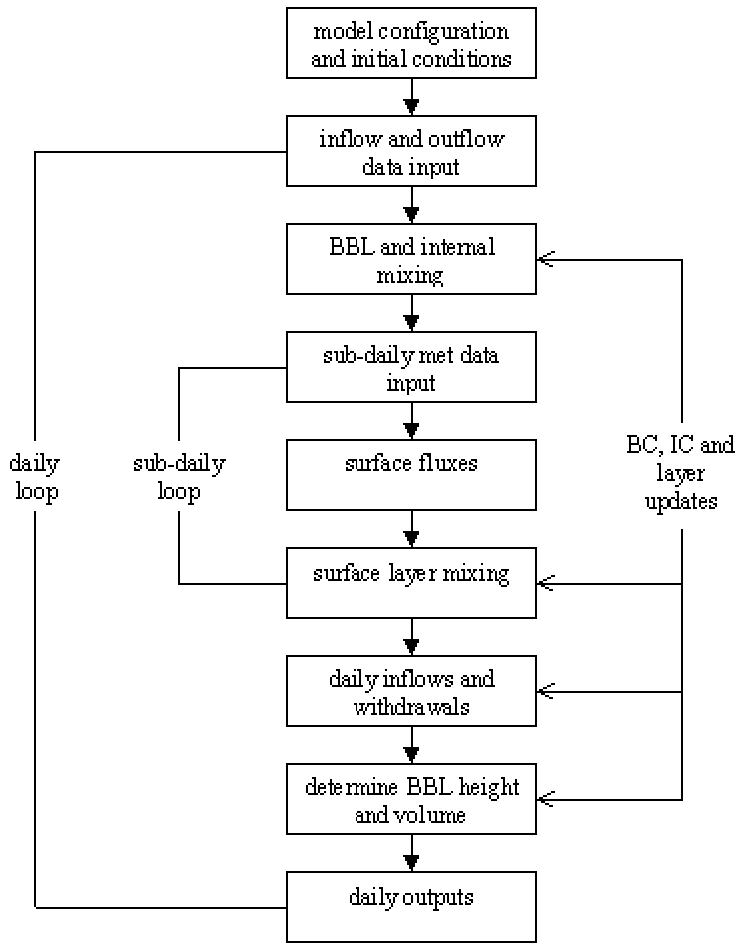

Figure 1. Flow chart for hydrodynamic and thermodynamic components of the one dimensional lake model DYRESM. BBL is the benthic boundary layer, IC is the initial condition and BC is the boundary condition (i.e., meteorology, inflows and outflows).

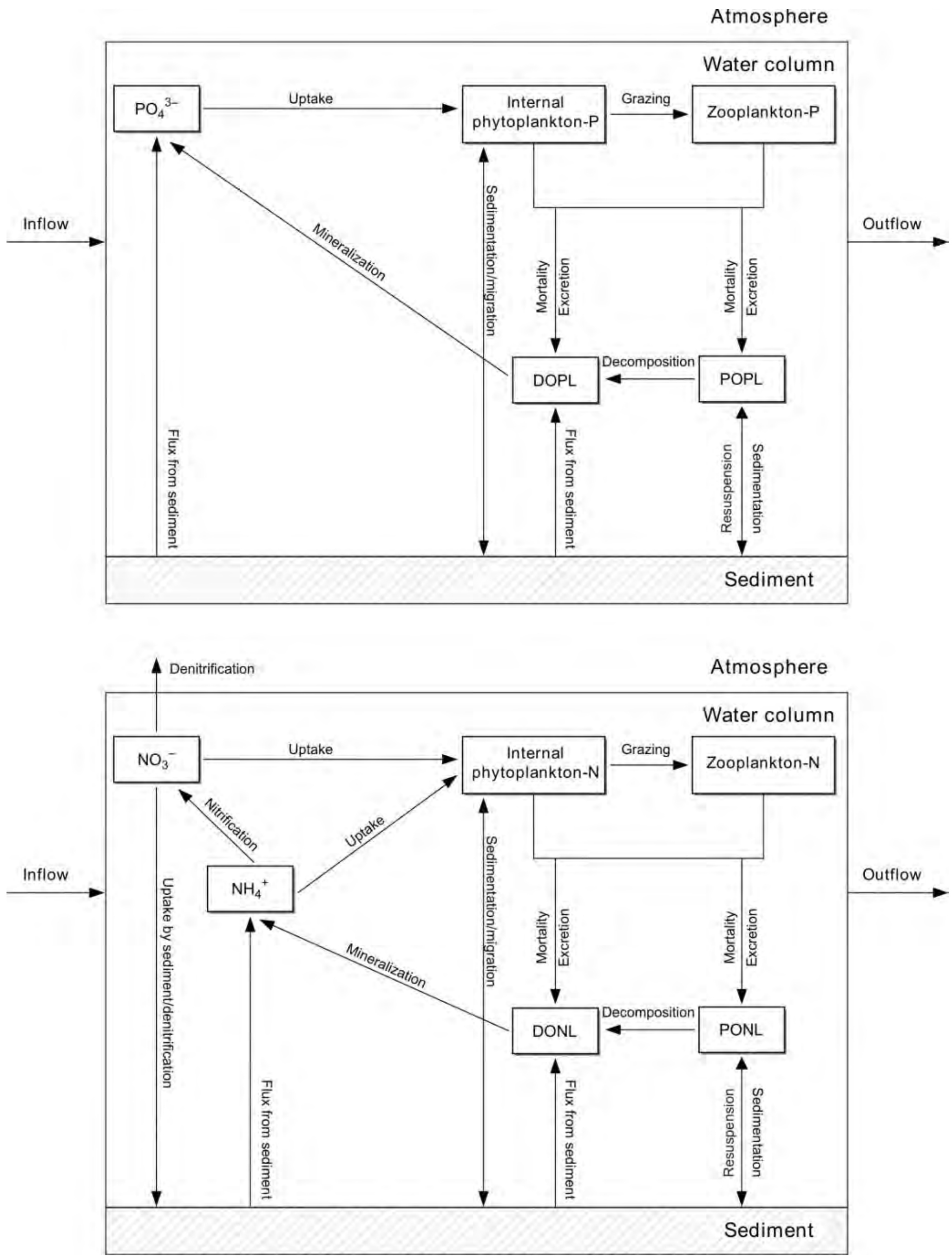

Figure 2. Conceptual diagram of the phosphorus (upper panel) and nitrogen (lower panel) cycle in the DYRESM-CAEDYM model. Note that zooplankton dynamics were not simulated explicitly and were represented by a constant rate of loss. POPL and PONL represent particulate labile organic phosphorus and nitrogen, respectively, and DOPL and DONL represent dissolved labile organic phosphorus and nitrogen, respectively.

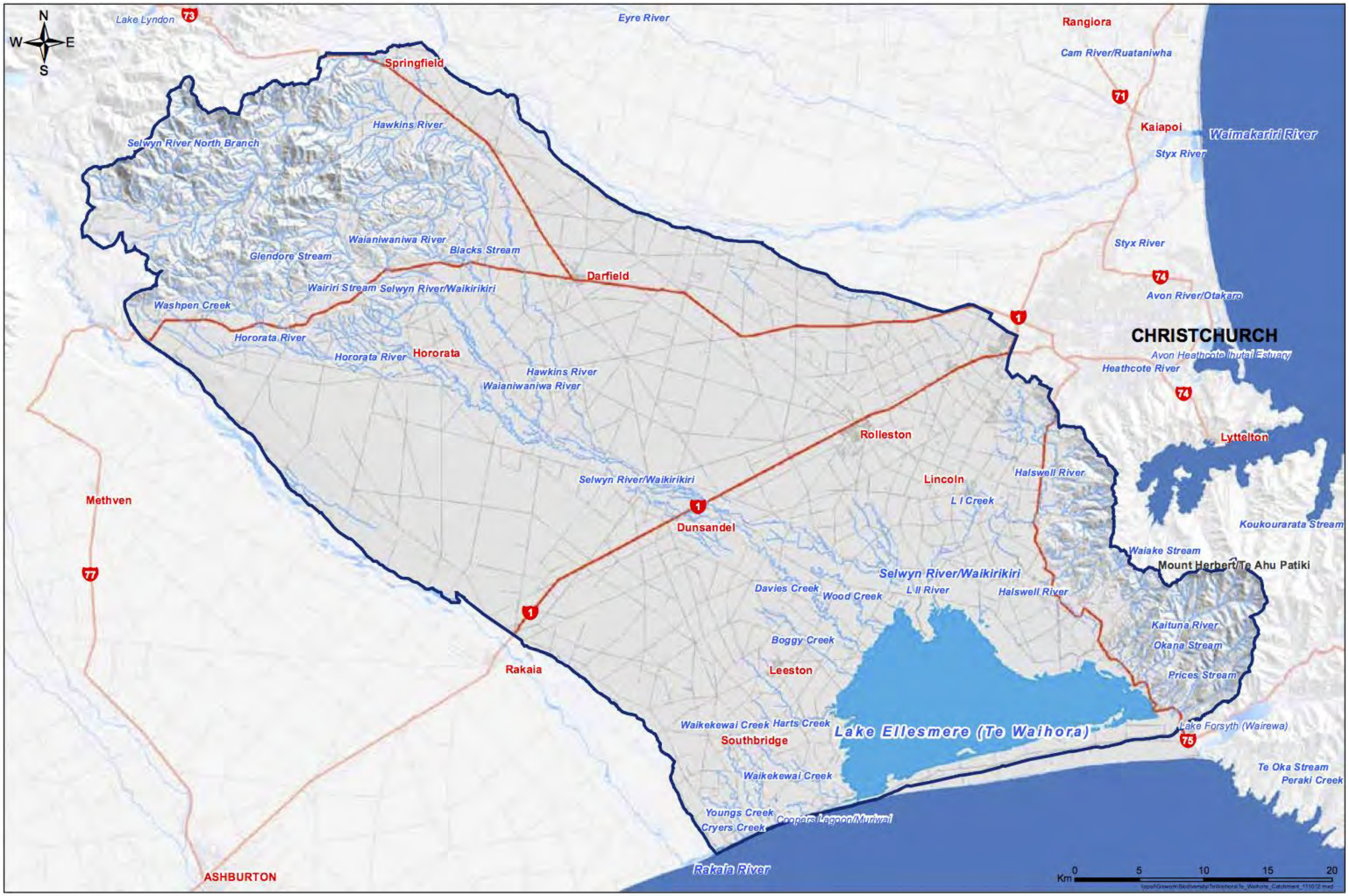

Figure 3. Regional setting of Te Waihora / Lake Ellesmere and its catchment. Source: Hughey et al. (2013).

1.7. Lake model configuration

1.7.1. Bathymetry

Lake bathymetry input to the model was represented using a lake–area relationship adapted from the North Canterbury Catchment Board Plan L82 in 1980 and a Department of Scientific and Industrial Research Bathymetric Survey completed in 1988. A plot of lake area and volume used in the bathymetry input file is shown in Figure 4. This hypsography is similar to that used by Horrell (1992), although it allows for elevated water levels necessary for hydrological scenario generation, by linear extrapolation of lake area above a water level of 2.7 m.a.s.l. (= 4.3 m depth). These data form the basis for relating storage and water levels at each time step. It also enables a lake elevation and area to be determined from the net change in inflows, outflows, evaporation and rainfall (the latter two pertaining to the lake itself).

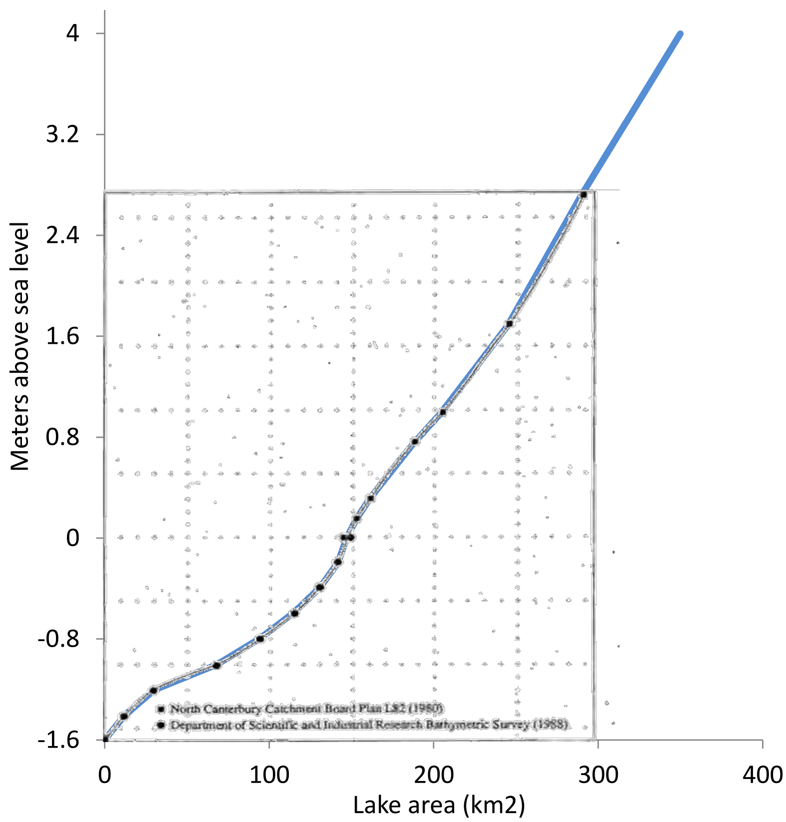

Figure 4. Relationship between lake area and height: Te Waihora/Lake Ellesmere, reproduced from Horrell (1992) (black points) and from the current study (blue line).

1.7.2. Meteorology

Meteorological data required for model input (2011-2015) were taken from local weather stations as close to the lake as possible. Measurements of daily mean air temperature (°C), shortwave radiation (W m^{-2}), cloud cover (fraction of whole sky), vapour pressure (hPa), and daily total rainfall (m) were obtained from the National Climate Database (http://cliflo.niwa.co.nz)for the 'Lincoln Broadfield' Station (station identifier 17603). Wind speed data were obtained from a monitoring station maintained by Environment Canterbury at Taumutu (near the lake outlet. Wind speed and air temperature records for July 2015 to June 2016 were regressed against data from a central lake monitoring station (installed May 2015) and correction factors were applied to the long-term record in order to represent conditions over the lake as closely as possible. Central station wind data, which are collected at a height of on average 5 m above the water surface were corrected using the wind power law. Daily cloud cover was estimated based on the difference between observed daily mean short–wave solar radiation and estimated theoretical maxima and minima (Luo et al., 2010). Input meteorological data are shown in Figure 5 and summary statistics are presented in Appendix A.

1.7.3. Water balance

A daily water balance model was constructed, by adaption of methods described Horrell (1992), and based on the equation:

$$\Delta S = \mathrm{O}_e + \mathrm{F}_m + \mathrm{F}_g + \mathrm{F}_r + \mathrm{M}_o + + \mathrm{P} - \mathrm{L}_s - \mathrm{E} \qquad (1)$$

where

- ΔS is the change in lake storage due to water level change,
- O_e is exchange between the lake and ocean (only when the barrier was open),
- F_m is gauged or estimated discharge of major streams, rivers and drains,
- F_g is discharge of groundwater direct to the lake,
- F_r is the contribution of freshwater from ungauged areas of the lake catchment,
- M_o is rough weather overtopping of sea water,
- P is precipitation directly on the lake,
- L_s is barrier seepage of lake water into the ocean
- E is evaporation.

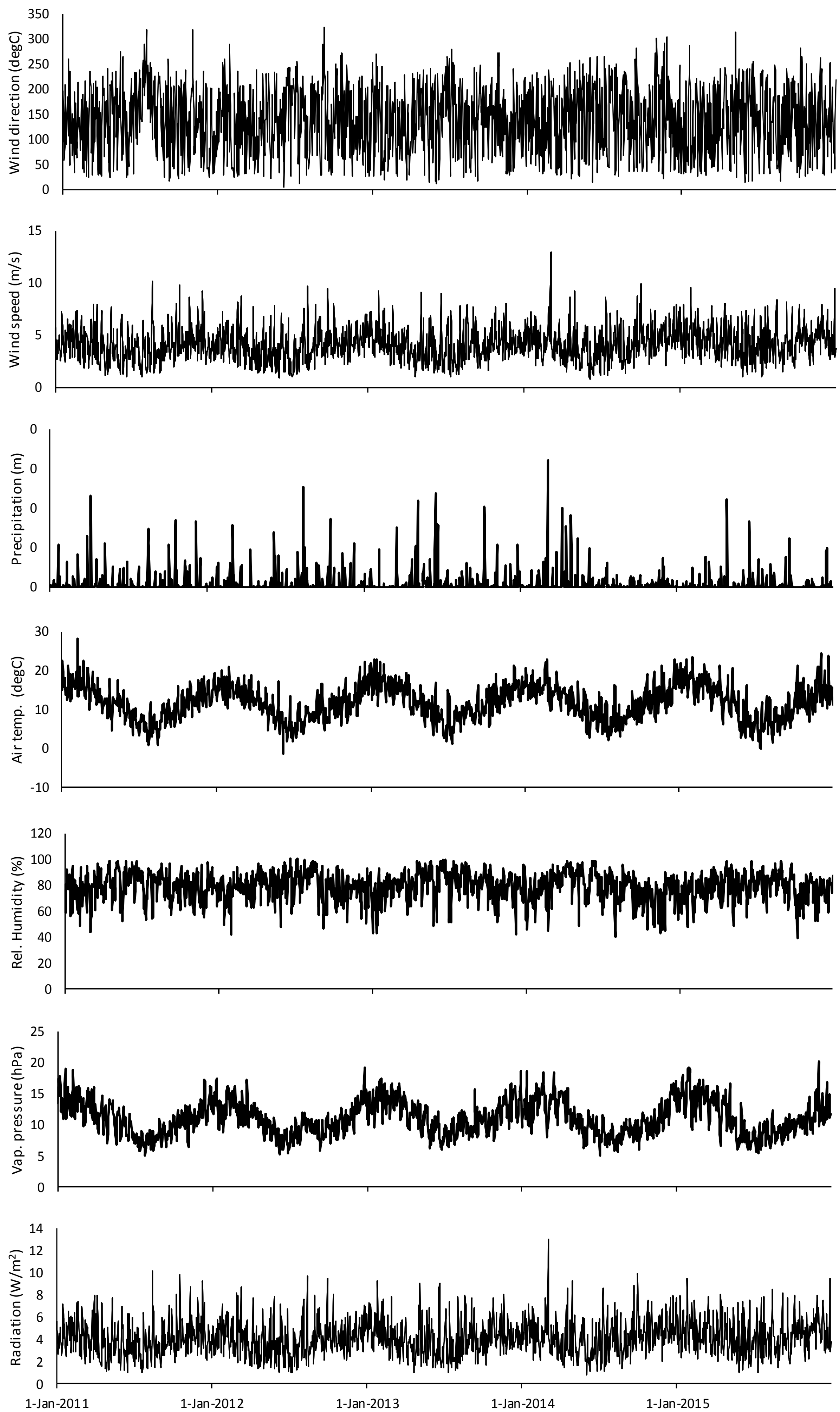

Figure 5. Daily meteorological data used for the 2011-2015 modelling period.

1.7.3.1. Storage change

Lake level data were obtained from Environment Canterbury's monitoring site at Taumutu and the mid-lake. Because Te Waihora is so large and shallow, any noise in the water level record (typically caused by tilting of the lake water column during strong directional winds) will in turn have a substantial impact on water balance calculations. Therefore, it was necessary to 'smooth' the water level record. Obvious outlying data associated with strong winds were removed manually and replaced using linear interpolation of adjacent measurements. During periods of barrier closure a three-day centred rolling average was applied to water level measurements. During periods of barrier opening, noise in the water level record is more complex due to potentially large volumes of water exchanged between the lake and ocean. During barrier opening, storage change was used to calculate the exchange of ocean and lake water at the barrier.

1.7.3.2. Open barrier exchange

The current Kaitorete Spit opening prescriptions are based on water surface elevations. Specifically, the lake is opened when the water level near the barrier reaches 1.05 m above mean sea level (a.s.l.) (August–March), or 1.13 m.a.s.l. (March–August) (Schallenberg et al., 2010). Summaries of Lake Ellesmere opening and closing times (2011-2015) were obtained from ECAN. A number of adjustments in the lake opening data were necessary to match observed lake level changes. Adjustments were made in 20 instances, representing less than 5% of the number of open days, bringing the total number of days in which the lake was open in the modelling period to 415.

Open barrier exchange was determined by rearranging the water balance equation, such that:

$$\mathrm{O}_e = \mathrm{F}_m + \mathrm{F}_r + \mathrm{F}_g + \mathrm{M}_o - \Delta S + \mathrm{P} - \mathrm{L}_s - \mathrm{E} \tag{2}$$

When this equation yielded a positive value, this volume was removed from the lake via barrier outflow to the ocean. When negative, an equivalent (absolute) volume of marine water was input to the lake as an inflow. In practice, this means that the 'noisiness' of the lake level data during each period of barrier opening dictated the net exchange of lake and oceanic water during opening. Therefore, a manual process of water level smoothing was undertaken for each period of barrier opening in order to optimise the fit of the salinity balance in the lake.

1.7.3.3. Major freshwater inflows

Although forty tributaries flow into Te Waihora, continuous measurements of flow (2011-2015) were available for only six (Kaituna, Selwyn, Doyleston, Halswell, LII and Harts). For three major streams without a permanent gauge, mean discharge was estimated from daily measurements of discharge in comparable streams, as in Trolle et al. (2011). Specifically, the discharges of

Irwell and Boggy rivers were derived from Harts Creek and the discharges of Hanmer River from Doylestone River, in each case assuming the equivalent areal rate of discharge as for the gauged site.

1.7.3.4. Groundwater inputs

Groundwater inputs direct to the lake were determined from literature values presented in Ettema and Moore (1995), Trolle et al. (2011) and Horrell (2011).

1.7.3.5. Residual freshwater inflows

Freshwater inputs from areas of the catchment not captured by the nine major streams were input to the lake model as a single surface inflow. The volume of discharge was considered to be a fraction of the total gauged flow, with the multiplier determined by optimising the goodness of fit between measured and observed water level during sustained periods of barrier closure (i.e., where the total lake water balance is not complicated by substantial and highly variable exchange between the lake and ocean).

1.7.3.6. Marine overtopping

Rough sea 'overtopping' of sea water into the lake occurs during periods of high waves and strong southerly winds. Daily overtopping inflow into the lake was estimated in this study using wave height and wind direction measured by a 'wave buoy' operated by Environment Canterbury 17 kilometres east of Le Bons Bay, Banks Peninsula at Latitude 43° 45' South, Longitude 173° 20' East. Criteria for overtopping were based on Horrell (1992). Overtopping was estimated to occur when wind speed and wave height were above the 80th percentile of all measurements and wind direction was from the south (between 135 and 225 degrees). Volumes of sea water inflow as a result of overtopping were estimated as the product of wind speed, wave height and multiplied by a coefficient, which was determined by optimising the fit of the salinity balance in the lake (section 3.2.2) during periods of sustained barrier closure.

1.7.3.7. Precipitation

Total daily precipitation from the Lincoln (Broadfield) monitoring site was multiplied by lake area to represent rainfall directly to the lake. An additional 5 % was added to the rainfall inflow, to represent direct surface runoff of precipitation at the lake margins.

1.7.3.8. Barrier seepage

Daily seepage of lake water through Kaitorete Spit and into the ocean was estimated by the equation of Horrell (2011):

$$L_s = 3.647WL - 1880 \qquad (3)$$

where WL is water level in millimetres above mean sea level and L_s is seepage in $m^3\ s^{-1}$. Very low water levels result in negative seepage (i.e. marine intrusion) but instances were uncommon, of very small volume and only during times of barrier opening. Therefore, seepage from the ocean via the barrier and into the lagoon was considered to be accounted for by the salinity balance during barrier opening, and was thus excluded from consideration for the water balance.

1.7.3.9. Evaporation

Apart from outflows through Kaitorete spit, loss of water occurs via evaporation over the entire lake surface. While the influence on water quality (specifically salinity) from ocean influxes is diluted within the lake by freshwater inflows (streams, groundwater inflows, rain), salinity increases in the lake by evaporation from the water surface. Daily loss of water by evaporation was obtained from hourly mean evaporation rate (E; L/s) calculated based on Fischer *et al*. (1979):

$$E = \frac{A\left(\frac{-0.622}{P} C_L\, \rho_a\, L_E U(e_a - e_s)(T_{surf}))\right)}{L_v} \qquad (4)$$

where A is the area of the lake (m^2), C_L is the latent heat transfer coefficient for wind speed (0.0013), ρ_a is air density (kg/m^3), L_E is the latent heat of evaporation of water (2,453,000 J/kg), U is measured wind speed (m/s), e_a is the vapour pressure of the air (Pa), e_s is the saturated vapour pressure of the air (Pa) corresponding to the lake water surface temperature (°C), P is the atmospheric pressure (Pa), L_v is the latent heat of vaporisation (2,260,000 J/kg) and T_{surf} is the surface water temperature (°C) estimated using a relationship established between day of the year and historic measurements. A value of 0 was substituted where E < 0 as the model does not simulate condensation effects.

e_s was calculated by the Magus–Tetens formula (Hodges & Dallimore, 2011):

$$e_s(T_{0.5}) = 100 \exp\left[2.3026\left(\frac{7.5\, T_{0.5}}{T_{0.5}+237.3}\right) + 0.758\right] \qquad (5)$$

1.7.4. Inflow water quality

1.7.4.1. Temperature

Hourly mean temperature (°C) of precipitation was set to lake surface water temperature, estimated using an empirical relationship between historical measurements and day of year. Hourly mean temperatures (°C) of remaining surface inflows (Ts) were estimated using an empirical model described by Mohseni *et al*. (1997):

$$T_s = \mu + \frac{\alpha}{1+e^{\gamma(\beta - T_a)}} \qquad (6)$$

where T_s is the estimated stream temperature, T_a, is the measured air temperature, the coefficient α is the estimated maximum stream temperature, γ is a measure of the steepest slope of the function, μ is estimated minimum stream temperature and β represents the air temperature at the inflection point. The exponent γ, a function of the slope tan θ at the point of inflection, was estimated as:

$$\gamma = \frac{\tan\theta}{\alpha - \mu} \tag{7}$$

Figure 6 shows the relationship between stream water temperature and air temperatures; the relationship is described well by a logistic function with a characteristic S-shaped trend as described by Mohseni *et al*. (1997). The same approach was used to fit stream water temperature for the remaining surface inflows.

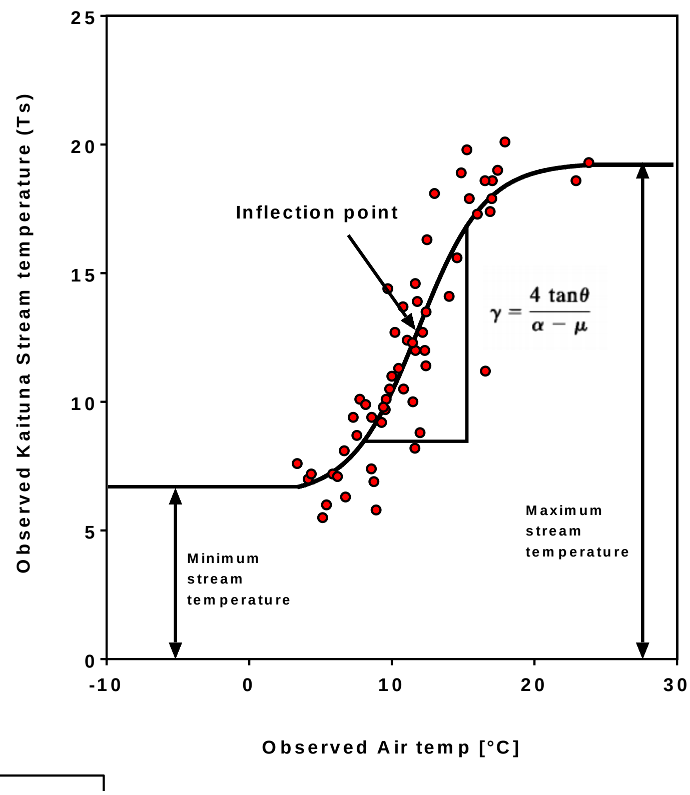

Figure 6. Fit of Kaituna stream water temperature using air temperatures based on the logistic function methodology described by Mohseni et al. (1997)

Estimates of stream temperature from air temperature using this approach produced good agreements with observations during the study period.

1.7.4.2. Dissolved oxygen

Dissolved oxygen (DO) concentrations of all inflows were assumed to be 100% saturated based on estimated water temperature. DO saturation concentrations were estimated using the equation of Mortimer (1981):

$$DO = \exp\big(7.71 - 1.31\, ln(T_s + 45.93)\big) \quad (8)$$

where DO is dissolved oxygen at saturation (mg/L) and T_s is the stream temperature (degC).

1.7.4.3. Nutrient and suspended sediment concentrations

Monthly grab samples of water quality for six major inflows (Boggy Creek, Selwyn, Kaituna, Doyleston Drain, Harts Creek, Halswell and LII River) were available from ECAN for the period 2011-2015. For these inflows daily concentrations of nutrients and sediment were estimated by linear interpolation of available measurements. Measurements were not available for Hanmer Road drain, Boggy Creek or Irwell River. Concentrations for Hanmer Road drain were assumed similar to Doyleston Drain, whereas Boggy Creek and Irwell River were assumed to be similar to Hartstone Creek, based on similarities between these inflows as described in Sukias et al. (2016). Aerial deposition (precipitation) was assigned constant nutrient concentrations of 0.2 mg NO_3-N L^{-1} and of 0.01 mg PO_4-P L^{-1}, and groundwater was assigned constant concentrations based on those used by Trolle et al. (2011). Nutrient concentrations and salinity for the ocean inflow were based on a previous coastal study (Bolton-Ritchie, 2006). Daily nutrient and ISS concentrations in the residual inflow file were assigned using discharge–weighted concentrations for the nine major stream inflows (after Abell et al., 2015).

1.7.5. Model time steps and baseline simulation period

DYRESM-CAEDYM was run at hourly time steps between January 2011 and December 2015, with daily averaged input data and daily output data at 1200 h. In deciding the years captured in the simulations, it was deemed important to select a period that was as recent as possible to help to assess effects relative to current water quality.

1.7.6. Model calibration and validation

Model performance for each period was quantified by comparing modelled and measured values of the following water quality parameters in the lake: temperature, dissolved oxygen, nutrients and chlorophyll *a.* Performance was assessed with a suite of statistical indices as detailed in Table 2. ECAN undertakes monthly lake water quality monitoring at five locations on the lake using near-surface grab samples. These locations include (a) South of Timber Yard Point Site (b) Mid lake Site (c) near the Selwyn River mouth (d) Taumutu (at gauge) and (e) Kaituna Lagoon, 1.7km from Kaituna Recorder. Comparisons of model simulation output were made against measured data collected by ECAN at the mid-lake station. The model output represents a horizontal average for the lake so some variability between model output and observations may be attributed to this difference. The model was run with an input and output time step of one day, with an internal model time step of one day. The model was initialized with mid-lake water quality data that was closest in time to the start date of the model simulations.

Table 2. Statistics used to evaluate lake model performance.

Abbreviation	Statistic	Details	Equation
r	Pearson product moment correlation	Measures the strength of the correlation between modelled and measured data, i.e. how 'in phase' the two signals are. Values range from -1 (perfect negative correlation) to 1 (perfect positive correlation).	$\frac{\sum_{i=1}^{n}(o_i-\bar{o})\times(m_i-\bar{m})}{\sum_{i=1}^{n}(o_i-\bar{o})\times\sqrt{\sum_{i=1}^{n}(m_i-\bar{m})}}$
RMSE	Root mean square error	A measure of the magnitude of the error between modelled and measured data which is disproportionately affected by large errors.	$\sqrt{\frac{\sum_{i=1}^{n}(m_i-o_i)^2}{n}}$
MAE	Mean absolute error	Measures the average error, irrespective of whether the model under– or over–predicts measurements.	$\frac{\sum_{i=1}^{n}\lvert(m_i-o_i)\rvert}{n}$

1.8. Scenario modelling

The baseline model configuration (Table 3; 'Base_OBS') was altered to represent the effects of two different types of management interventions on water quality, where each of the two management interventions had a number of variations (i.e., several different scenarios for each case).

1.8.1. Nutrient load scenarios

Given the potential for increased or decreased nutrient loading depending on factors such as population growth, proposed or future land use changes, and/or legacy loads from existing land uses, five nutrient loading scenarios were considered. These were represented by a reduction or increase in nitrate (NO_3) or total phosphorus (TP) concentrations in all freshwater inflows, but excluding aerial deposition (i.e., wet and dry deposition) to the lake.

1.8.2. Lake water level scenarios

In order to assess the possible effects of changes in barrier opening, i.e. altered frequency and timing, a water balance model was constructed to allow the generation of lake water levels under different barrier opening scenarios. The timing and duration of barrier opening and lake-ocean exchange for the baseline case ('Base_OBS') was calculated using recorded openings and closings. For hypothetical scenarios of different barrier openings, it was necessary to construct a model that would predict opening and closing of the barrier. This model has been previously described by Horrell (1992, 2009). His approach was adapted for the present study in order to generate the hydrological scenarios summarised in Table 3.

Table 3. Model scenarios showing the modifications to nutrient loading (above grey line) and water level threshold (below grey line).

Scenario	Water & salinity balances	Tributary nutrients	Outflow control (m^3/s)	Water level threshold (m asl)*	Number of openings**	% barrier open***
Base_OBS	Observed	Observed	na	1.13, 1.05*	20	23.0
Base_+20N	Observed	+20% NO3	na	1.13, 1.05*	20	23.0
Base_+40N	Observed	+40% NO3	na	1.13, 1.05*	20	23.0
Base_+60N	Observed	+60% NO3	na	1.13, 1.05*	20	23.0
Base_-20N	Observed	-20% NO3	na	1.13, 1.05*	20	23.0
Base_+20P	Observed	+20% TP	na	1.13, 1.05*	20	23.0
Base_MOD	Simulated	Observed	na	1.13, 1.05*	15	20.2
Pre-human	Simulated	Observed	na	4	0	0.0
Pre-European	Simulated	Observed	na	3	2	1.0
Limit_2m	Simulated	Observed	na	2	4	5.2
Limit_1.4m	Simulated	Observed	na	1.4	8	4.1
Control_a	Simulated	Observed	12 (0.75 - 0.9 m) 50 (> 0.9 m)	1.3	1	1.1
Control_b	Simulated	Observed	20 (0.75 - 0.9 m) 150 (> 0.9 m)	1.3	0	0.0

*The threshold water level at which the ocean barrier will be opened; this differs by season (summer, winter)

**Total number over simulation period

***Modelled percent of time during which the ocean barrier is open

1.8.2.1. Predicting the duration of barrier opening

After manual opening of the barrier, controlled closure of the spit is generally not feasible, rather, wave action closes the breach naturally. Horrell (1992) describes in detail the processes that close the barrier, either by peak (storm) events that close it rapidly, or by gradual ‘infilling’ of the cut via wave action. Criteria for the barrier closure model were taken from Horrell (1992), but with the benefit of improved monitoring over recent years (i.e., ECAN’s wave buoy), and included:

- Daily wave height threshold for automatic (single day) closure
- Daily wave height threshold for gradual infill
- Wave direction minimum and maximum for closure or infill to occur
- Days of infill for barrier closure

The above parameters were optimised for goodness of fit between observed and predicted opening duration across all barrier opening events recorded between 2011 and 2015. However, it was found that model performance could be improved by inclusion of the following additional controls:

- Lake level threshold above which infill cannot occur (due to rapid outflow from the lake under high hydraulic head).
- A lower threshold for automatic closure when lake level was above the infill threshold.

1.8.2.2. Predicting the occurrence of lake barrier opening.

Hydrological scenarios were generated using various thresholds for barrier opening (Table 3), however, barrier opening takes considerable effort and requires conditions conducive to barrier digging once the required lake level threshold is reached. Therefore, and additional component of the water balance model was required to predict when a successful barrier opening would occur. This was again estimated after the methodology of Horrell (1992), with some adjustments for different time periods and data sources. Variables used for this prediction included:

- Lake level threshold for opening to begin;
- Wave height below which, and direction criteria within which, digging is feasible;
- Number of days required to dig out the barrier.

The above parameters were optimised so that the predicted number of openings, and the total number of days the barrier was open for the period 2011 to 2015 matched observations as closely as possible.

1.8.2.3. Water balance under hypothetical hydrological scenarios.

The lake water balance for the hypothetical hydrological scenarios was again calculated using Equation 2, however, the occurrence of barrier opening was dictated by the barrier model, and thus it was no longer possible to calculate lake-ocean exchange using the same methodology as the base case (Base_OBS). Therefore, the rate of outflow from the lake to the ocean, and the influx of sea water to the lake during barrier opening were predicted by examining relationships between lake level, duration of barrier opening and volume of sea water intrusion across all observed periods of opening for the base case. This yielded fixed estimates of:

- Daily lake outflow through the barrier under conditions of high hydrological head (water level);
- Daily lake outflow through the barrier under conditions of low lake water level;

- Daily seawater intrusion to the lake during conditions of low lake water level.

A hypothetical 'base case' was constructed using baseline water level thresholds for initiating the barrier opening process (Base_MOD), and output of this model was compared with the model using observed timing of barrier opening/closing (Base_OSB) to ensure that the hypothetical barrier model satisfactorily reproduced lake dynamics in terms of the number and duration of barrier openings, lake water levels, and salinity balance. After obtaining a satisfactory match using the hypothetical water balance model, a range of scenarios was generated using alternative water level thresholds for barrier opening (see Table 3), in order to simulate the effects of these regimes using DYRESM-CAEDYM. Two additional scenarios were established (control_a and control_b) using an adaptation of the water balance model, in order to

1.8.3. Scenario outputs

Water quality for all modelled scenarios was summarised as annual Trophic Level Index (TLI) values for comparison of the likely effects of the various future catchment inputs and management scenarios simulated.

RESULTS

1.9. Te Waihora/Lake Ellesmere water quality trends (2011-2015)

1.9.1. Nutrients

Figure 7 summarises nutrient and total suspended solids concentrations based on ECAN monitoring data for the five lake monitoring sites for the period 2011-2015. Figure 8 shows the time series of nutrient concentrations for water collected at the five sites for this period. The highest concentrations and greatest variability of ammonium-N and dissolved reactive phosphorus occurred in Kaituna Lagoon, while total N, total P and total suspended solids (TSS) concentrations were lowest at this site amongst the five monitoring sites. Total N and nitrate-N concentrations were highest in samples collected off Selwyn River mouth and lowest in samples collected in the middle of the lake (Figure 8, 9).

1.9.1.1. Influence of Lake Ellesmere opening and closing regimes on water quality trends

Annual frequency of Lake Ellesmere openings and observed mid-lake nutrient and suspended solids concentrations are presented in Figure 10. The Lake Ellesmere outlet was open for 89, 84, 163, 64 and 35 days in 2011, 2012, 2012, 2013, 2014 and 2015, respectively. A two-tailed Mann Whitney test revealed no significant difference in total P, dissolved reactive P, total N, nitrate-N and TSS concentrations between periods when the lake was open and when it was closed. A smaller number of samples were taken when the lake was open (n = 14) than when the lake was closed (n = 44) for the 2011-2015 period (Figure 11).

1.9.2. Salinity

Samples from Kaituna lagoon had lowest salinity ($p<0.0001$) amongst the five monitoring stations for the study period (2011-2015) (Figure 12). Differences in salinity amongst the other four stations were not significant (Figure 12). Te Waihora/Lake Ellesmere is generally well mixed but there may be occasional periods when thermal and/or salinity stratification occur. The measurements presented in Figure 12 represent only surface samples.

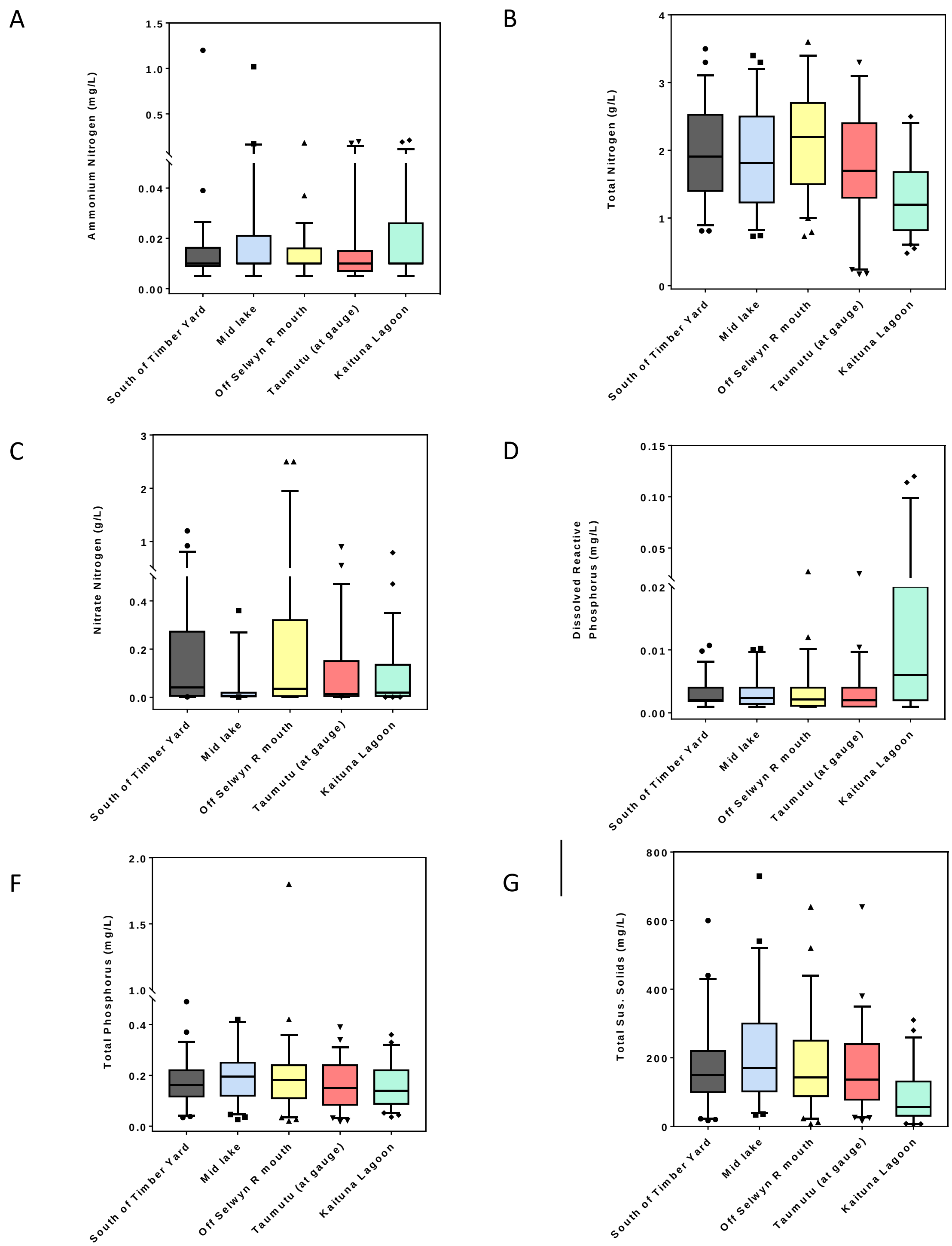

Figure 7. Mean (middle line), standard deviation (box), 95% confidence intervals and outliers of concentrations of nutrients and suspended solids at five sampling sites on Te Waihora/Lake Ellesmere, 2011 to 2015.

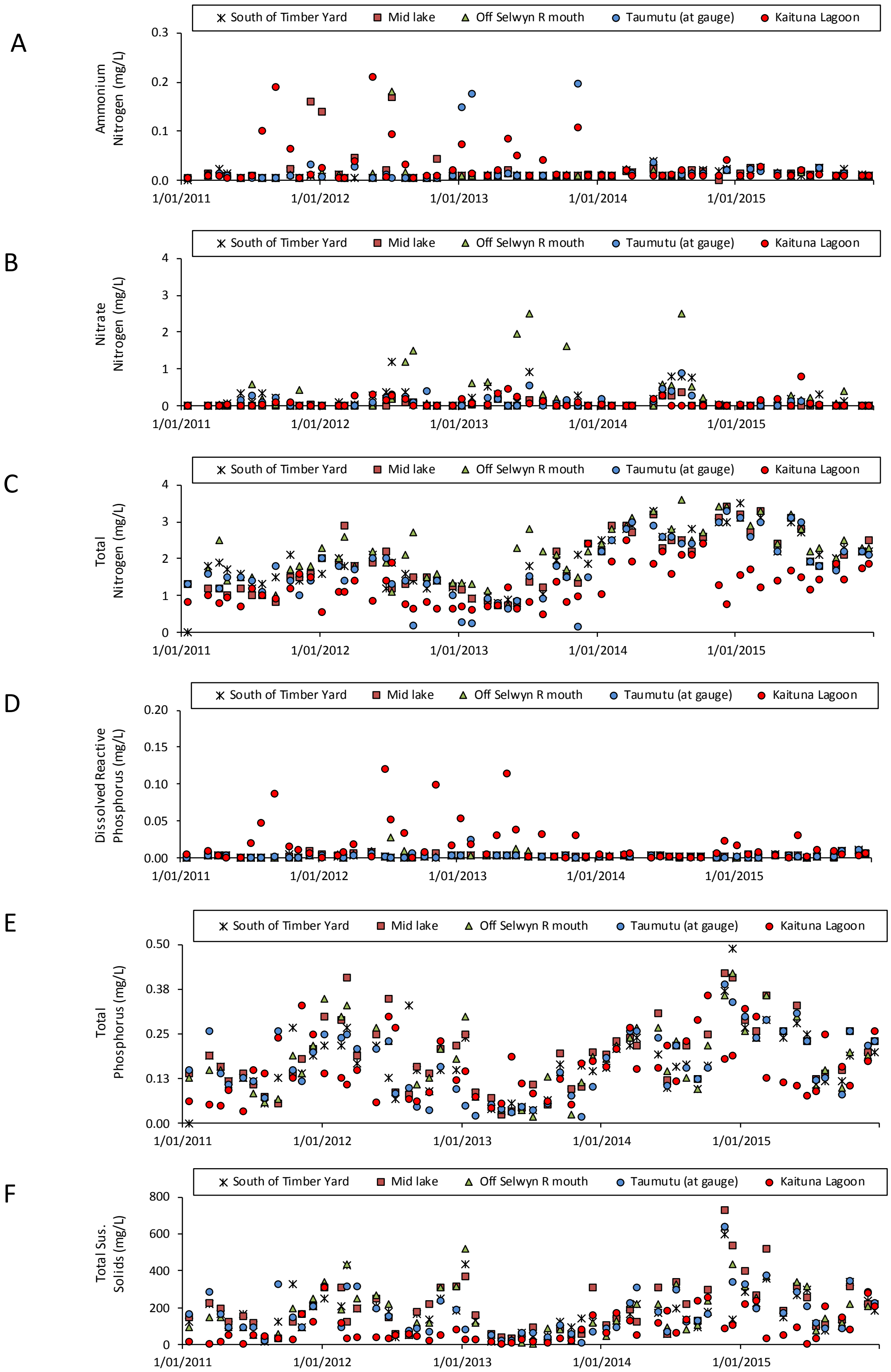

Figure 8. Concentrations of nutrients and suspended solids at five sampling sites on Te Waihora/Lake Ellesmere, 2011 to 2015.

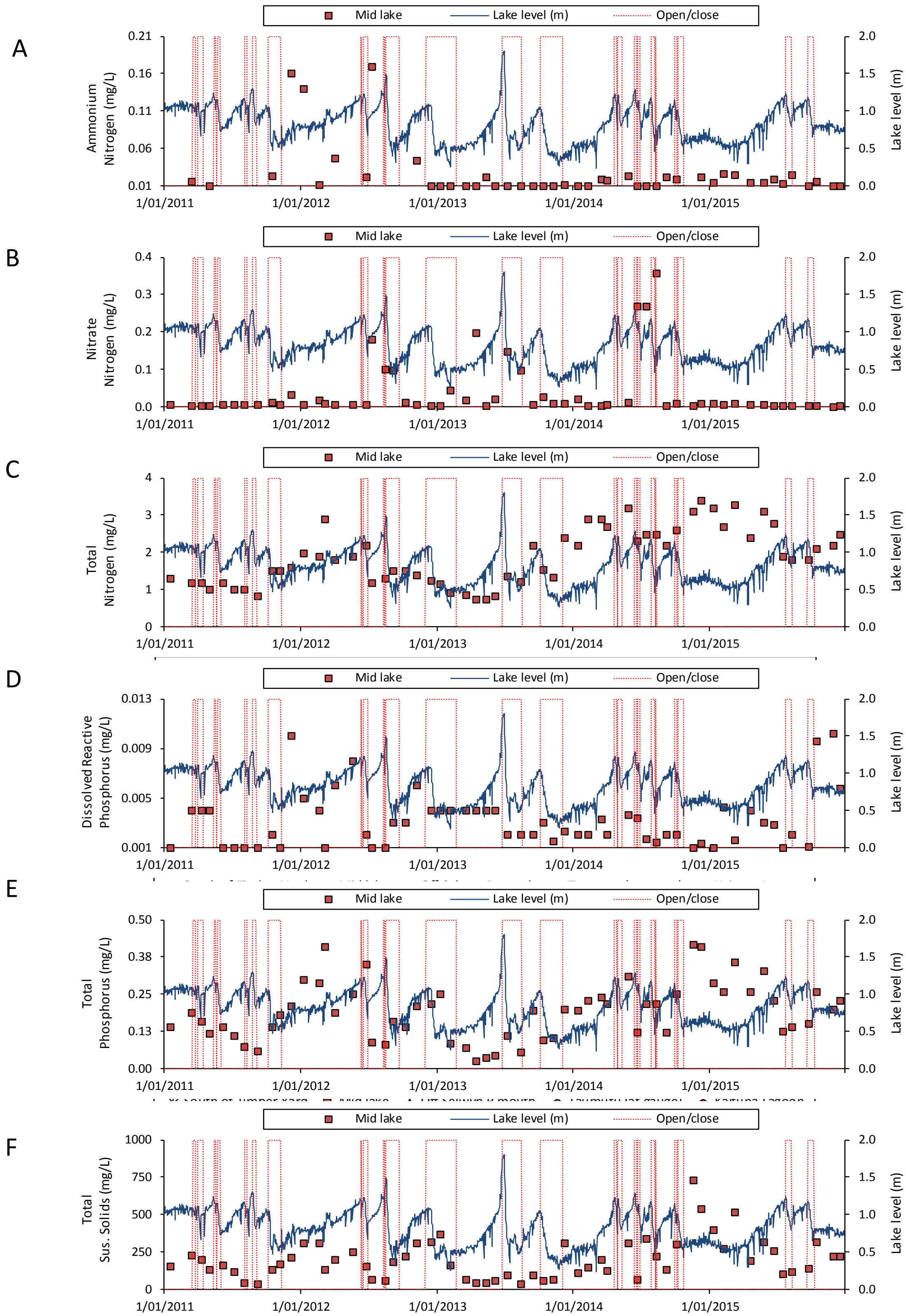

Figure 9. Lake openings and concentrations of nutrients and suspended solids at mid-lake site, Te Waihora/Lake Ellesmere, 2011 to 2015.

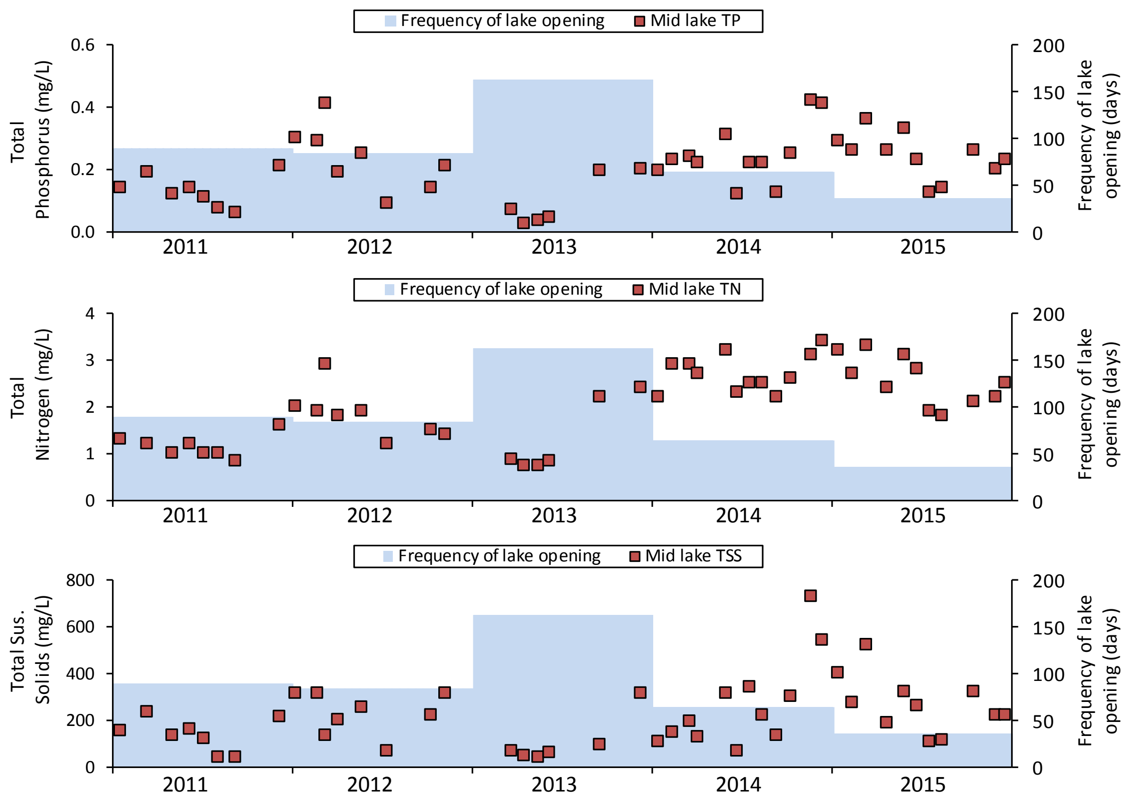

Figure 10. Frequency of openings for each year and observed nutrient and suspended solids concentrations for Te Waihora/Lake Ellesmere, 2011 to 2015.

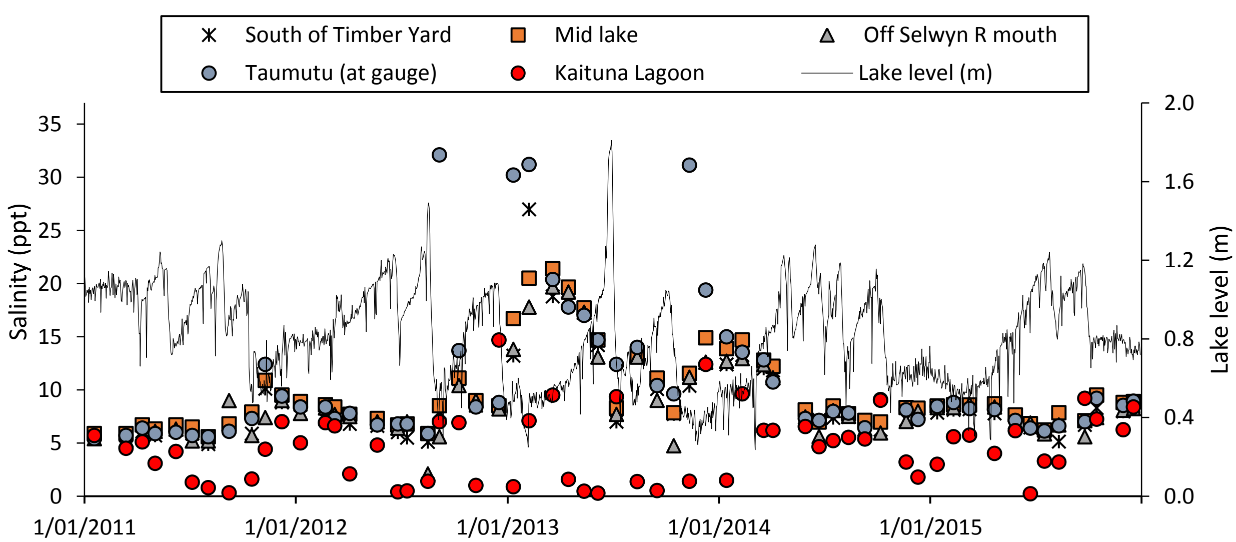

Figure 11. Observed salinity at the five ECAN sampling sites on Te Waihora/Lake Ellesmere, 2011 to 2015.

The observed salinity of Te Waihora/Lake Ellesmere for the 2011-2015 period was generally < 10. Salinity increased to > 10 towards the end of 2012, as well as for prolonged periods in 2013 and 2014. During the study period (2011-2015), the lake was open to the sea for a total of 435 days. There was a strong correlation between the number of days that the lake was open and salinity recorded at the lake buoy (Figure 13). During opening, salinity most frequently exceeded 10 when the lake was open continuously for 10 days or more (Figure 13). For periods of opening < 10 days, the salinity was relatively constant and the regression relationship of Figure 13 is probably not appropriate for application to this situation. Lake water level could be related to salinity in a non-linear regression (Figure 14b). Following opening, the water level usually decreased towards sea level within 11 to 13 days (Figure 14a).

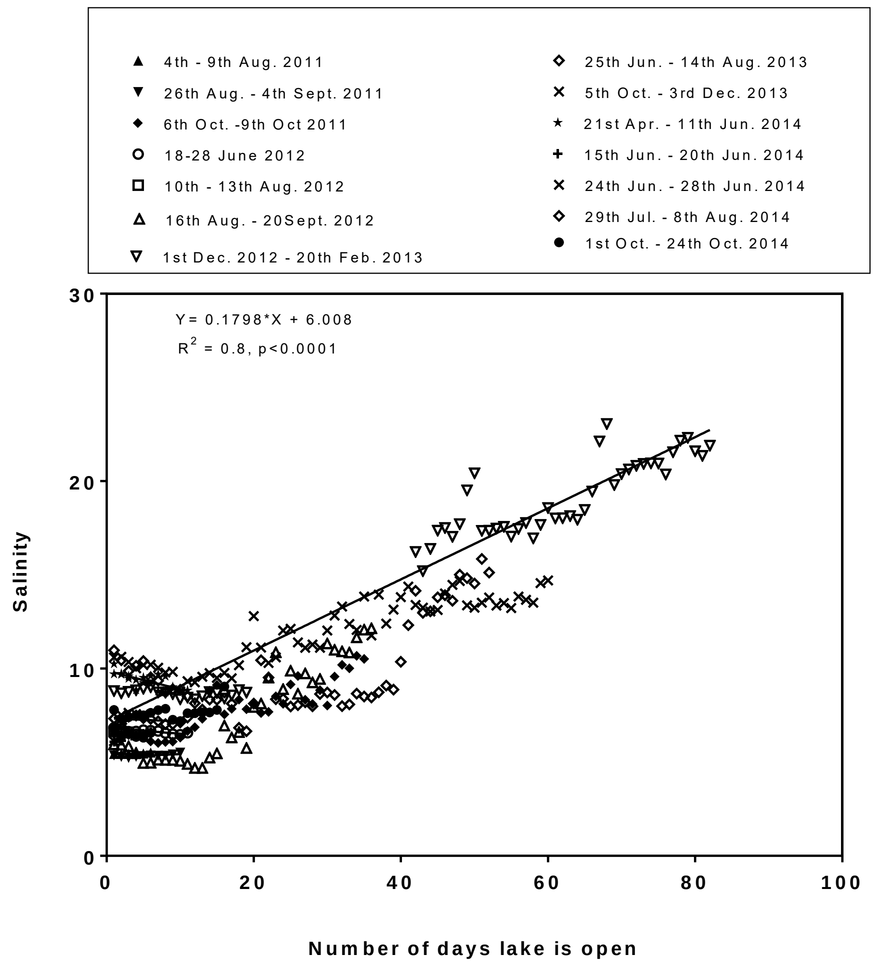

Figure 12. Number of days that Te Waihora/Lake Ellesmere is open and observed lake salinities, 2011 to 2015. Salinities are based on lake buoy readings at the middle of the lake.

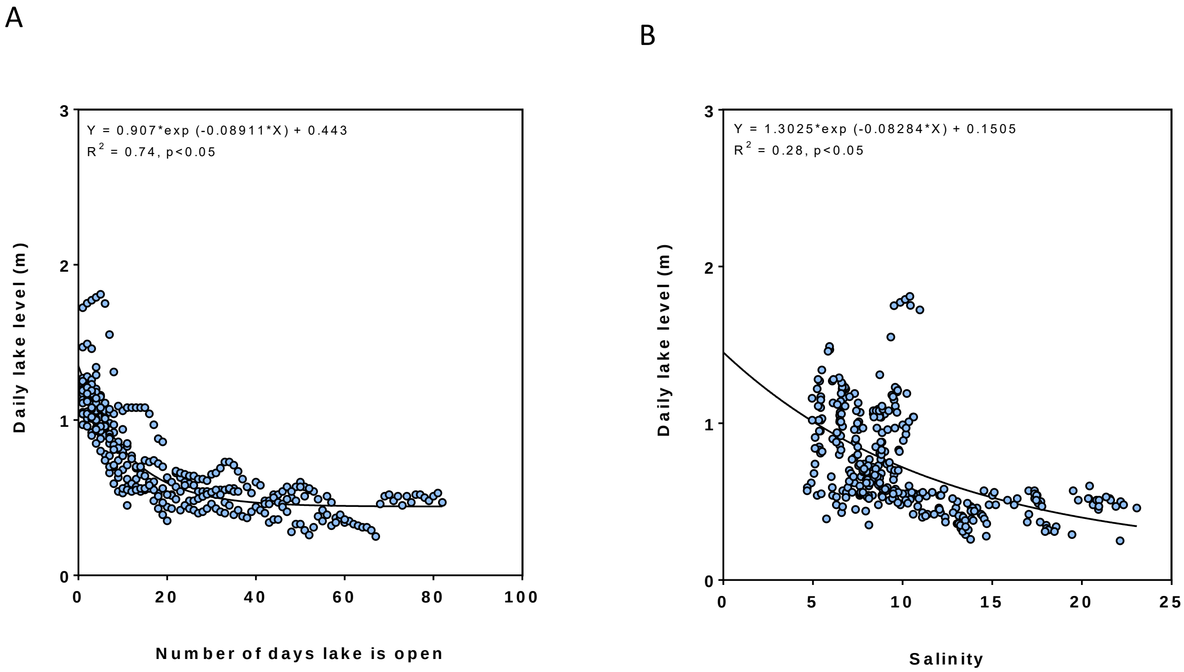

Figure 13. Observed water level in meters a.s.l and (a) number of days that the lake was open and (b) salinity forTe Waihora/Lake Ellesmere, 2011 to 2015.

1.9.2.1. Water level and storage change

Water level measurements were taken from ECAN's station at Taumutu, near the lake outlet. Raw measurements included some 'noise', most likely due to tilting of the lake surface during consistently strong wind events. In order to construct the lake water balance model, raw water level data were manually edited for outliers during strong winds. Subsequently, a three-day rolling average was applied to the dataset for measurements during periods of barrier closure. During barrier opening, data were smoothed manually, with the degree of smoothing determined by the lake salinity balance (see Section 1.7.3.2). Raw and smoothed lake level data are shown in Figure 14.

1.9.2.1. Freshwater inputs

A separate inflow file was included for groundwater inputs from seepage that occurs when artesian water percolates upwards through layers of silt, peat or marine and estuarine sands which make up the lake bed. Estimated groundwater seepage in this study was 0.45 m^3 s^{-1} (Table 4) which is consistent with the findings of Horrell (2010). Daily rainfall direct to the lake was represented in the model as a surface inflow to the uppermost model layer. This was done in order to account for atmospheric deposition of N and P, and an additional 5% of observed rainfall on the lake was included to represent direct surface runoff at lake margins.

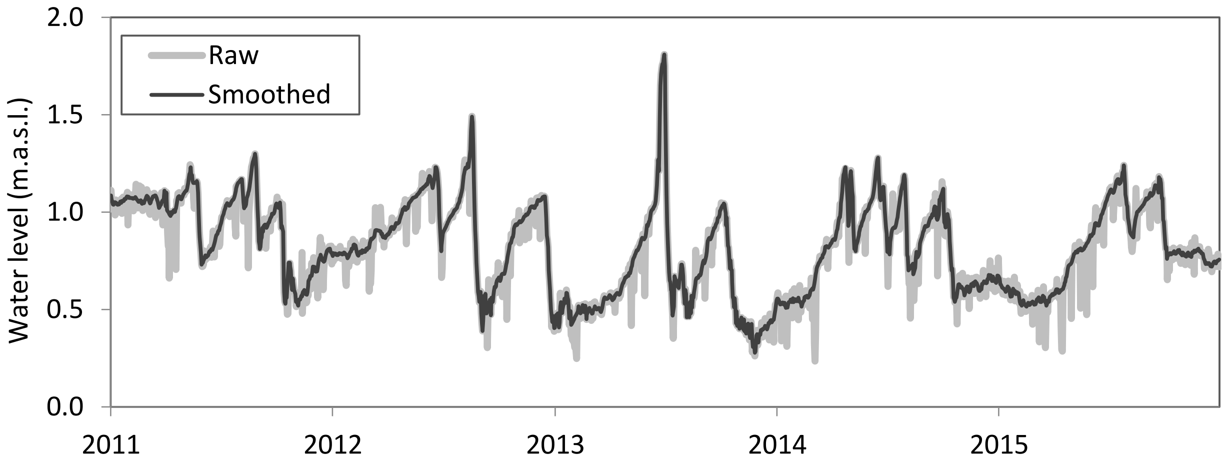

Figure 14. Smoothed versus observed lake level for Te Waihora/Lake Ellesmere, 2011 to 2015.

Table 4. Summary of water balance values ($m^3\ s^{-1}$), comparing Horrell (2010; period 1986 to 2007) with the water balance for the present study (2011 to 2015).

Source	Horrell (1986-2007)	Present study
Tributaries	12.50	14.97
Rainfall to lake	3.30	3.93
Groundwater	0.40	0.45
Lake opening inflows	2.60	3.75
Rough weather	1.50	0.88
Barrier seepage out	1.20	1.15
Evaporation	6.60	5.34
Barrier opening outflows	11.50	17.90
Storage change	0.10	-0.41
Balance	-0.90	0.00

Summary statistics of daily discharge for inflows are presented in Table 5. Surface discharges from the gauged and ungauged inflows were on average 14.97 $m^3\ s^{-1}$. Among the surface inflows, Selwyn River had the highest daily maximum discharge (13,659,754 $m^3\ d^{-1}$). Selwyn, LII and Halswell rivers, as well as Harts Creek, accounted for about 80% of the gauged and ungauged surface discharge to the lake during the study period (2011-2015) (Figure 16). Selwyn and LII Rivers had the highest mean discharge (279,158 $m^3\ d^{-1}$ and 194,142 $m^3\ d^{-1}$, respectively) during the study period (Table 5). Rainfall direct to the lake was an important contributor to the water balance (Figure 16) but total discharge from the nine major tributaries (shown in Figure 16), exceeded total rainfall inputs into the lake; this pattern was clearly evident during winter 2012, 2013, 2014.

Daily seepage outflows were estimated to have a five-year average flow rate of 1.15 $m^3\ s^{-1}$ (Table 4) and accounted for about 2% of the lake outflow. In agreement with Horrell (2011), seepage flows out of the lake coincided with periods when the lake level was >0.5 m.a.s.l. When lake levels are below this height, coastal water seepage is into the lake, yielding negative values, with an intrusion of marine water. Compared to seepage outflow from the lake, ocean seepage inflows to the lake occur infrequently. Seepage outflow was therefore set at zero in the course of preparing the water balance for the model.

Table 5. Summary statistics of daily discharge ($m^3\ d^{-1}$) of Te Waihora/Lake Ellesmere inflows, 2011 to 2015.

Statistics	Minimum	25% Percentile	Median	75% Percentile	95% Percentile	Maximum	Mean	Std. Deviation	Std. Error of Mean
Kaituna	2851	8294	17410	35424	163793	2981232	55180	188402	4411
Selwyn	2592	57542	87653	163274	1001916	13659754	279158	880408	20614
Doyleston	0	1123	10584	21665	51451	457315	17215	30984	725
Halswell	32350	57802	73656	97200	152906	1092096	89795	69991	1639
LII	84499	157939	188827	222286	276826	870653	194142	65678	1538
Harts	54086	98237	123379	145066	203450	805421	127492	48276	1130
Irwell	14743	28610	37119	52771	142413	1177294	55662	84273	1973
Hanmer	6482	12579	16320	23202	62614	517611	24472	37052	868
Boggy	5312	10309	13375	19015	51315	424211	20057	30366	711
Ocean	0	0	0	0	1729560	27804157	398815	1704353	39907
Groundwater	4752	28512	42768	57024	57024	57024	38571	17345	406
Aerial	0	0	0	87181	1971393	12439262	340257	1093600	25606
Residual	114314	221834	287812	409175	1104232	9128411	431587	653432	15300

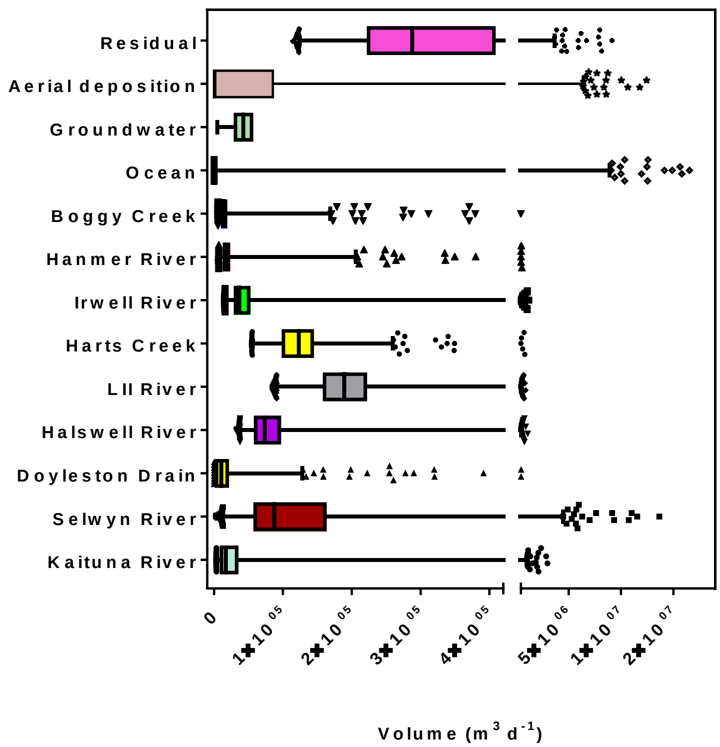

Figure 15. Mean (middle line), standard deviation (box), 95% confidence intervals and outliers of surface and ground water input into Te Waihora/Lake Ellesmere, 2011 to 2015.

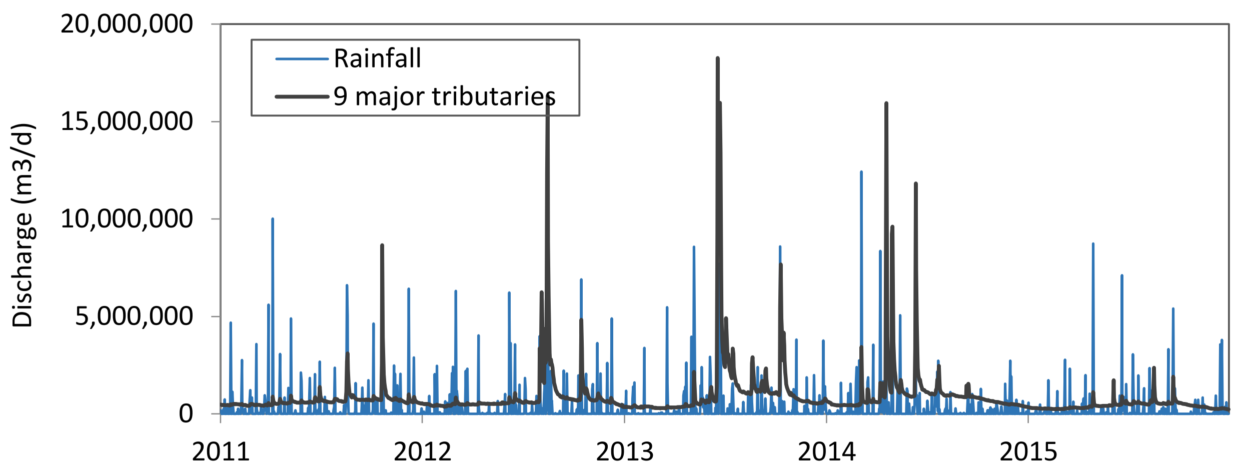

Figure 16. Rainfall direct to Te Waihora/Lake Ellesmere and total inflow from nine major streams rivers and drains, 2011 to 2015.

1.9.2.2. Marine inputs

Figure 18 shows the time series of wave height and overtopping inflow. Periods of rough sea conditions with characteristic high waves and strong southerly winds were associated with large sea water incursions.

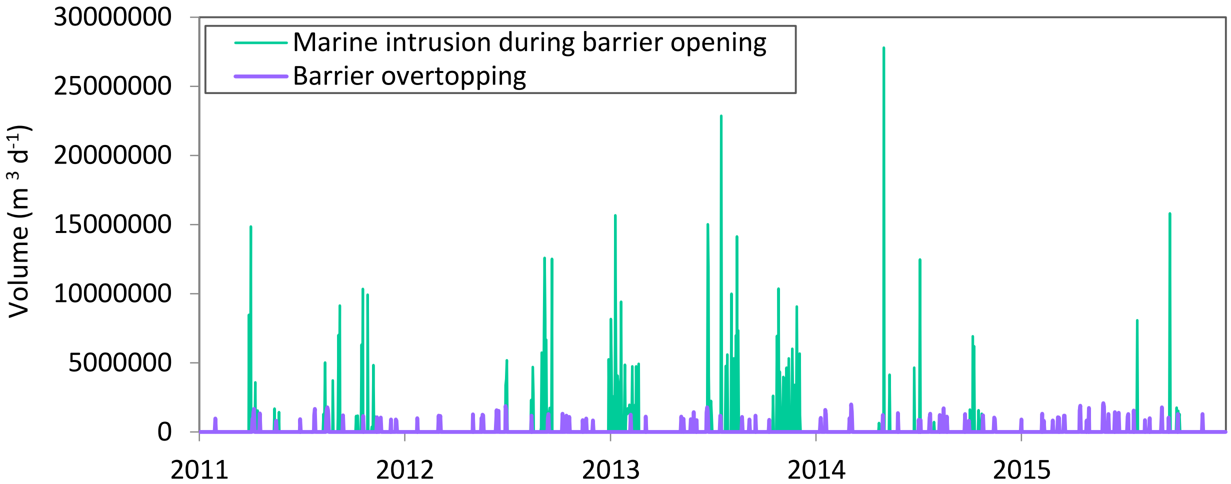

Figure 17. Ocean wave height and estimated marine water intrusion due to rough weather conditions at Te Waihora/Lake Ellesmere, 2011 to 2015.

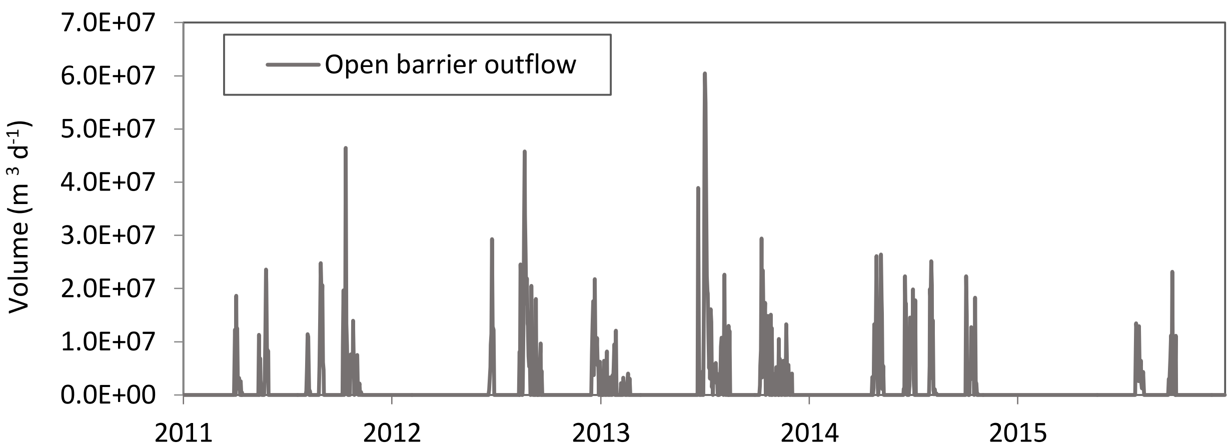

Figure 18. Open barrier outflow estimated by water balance for Te Waihora/Lake Ellesmere, 2011 to 2015.

1.9.3. Inflow water quality

Figure 19 shows suspended solids, dissolved reactive phosphorus, ammonium, nitrate, total nitrogen and total phosphorus concentrations in the inflows. Halswell River showed high variability and high concentrations of TSS (Figure 20a), but nutrient concentrations in this tributary were not exceptional compared with the other tributaries. Kaituna, Selwyn and Boggy Creek had occasional high concentrations of TSS, as indicated by outliers in the box-and-whisker plots of Figure 21a. These instances are also visible in Figure 21f which shows a time series of suspended solids data for 2011 to 2015.

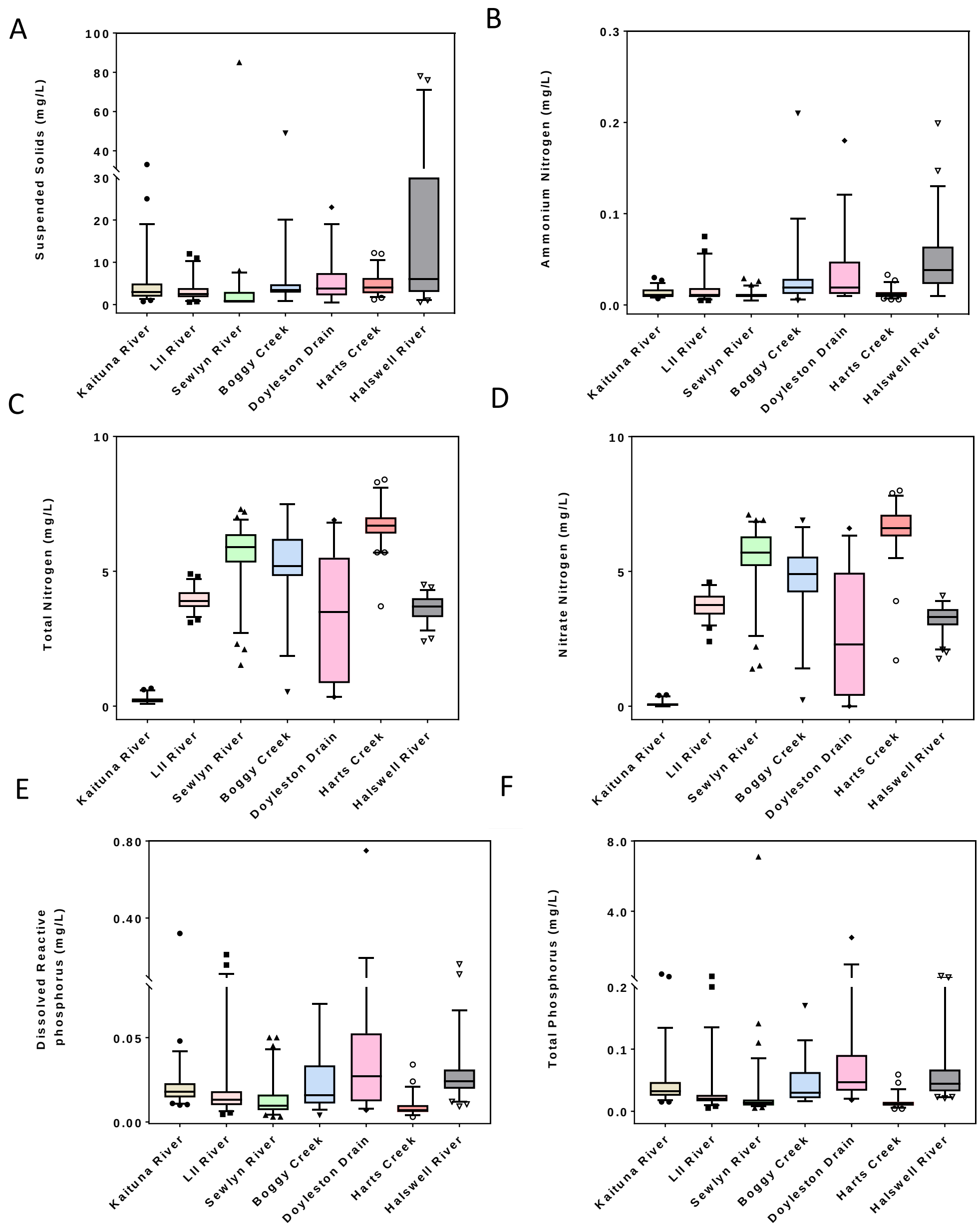

Figure 19. Mean (middle line), standard deviation (box), 95% confidence intervals and outliers of concentrations of nutrients and suspended solids at Te Waihora/Lake Ellesmere inflows, 2011 to 2015.

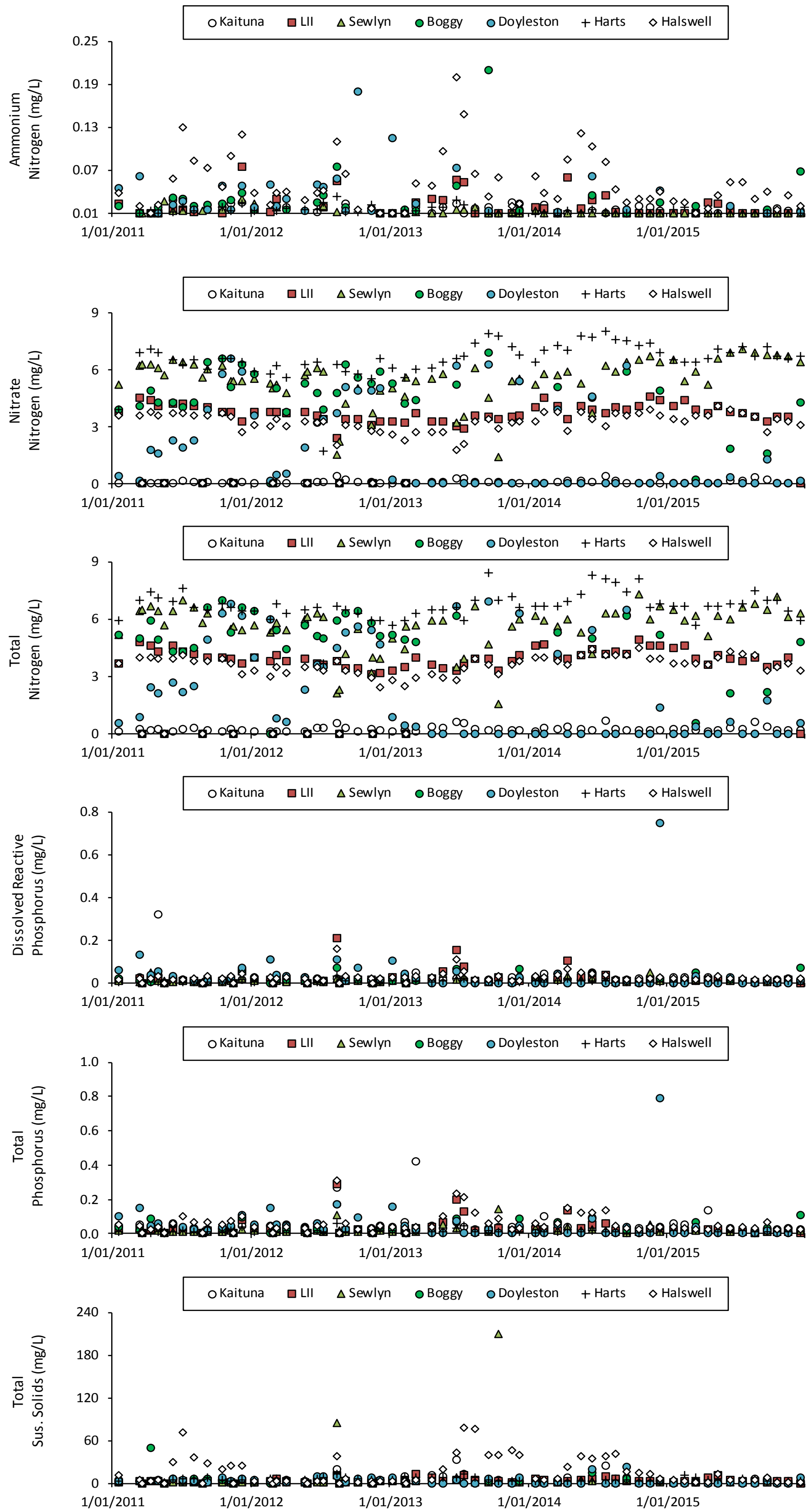

Figure 20. Time series of nutrient and suspended solids concentration data for monitored inflows to Te Waihora/Lake Ellesmere, 2011 to 2015.

Concentrations of ammonium-N in Kaituna, Selwyn and Harts Creek varied little through the study period (Figure 21b). There were, however, marked variations in the ammonium-N concentrations in Doyleston Drain, Halswell River and Boggy creek (Figure 21b, Figure 22a) and concentrations were generally highest in these inflows over the five-year study period (Figure 21b). There were also a number of outliers that markedly exceeded the fourth quartile (95% percentile) of observed nutrient concentrations. These outliers are also visible in Figure 22 and 23, these generally coincide with wet days and elevated mean river flow. A similar pattern of variability was observed in the concentrations of total N and nitrate-N from water samples collected at the seven inflows during the period 2011-2015 (Figure 21 c and d). Among the seven rivers, total nitrogen and nitrate concentrations were highest and showed high variability for Doyleston Drain, followed closely by Boggy Creek and Selwyn River (Figure 21c, d). Unlike the Kaituna River, nitrate-N strongly dominated TN concentrations (usually >95%) in samples from Selwyn River (see raw data, Appendix B2). Among samples collected from Doyleston Drain, observations of high total N and nitrate concentrations generally coincided with high daily mean flow, while a less distinct pattern was observed between ammonium and daily mean flow (Figure 22).

1.9.3.1. Summary of input nutrient loads

Daily nutrient and TSS concentrations are summarised as mean annual loads to the lake over the modelling period (2011-2015) in Table 6.

Table 6. Summary of nutrient loads (t yr^{-1}) from inflows in the 1–D model, based on daily concentrations obtained from linear interpolations of observed data, 2011–2015.

Inflow	PO_4-P	TP	NH_4-N	NO_3-N	TN	TSS
Kaituna	0.36	1.28	0.27	4.20	7.9	200.4
Selwyn	1.74	4.04	1.15	527.6	555.7	1660.1
Doyleston	0.26	0.41	0.25	34.38	37.7	48.2
Halswell	1.18	2.63	2.01	125.9	140.4	743.8
L2	1.94	2.73	1.28	314.5	332.0	246.1
Harts	0.42	0.67	0.60	370.3	384.4	218.3
Irwell	0.23	0.36	0.30	162.8	168.5	105.6
Hanmer	0.51	0.72	0.34	42.0	46.9	61.4
Boggy	0.08	0.13	0.11	58.7	60.7	38.1
Ocean inflow	1.53	9.17	3.64	5.82	44.4	292.4
Groundwater	0.56	1.13	0.14	6.33	13.0	0.6
Rainfall	1.12	1.12	6.21	3.72	9.9	0.00
Ungauged catchment	4.79	8.04	4.22	831.5	887.4	1382.4
Total	**14.72**	**32.41**	**20.52**	**2487.7**	**2688.7**	**4997.3**

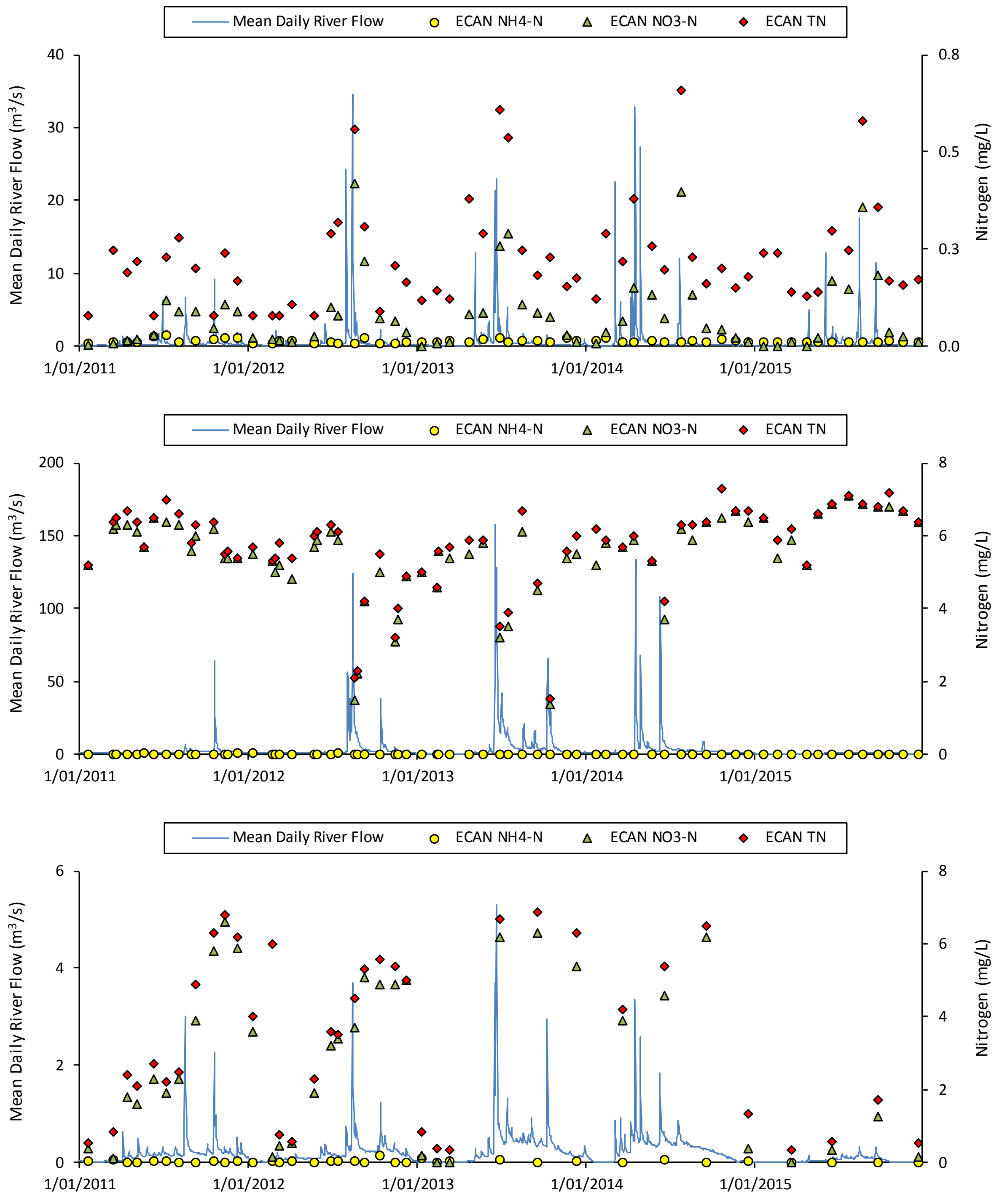

Figure 21. Nitrate-N, ammonium-N and total N concentrations and mean daily flow, Te Waihora/Lake Ellesmere inflows, 2011 to 2015. (A) Kaituna River, (B) Selwyn River and (C) Doyleston Drain (2011-2015).

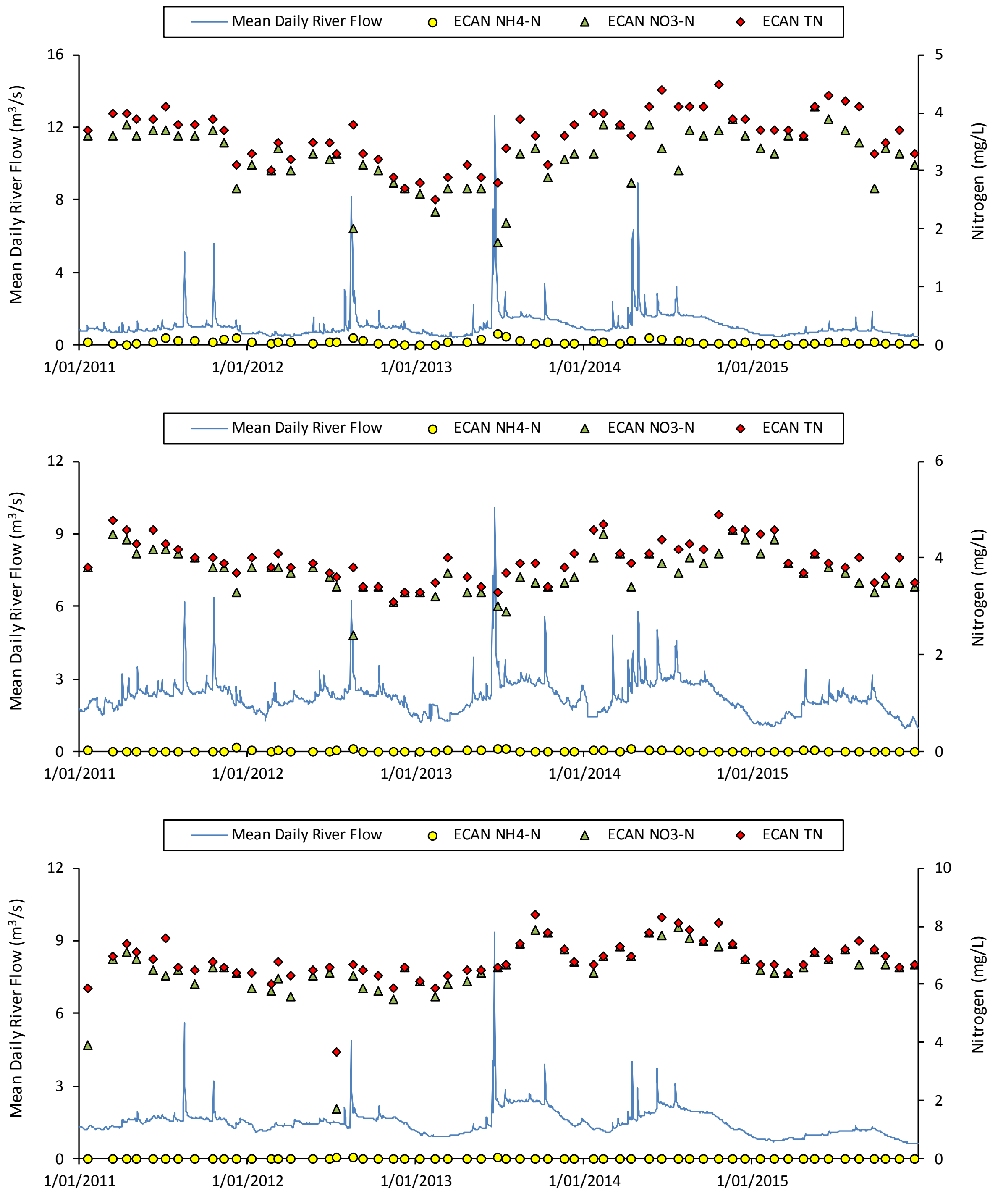

Figure 22. Nitrate-N, ammonium-N and total N concentrations and mean daily flow, Te Waihora/Lake Ellesmere inflows, 2011 to 2015. (A) Halswell River, (B) LII River and (C) Harts Creek (2011-2015).

1.10. Model calibration

1.10.1. Water level

Lake openings were associated with sharp decreases in lake levels (Figure 23). High salinity generally coincided with days of lake openings with concomitant massive ocean water inflows. Based on the water balance estimations, the 5-year average residual inflow (Table 5) was 431,587 m^3 d^{-1}. This term reflects ungauged inflows and overland flow inputs, particularly those following high rainfall, as well as errors arising from estimations of the gauged inflows.

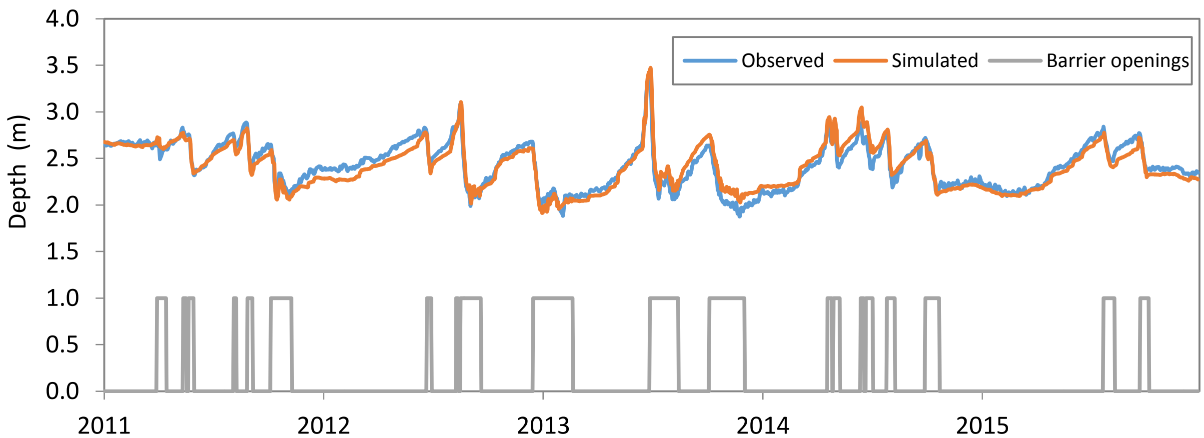

Figure 23. Modelled versus observed lake water level, Te Waihora/Lake Ellesmere, 2011 to 2015. The lake is open when barrier openings =1 and closed when barrier openings =0.

1.10.2. Salinity balance

The modelled period of 2011 to 2015 was characterised by large variations in salinity at the mid-lake station, from a minimum close to 5 to a maximum > 20. The early period of 2013 is notable for consistently high salinity, peaking at nearly two-thirds of marine salinity at the mid-lake station. This sustained period of high salinity is unprecedented in the record of recent decades. Considering that various assumptions had to be made about the magnitude and nature of the lake discharge to the ocean and the marine incursion into the lake when the barrier was open, and that these assumptions were simplistic (e.g., did not take into account variables such as outflow channel morphology which would have acted as a natural control on inflow and outflow discharge), the match of modelled salinity against measured values was considered good (Figure 25). Combined with the accurate correspondence of observed and simulated water level variations (Figure 24), it can be surmised that the balance of freshwater and marine inputs to Te Waihora/Lake Ellesmere is reasonably well represented in model simulations. This 'closure' of the water and salinity balance is an important prerequisite for being able to more accurately represent nutrient loads into and out of the lake, and to be able to simulate the biological response.

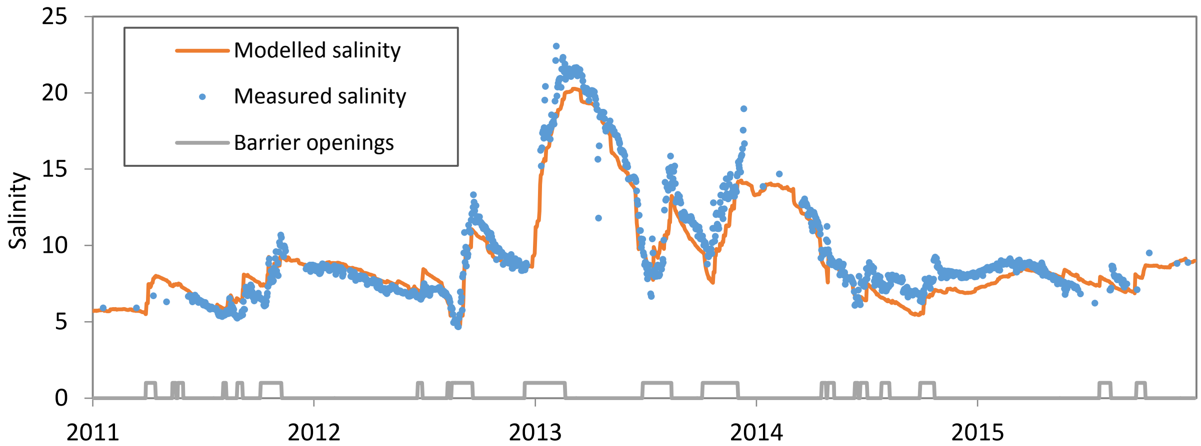

Figure 24. Plot of modelled versus observed salinities, Te Waihora/Lake Ellesmere, 2011 to 2015. Lake is open when barrier openings =1 and closed when barrier openings =0

1.10.3. Water temperature, dissolved oxygen and quality constituents

The observed seasonal variation in surface water temperature over the 2011-2015 study period was well represented in the model simulations (Figure 26). Capturing this seasonal variation is an important prerequisite for the CAEDYM component of the model as biogeochemical processes generally have strong dependence on temperature. These processes are commonly represented in the model using an Arrhenius function which approximates to a doubling of biological reaction rates for a 10 ^{o}C rise in temperature. Capturing this variation is also important because of the wide range of water temperature observed annually; from around 3 ^{o}C in mid-winter to 21 ^{o}C in summer.

The lake monitoring buoy has depth-resolved temperature sensors recording at intervals of 15 minutes. These data allow for evaluation of whether water column stratification occurs and, in combination with a near-bottom oxygen sensor, allow for a preliminary evaluation of the biological implications of stratification. Schallenberg and Crawshaw (2016) have made such an evaluation and found that temporary stratification events (of the order of a few hours) could result in strong depletion of dissolved oxygen in bottom waters. These events are not clearly evident in daily average sensor data (derived from 15-minute readings) which are used to compare against the daily frequency of model output. Therefore, while the model was not able to be tested robustly for its capability to represent water column stratification, it was deemed adequate for the daily time scales in the model output. One important aspect of the dissolved oxygen data evaluated by Schallenberg and Crawshaw (2016) is that it allowed for consideration of rates of oxygen depletion in bottom waters. A parameter representing the measured rate of oxygen demand of bottom sediments was input directly to the model and provided a level of confidence that, if scenarios were to be run that led to more prolonged stratification, the oxygen depletion rate would be well represented.

Figure 26 also shows dissolved oxygen concentrations measured monthly in surface waters at the mid-lake station and the model output at daily frequency. Seasonal variations in dissolved oxygen mostly reflect changes in oxygen saturation with temperature, with concentrations exceeding 12 mg L^{-1} in mid-winter when water temperature is around 3 ^{o}C and 8 mg L^{-1} in summer at a water temperature of around 21 ^{o}C. The model showed a slight tendency to under-predict concentrations. This under-prediction has been a consistent feature of model simulations for many other lakes and may represent a consistent shortcoming of the oxygen process representation, but is of no consequence in the present simulations.

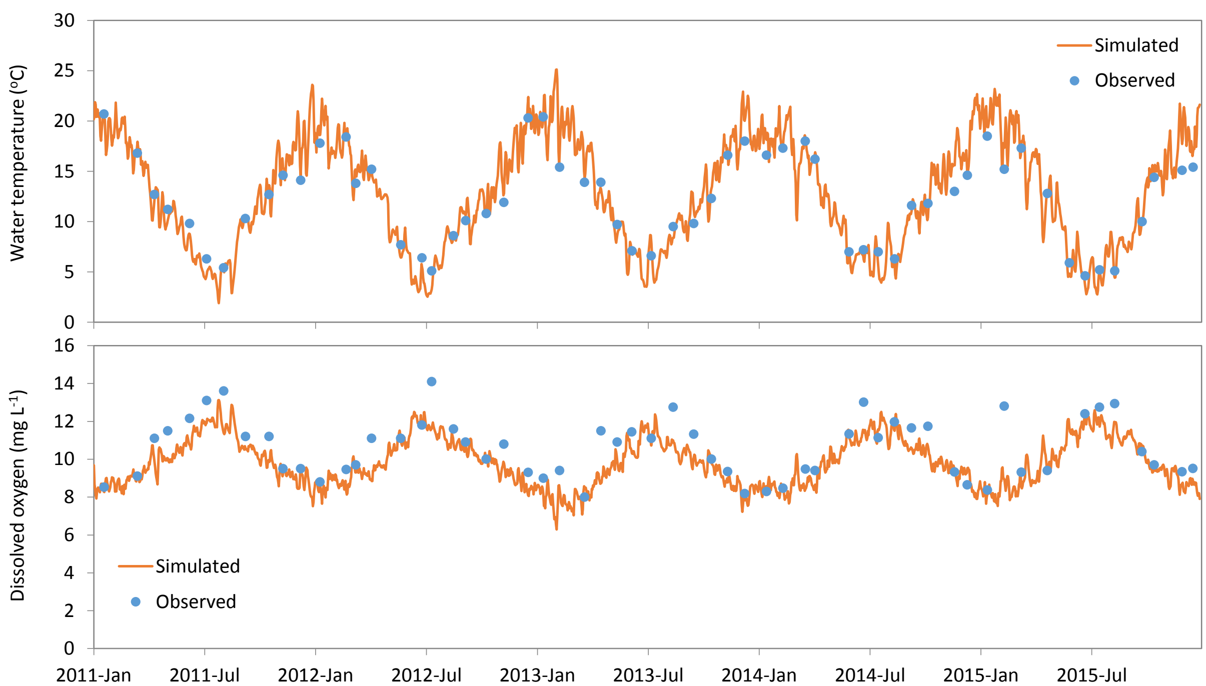

Figure 25. Simulated versus observed temperature and dissolved oxygen, Te Waihora/Lake Ellesmere, 2011 to 2015.

Figure 27 shows three nitrogen species of interest (nitrate, ammonium and total N) over the modelled period of 2011 to 2015. For each species the model simulation provides a reasonable representation of the monthly observed data at the mid-lake station. Simulated nitrate concentrations show a winter peak quite similar to those in the observed data in each of the years, particularly considering that observed data is only at monthly intervals, but the precise timing of the peaks varies from the observations. This result is considered adequate, however, considering that a large proportion of the inflow was ungauged and that assumptions were made about its composition.

Monthly ammonium-N concentrations at the mid-lake station were at or just above detection limits in most cases (see the series of values consistently at 0.01 mg L^{-1} in 2013) though the detection limit was lower from 2011 through 2012 (Figure 27). Three extremely high concentrations (> 0.14 mg N L^{-1}) were observed from late 2011 to mid 2012. These values were not picked up at all by the model. In the discussion section, we speculate on what may have caused these high values. The model gave concentrations at, or slightly below, the detection limit of 0.1 mg L^{-1} ammonium-N. We consider that the model performance in simulating observed ammonium-N concentrations is reasonable and that it may potentially be informative where observations are below detection limits.

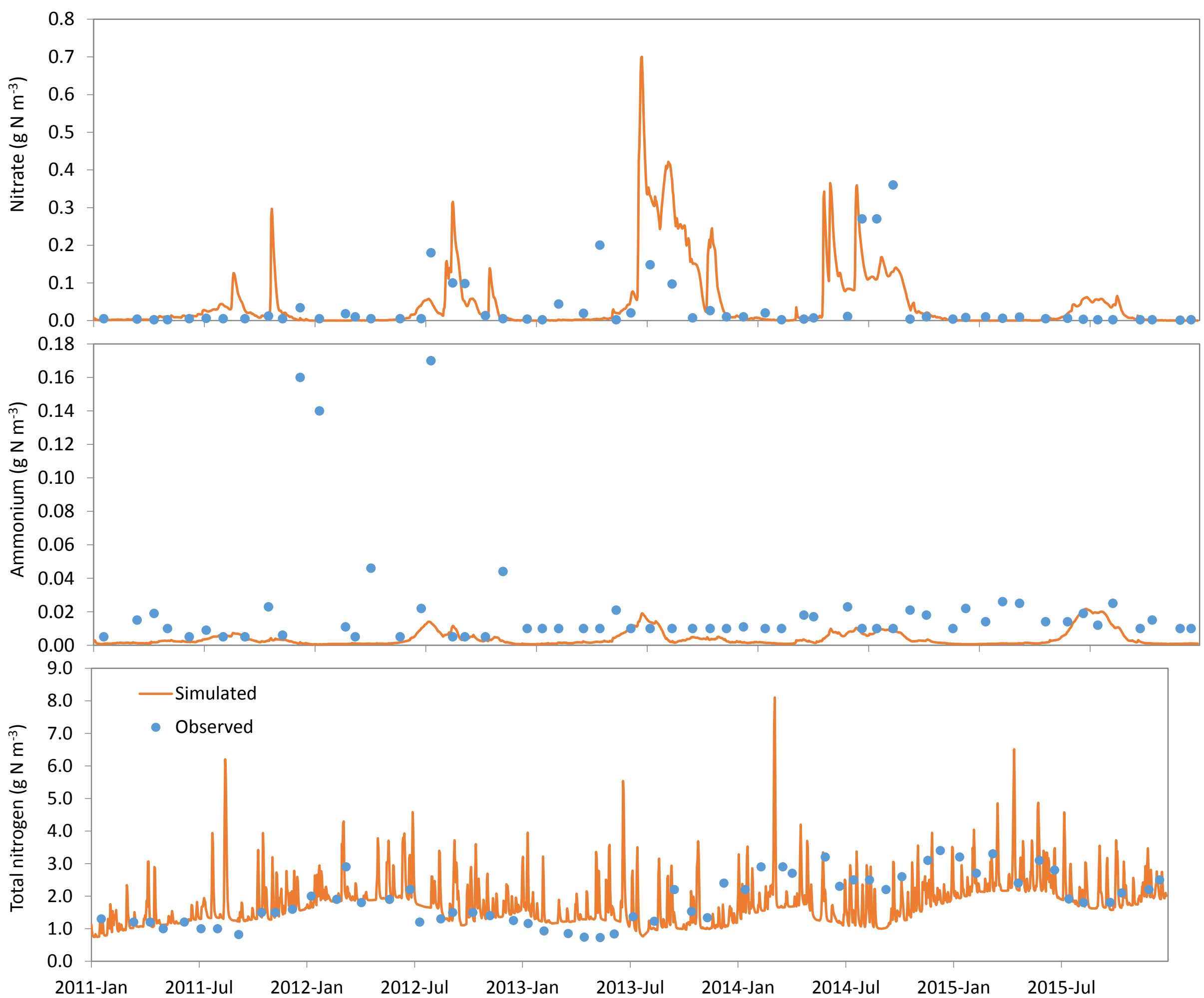

Figure 26. Simulated versus observed nitrogen (nitrate-N, ammonium-N and total N) concentrations at mid-lake station, Te Waihora/Lake Ellesmere, 2011 to 2015.

Observed concentrations of total N show an annual sinusoidal pattern of relatively high in summer and low in winter, but with considerable inter-annual variability (Figure 27). This pattern is quite different to the observed pattern of nitrate-N concentrations in the lake, which had a sharper peak which occurred in winter, not summer. The model simulations provided a reasonable representation of both the pattern and magnitude of total N concentrations but simulations tended to over-predict total N in 2013 and to under-predict from early 2014 to early 2015. The ‘spikey’ nature of the TN simulation is due to sediment resuspension of particulate N and its rapid sedimentation. Sediment resuspension occurs on a regular basis (usually at least 1-2 days each week) but varies in magnitude according to the intensity and duration of wind speed input to the model. Some of the extremely high total N concentrations simulated in the model are not evident in the measured data but it should be borne in mind that only about 3% of days are included in the regime of monthly sampling.

In the case of dissolved reactive phosphorus, because so many data points were at or below detection limits, there was little data with which to fully test and validate the model performance for this nutrient species. Detection limits were also reduced during 2013 (Figure 28). The model simulations showed occasional spikes above what were otherwise very low observed values. These spikes lasted from a few days to a few weeks, and were driven by elevated concentrations of dissolved reactive phosphorus in model tributary inputs. A greater level of confidence could be ascribed to the model simulations of total P. In this case the simulations captured a large part of seasonal and interannual variation, and also hinted that sediment resuspension at daily time scales could explain much of the residual variability once interannual and seasonal variations had been removed. There was one period in particular, when the simulations did not capture consistent changes in measured total P concentrations. In autumn 2013, total P concentrations were extremely low (< 0.03 mg L^{-1}) compared with the long-term average for the lake. Concentrations recovered relatively rapidly during winter 2013 and at this time the model again gave a good fit of concentrations of total P (Figure 28).

Simulated versus observed (mid-lake) chlorophyll *a* and TSS concentrations, as well as Secchi depth, are presented in Figure 29 for the modelling period of 2011-2015. The model performed modestly in capturing chlorophyll *a* concentrations (Figure 29). The performance in the first half of the simulation period was better than for the second half when the model failed to capture large increases in chlorophyll *a* in summer 2014-5 and more generally throughout 2015. Observed concentrations of chlorophyll *a* were extremely high in summer 2014-5 and even exceeded 200 mg m^{-3}. A more satisfactory aspect of the model performance was its ability to demonstrate a succession amongst modelled phytoplankton groups. Unfortunately this succession could not be validated with data but it fits with anecdotal information that cyanobacteria (predominantly picocyanobacteria) dominated through most of the sampling period, with smaller contributions by chlorophytes and diatoms, and the latter group being more prevalent in winter. A fourth group of marine phytoplankton was simulated in the model. This group increase briefly later in summer 2013 (Figure 30), after the peak of salinity but at a time when salinity was still strongly elevated. Despite some discrepancies between measured and simulated concentrations of chlorophyll *a*, suspended solids and Secchi disk depth were both reproduced reasonably accurately by the model. While the two variables of suspended solids and Secchi depth are influenced by phytoplankton biomass, the contribution of biomass is small. The dominant component of both of these variables in Te Waihora/Lake Ellesmere is inorganic suspended solids and therefore the model can still perform well in simulating TSS and Secchi depth whilst chlorophyll *a* (phytoplankton biomass) simulations are less representative.

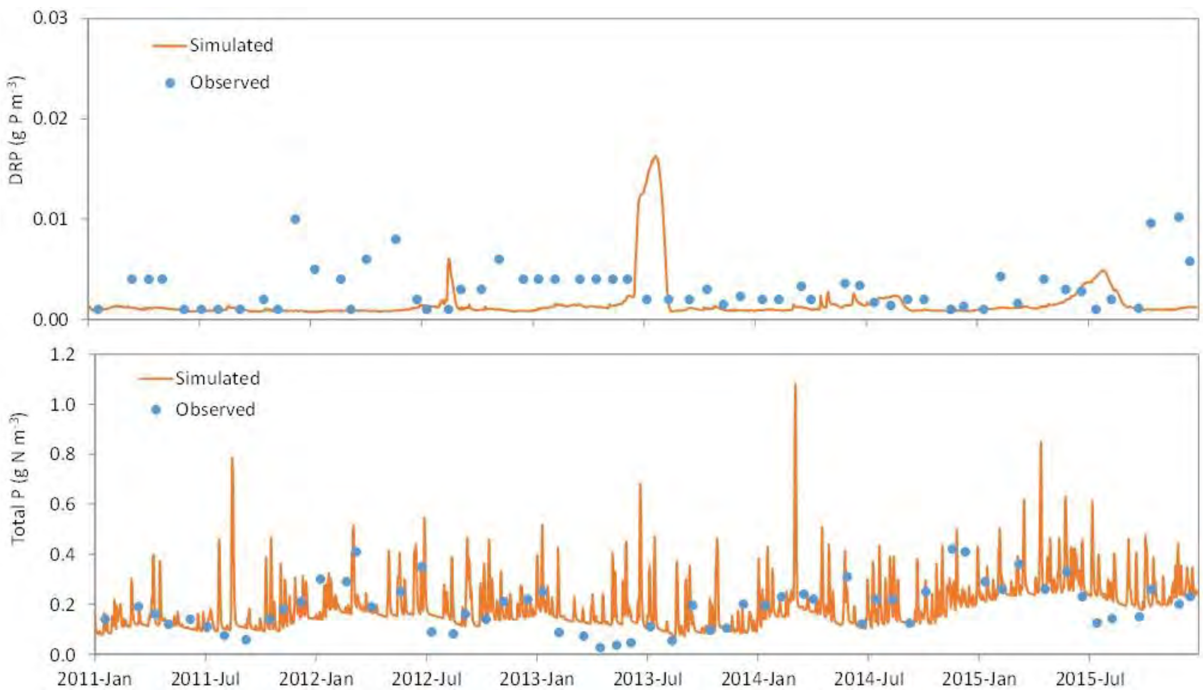

Figure 27. Simulated versus observed phosphorus concentrations, Te Waihora/Lake Ellesmere, 2011 to 2015.

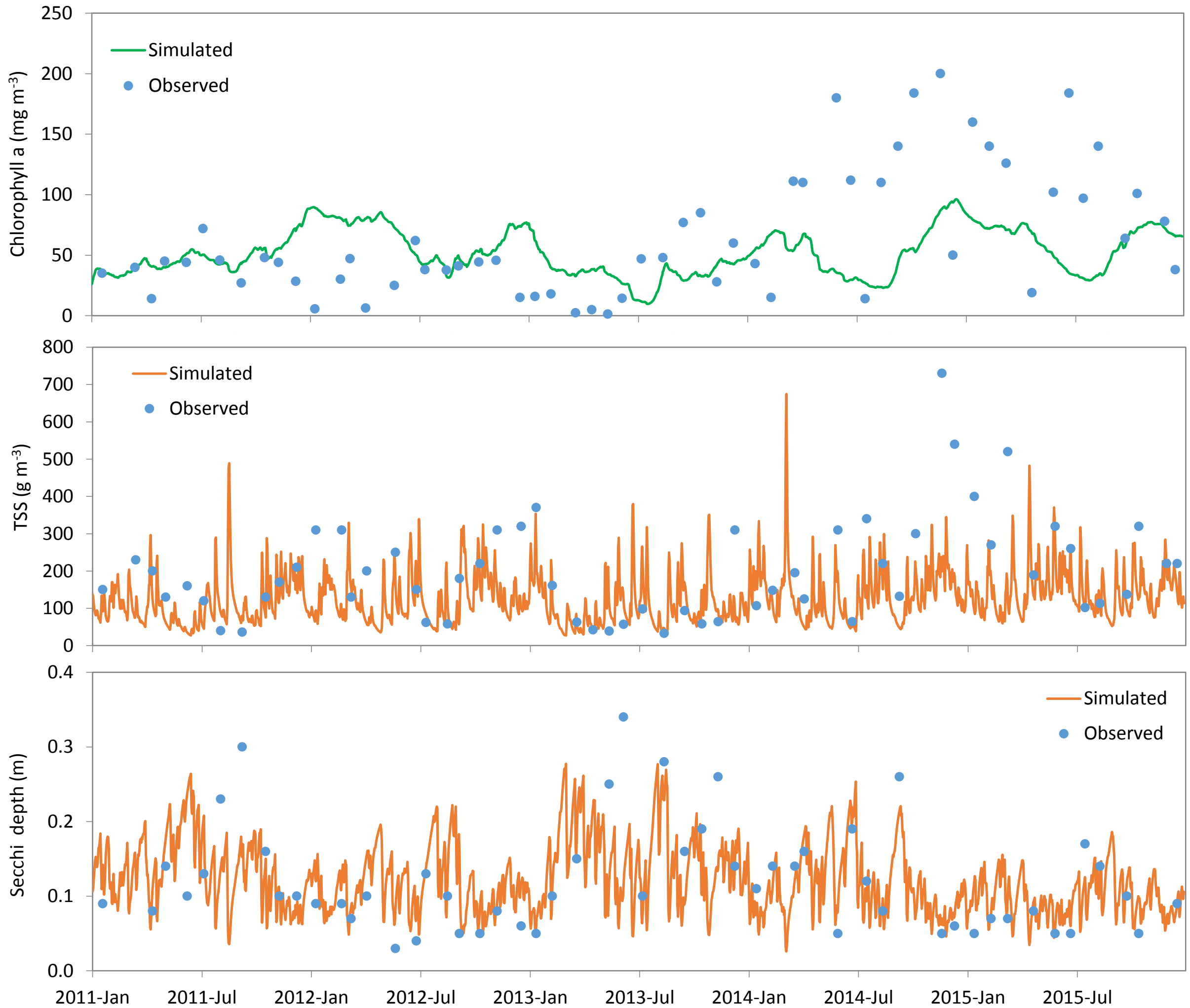

Figure 28. Simulated versus observed chlorophyll *a*, TSS and Secchi depth of Te Waihora/Lake Ellesmere, 2011 to 2015.

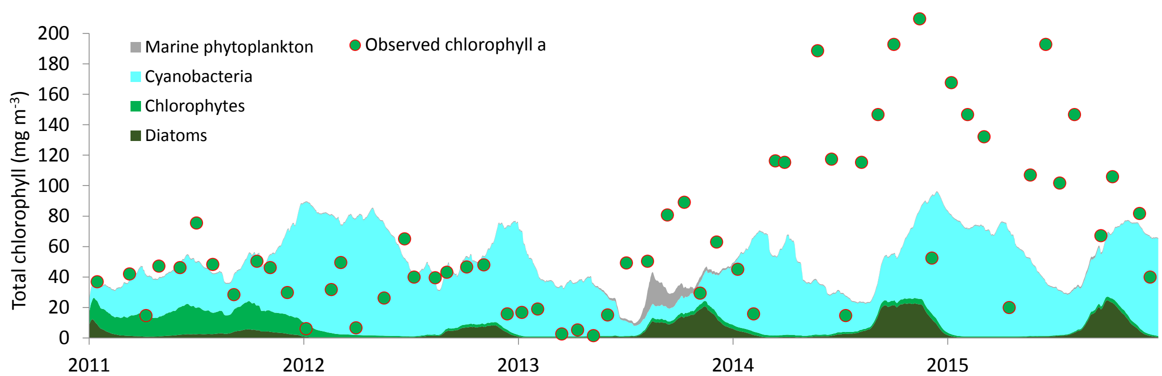

Figure 29. Observed chlorophyll *a* (dots) and simulated (coloured) phytoplankton species assemblages represented in model simulations of Te Waihora/Lake Ellesmere, 2011 to 2015

1.11. Scenario generation

1.11.1. Nutrient load scenarios

Five nutrient loading scenarios were set up, representing a reduction or increase in nitrate (NO_3-N) or total phosphorus (TP) concentrations/loads in the inflows to the lake. The projected changes in nitrate concentrations/loads were increases of 20, 40 and 60% and a decrease of 20%, as well as a 20% decrease in phosphorus concentration/load. No change was made to the inflow volumes or the load from the atmosphere. Concentrations that were simulated in this study are shown in Table 7.

Table 7. Nutrient Load Scenarios - Summary of nutrient loads (tonnes/yr) assigned to inflows represented in the Te Waihora/Lake Ellesmere 1–D model, 2011–2015.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Inflow	20% increase in NO_3-N	40% increase in NO_3-N	60% increase in NO_3-N	20% decrease in NO_3-N	20% decrease in TP
Kaituna	5.04	5.88	6.72	3.36	1.03
Selwyn	633.15	738.68	844.20	422.10	3.23
Doyleston Drain	41.26	48.14	55.01	27.51	0.33
Halswell	151.05	176.23	201.40	100.70	2.11
LII	377.36	440.25	503.14	251.57	2.18
Harts	444.36	518.42	592.48	296.24	0.53
Irwell	195.37	227.93	260.49	130.25	0.29
Hanmer	50.34	58.73	67.12	33.56	0.57
Boggy	70.40	82.13	93.86	46.93	0.10
Ocean inflow	6.98	8.15	9.31	4.66	7.33
Groundwater	7.60	8.86	10.13	5.07	0.90
Rainfall	3.72	3.72	3.72	3.72	1.12
Ungauged inflows	997.81	1164.12	1330.42	665.21	6.43
Total	**2984.4**	**3481.2**	**3978.0**	**1990.9**	**26.15**

1.11.2. Hydrological scenarios

1.11.2.1. Prediction of barrier opening duration

Modelled openings fit reasonably well with observed openings at Lake Ellesmere (Figure 30; see Methods for derivation of the basis for openings). Using the barrier opening/closing model and the water balance model, the modelled opening days differed from the actual lake openings by just five days (Table 8) during baseline conditions for the period of 2011-2015.

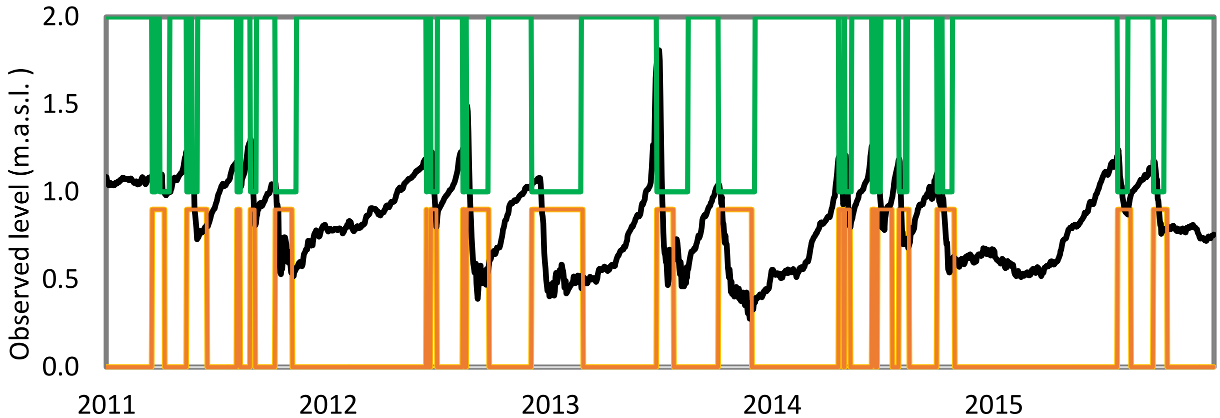

Figure 30. Observed barrier opening duration (green) and modelled opening duration (red) after calibration of the opening/closing model to match observations for Te Waihora/Lake Ellesmere, 2011 to 2015.

Table 8. Calibrated parameters for the barrier opening/closing and water exchange models for Te Waihora/Lake Ellesmere, 2011 to 2015.

Parameter	Variable	Value
Level threshold Winter	Water level (m.a.s.l.)	1.13
Level threshold Summer	Water level (m.a.s.l.)	1.05
Wave closure low level	Wave height (m)	6.5
Wave closure high level	Wave height (m)	5.5
Wind_min	Wind direction (deg)	90
Wind_max	Wind direction (deg)	270
Too rough to dig	Wave height (m)	3.6
Successful opening	Duration of excavation (days)	4
Infill	Wave height (m)	3
Days infill for closure	(days)	12
High level outflow threshold	Water level (m.a.s.l.)	0.8
High level outflow	Volume (m^3 d^{-1})	0.11 * lake area
Low level outflow	Volume (m^3 d^{-1})	1.44E+06
Low level inflow	Volume (m^3 d^{-1})	4.29E+06

1.11.2.2. Baseline simulation using hypothetical water balance model

The simulated frequency and duration of openings were also comparable to observations (Table 9, Figure 32). The model over-predicted the duration of lake opening days in some instances, particularly in mid-2011 and summer of 2014. Collectively, the opening/closing model and the water balance model used in this study captured the trends of lake openings for most of the modelling period (Figure 32) and provide a reasonable mass balance simulation for water (Figure 33) and salinity (Figure 34) in the lake.

While the lag in predicted opening days observed in 2014 did not markedly alter the modelled lake water level (Figure 33), notable however, was the model under-prediction of water levels in the lake in mid-2011 and most of 2012. Understandably, this is a result of the difference in the duration of opening modelled for these periods when compared with the actual duration of openings, indicating that less water flows into the lake as it would in reality. This notwithstanding, the model on the whole, adequately captures the trends in lake water level observable in the modelling period (2011-2015). There was also a reasonable level of agreement between predicted salinity concentrations using the model based on observed barrier opening and closing (green) versus the approach based on water level and barrier exchange predicted by the water balance model (black) (Figure 34).

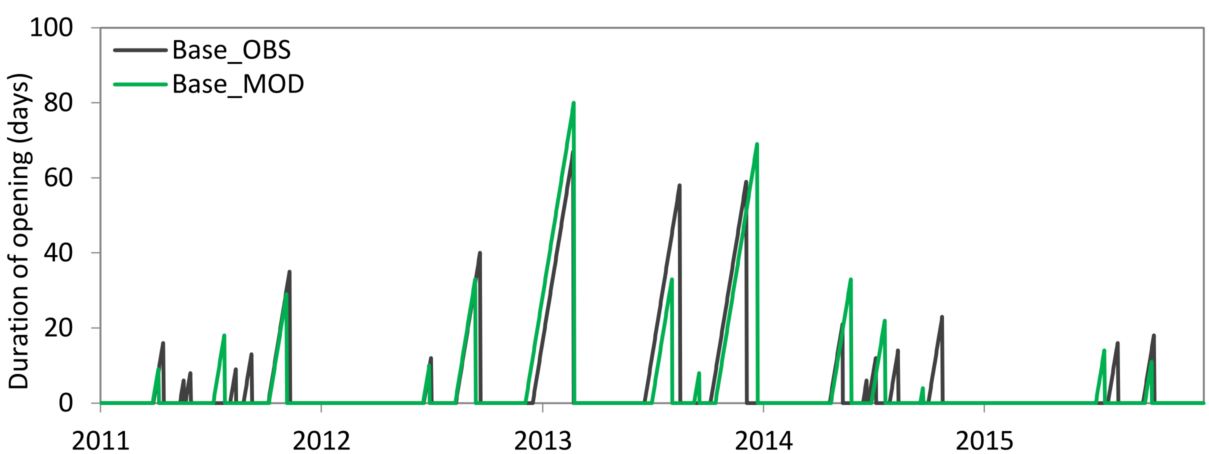

Figure 31. Opening timing and duration under the observed openings and closings (green), and water level simulated using barrier opening/closure model and water balance (black) for Te Waihora/Lake Ellesmere, 2011 to 2015.

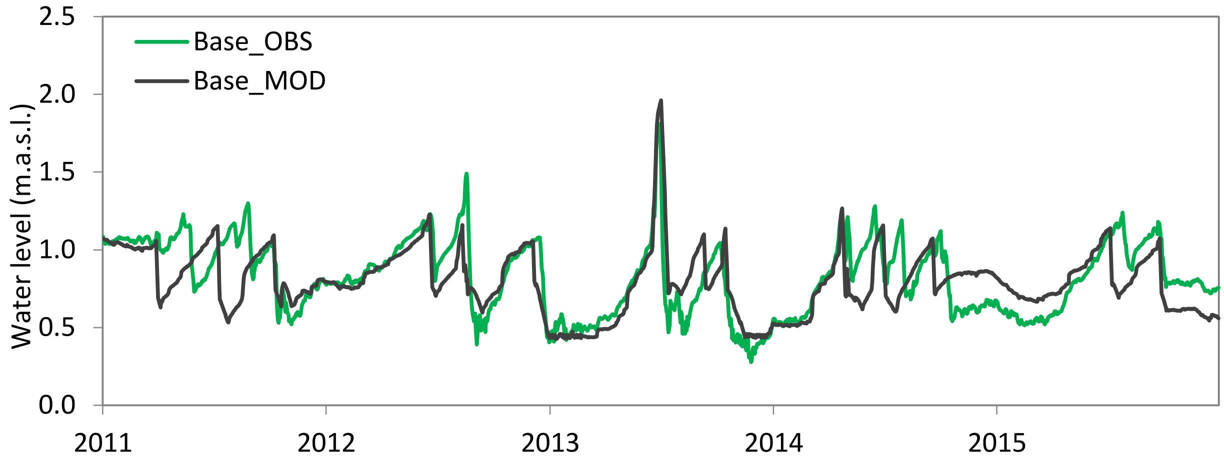

Figure 32. Comparison of water level under the observed openings and closing (green), with water level predicted using the barrier opening/closure model and water balance (black), Te Waihora/Lake Ellesmere, 2011 to 2015.

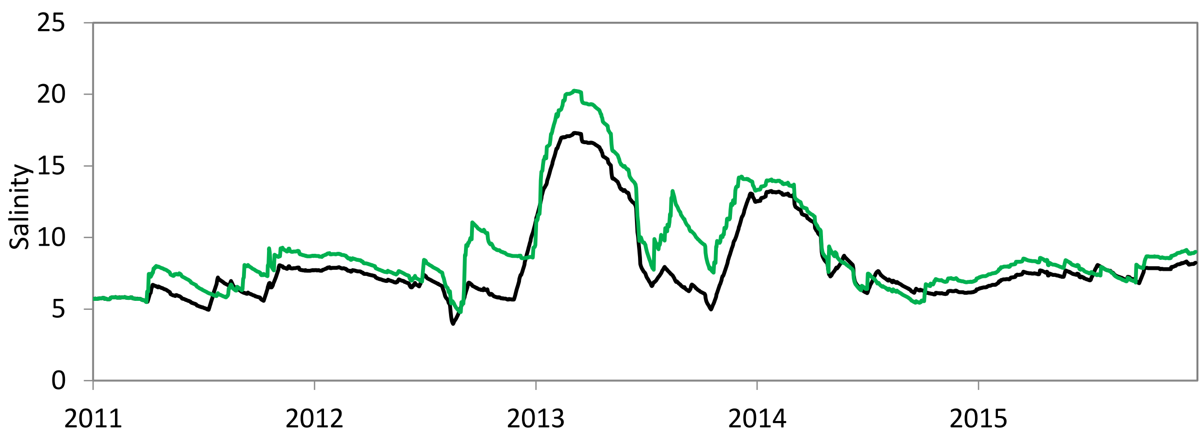

Figure 33. Comparison of salinity output of DYRESM-CAEDYM models based on observed barrier opening and closing (green), and using water level and barrier exchange predicted by the water balance model (black), Te Waihora/Lake Ellesmere, 2011 to 2015.

The current study used the barrier opening/closing and water balance models to predict lake levels under a number of management scenarios (Table 3). With the trigger limit for lake opening set at 1.4 m, the modelled lake level did not vary markedly from the observed lake level; this constituted a baseline scenario (Figure 34). This trigger level would, however, warrant the opening of the barrier only 8 times in the modelling period (2011-2015) as opposed to the current 20 times that the lake was opened. Further, a trigger level of opening at 1.4 m would reduce the number of days that the barrier should have been opened to 208, equivalent to a reduction by up to 50% of the current barrier opening days (see Table 9). When the trigger level of lake opening is set at 2 m, the barrier opening/closing and water balance models predicted that the lake should have been opened 4 times during the five-year modelling period, with a maximum single opening period not exceeding 31 days (see Table 9). With the trigger limit for lake opening set at 2 m, the modelled lake level varied markedly from the observed lake levels in baseline scenarios (Figure 35 and 36). Another scenario used in this study accounted for conditions during the pre-human era, with the barrier not opened at all, but allowing the lake level to rise continuously until the barrier breached naturally. Based on model predictions, this scenario would have led to an outflow in the wet autumn and winter months of 2014 (Figure 36).

While the modelled lake level did not vary markedly from the observed lake levels in baseline scenarios, particularly for trigger levels of 1.4 m and 2.0 m, there was the expected profound difference in modelled versus baseline water levels for pre-human and pre-European scenarios (Figure 34). In pre-European conditions, the water level threshold for barrier opening was set at 3 m. Based on model predictions, this would have produced a barrier breach that would have created a temporary outflow to the sea in winter 2013 and 2014, seen in the sharp decline in water levels in this season, with the potential for further barrier breaches in later years (post 2015) given the generally increasing trend of water lake level over the modelling period (see Figure 36).

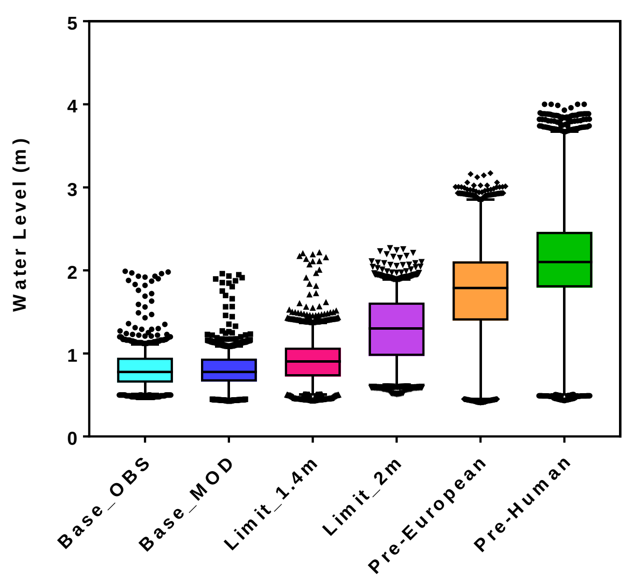

Figure 34. Variability and distribution characteristics of simulated lake water levels under scenarios of different water level thresholds, Te Waihora/Lake Ellesmere, 2011 to 2015.

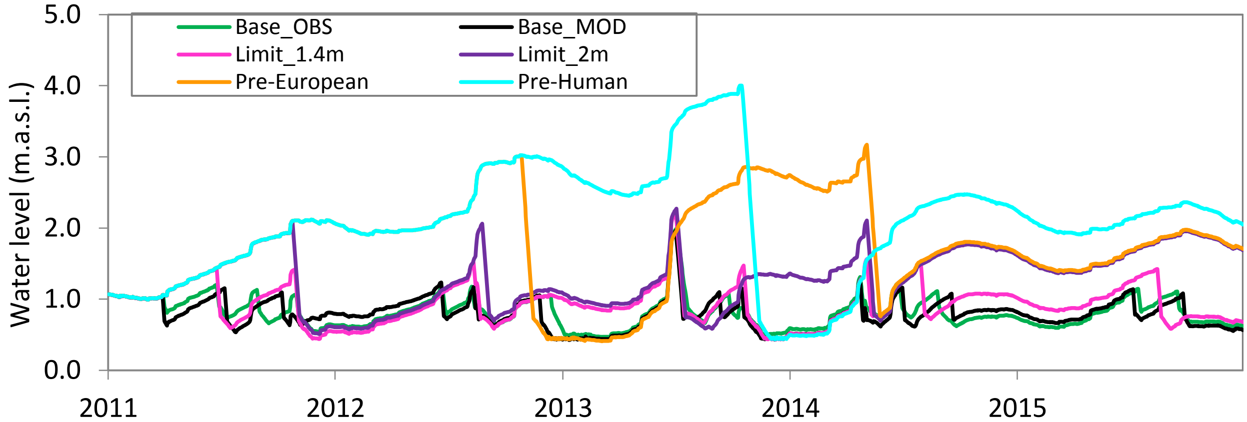

Figure 35. Simulated water level under scenarios of different water level thresholds, Te Waihora/Lake Ellesmere, 2011 to 2015.

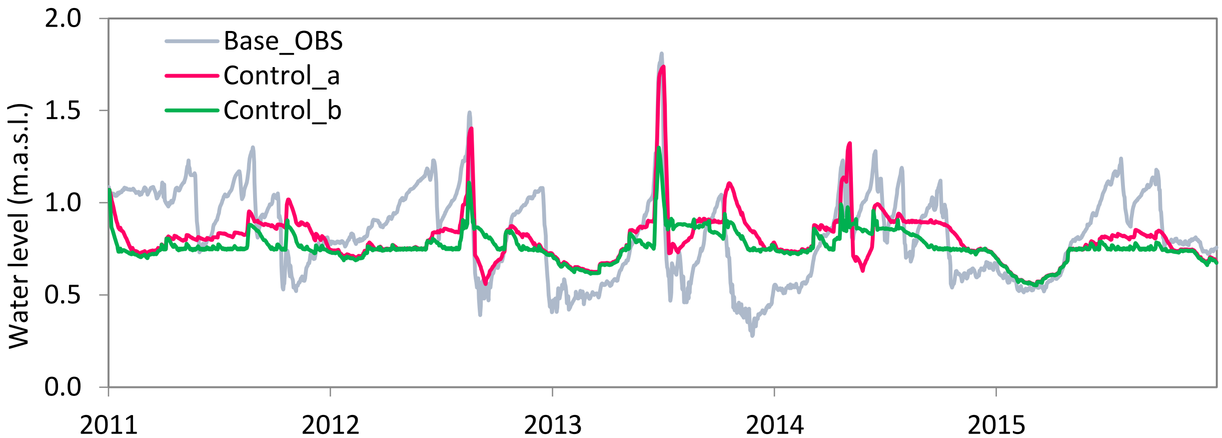

Figure 36. Simulated water level with and without control structure and under varying control structure flow capacities (Control_a and Control_b scenarios), Te Waihora/Lake Ellesmere, 2011 to 2015.

Two additional scenarios were modelled using the barrier opening/closing and water balance models, to represent continuously open, 'choked' outflows with constant discharge rates (and additional to any periodic barrier openings, which would be required only when the choked outlet was not sufficient to prevent water level rise to above the baseline scenario water level trigger thresholds). In Control_a, a controlled mean outflow of either 12 $m^3 s^{-1}$ was applied when the lake level was between 0.75 and 0.9 m, and 50 $m^3 s^{-1}$ for lake levels exceeding 0.9 m. For Control_b, a controlled mean outflow of 20 $m^3 s^{-1}$ was applied when the lake level was between 0.75 and 0.9 m and 150 $m^3 s^{-1}$ was applied when lake level exceeded 0.9 m. For both scenarios no water was withdrawn via the outflow if water level was less than 0.75 m. Based on model predictions, the controlled outflow would have warranted the need for lake opening only once during the five-year simulation period (Table 9). The controlled outflow prevented situations where water level would decline rapidly, as is usually observed under current opening regimes (see Figure 37). As a consequence this controlled outflow leads to fewer occurrences of lake opening and marine water intrusion. It should be noted that these scenarios are not representative of actual engineered designs (e.g., the control structure presented in Gibbs and Norton (2014)), rather they are intended for indicative testing of the revised lake model to assess hydrological modifications.

Table 9. Summary of modelled barrier opening characteristics under different opening management scenarios, Te Waihora/Lake Ellesmere, 2011 to 2015.

Scenario	Days open	n openings	Longest opening
Observed	433	18	67
1.05 m (1.13 m)	373	14	80
1.4	253	8	66
2.0	131	4	57
3.0	110	2	88
4.0	72	1	72
Control_A	47	2	24
Control_B	0	0	0

1.12. Calibration summary

Figure 38 shows component TLI variables for observed data and DYRESM-CAEDYM model simulations. Modelled TLI variables were derived either from the calibrated DYRESM-CAEDYM model using a water balance based on observed opening, closing and barrier exchange or from the barrier and water balance models. Regardless of the approach adopted, the target for the calibration was to obtain TLI values within a ± 0.1 range of the observed values. Figure 38 indicates a satisfactory outcome with only minor disparities between observed and simulated TLI values during baseline conditions. As part of the model updates, we developed an algorithm for estimating Secchi depth from model outputs. As such, here we present four-parameter TLI (after Burns 1999). It should be noted however, that the Regional Plan objectives use TLI3 (which is similar but slightly lower due to the very low transparency in Te Waihora).

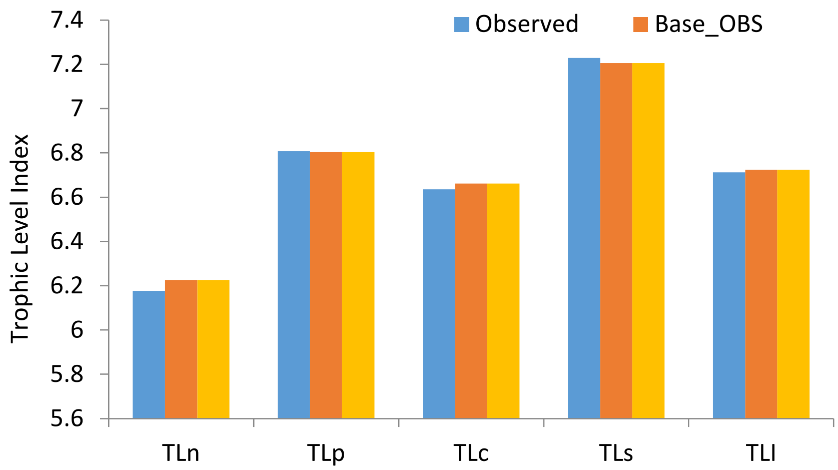

Figure 37. Component TLI variables for observed data and DYRESM-CAEDYM model simulations for Te Waihora/Lake Ellesmere, 2011 to 2015, using a water balance based on observed opening, closing and barrier exchange (Base_OBS) and barrier and water balance models.

1.13. Scenario results

1.13.1. Nutrient load and hydrological scenarios

Changes in lake opening trigger levels generally produced larger variations in simulated TLI than altered nutrient loading scenarios (Figure 39). Increases in nitrate loads of 20%, 40% and 60% had little or only modest effects on TLI constituent values of phosphorus (TLp), chlorophyll *a* (TLc) and Secchi depth (TLs). Counter-intuitively, the 20% increase in nitrate loading gave an aggregated TLI value that decreased marginally compared with the baseline simulation value (Figure 40). The simulation using a 40% increase in nitrate loading, however, was predicted to lead to a moderate increase (c. 0.2) in TLn, which was the primary factor leading to an increase in the TLI for this scenario. The result of the 60% increase in nitrate load was very similar to that for the 40% increase. For the 40% and 60% increases in nitrate load, TLc and TLp were marginally greater than in the baseline simulation but TLs was little changed. A reduction by 20% in nitrate loads produced lower simulated TLn and TLc than the respective observed and baseline values (Figure 29). The outcome for this case was a TLI value that was nearly 0.1 units lower than values for the observed case and the baseline simulation. A 20% increase in total phosphorus load produced little change in any of the constituents of TLI with the possible exception of TLc, which decreased by c. 0.1 units. As a consequence there was very little change in the aggregated TLI value (Figure 40).

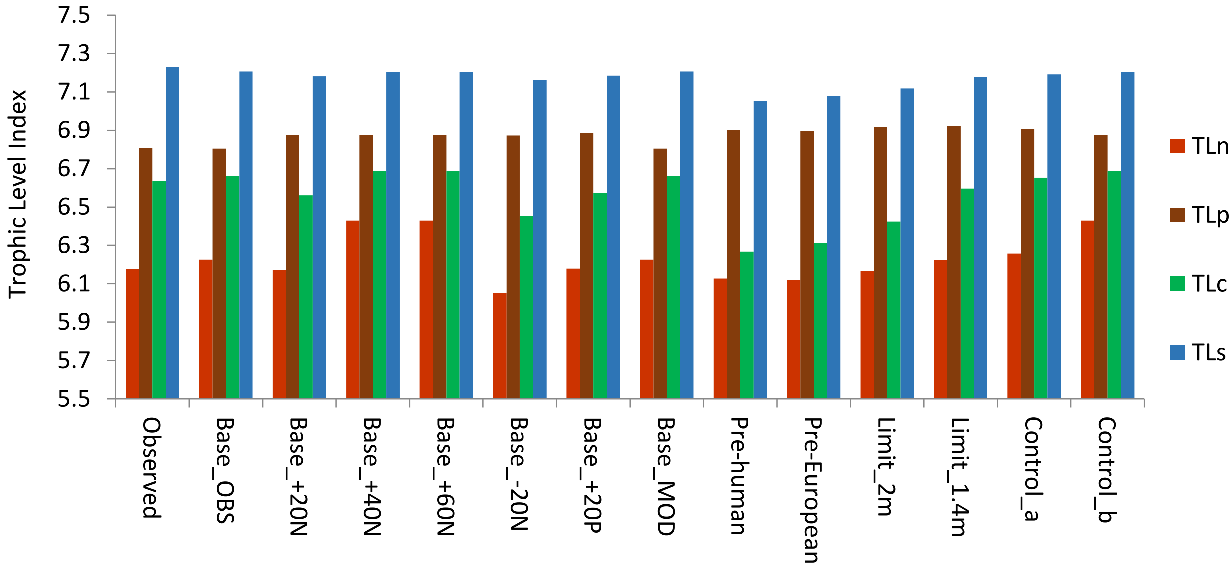

Figure 38. Comparison of TLI variables among all scenarios, Te Waihora/Lake Ellesmere, 2011 to 2015.

TLI values were also simulated during conditions when the trigger limit for the lake opening was set at varying depths (1.4 m, 2.0 m, pre-European (3 m) and pre-human (4 m), as well as the controlled openings described in Section 2.4.2 and in Table 9). The baseline for this case (Base_OBS), using modelled barrier opening and closing, accurately replicated the observed TLI constituent values (Figure 39) and the aggregated TLI values (Figure 40) and was used as a basis to compare the different opening and closing scenarios. A reduction of TLn, TLc and TLs (by c. 0.1 for each constituent) was simulated for the scenario of pre-human (4 m opening) and pre-European conditions but TLp increased by around 0.1 units; the net result being a decrease in TLI of c. 0.12 units. A low trigger limit water level of 2 m produced a TLI value that was intermediate between the pre-human/pre-European scenarios and the baseline simulation, while the trigger of water level of 1.4 m produced very little change at all from the baseline and observed cases. Interestingly, the control-a and control-b cases actually increased most TLI constituents and the aggregated TLI itself although the control_a scenario (12 $m^3\ s^{-1}$ for lake level 0.75 - 0.9 m and 50 $m^3\ s^{-1}$ for lake level > 0.9 m) showed changes that were likely within the bounds of error of the baseline simulation. The control_b scenario (20 $m^3\ s^{-1}$ for lake level 0.75-0.9 m and 150 $m^3\ s^{-1}$ for lake level > 0.9 m) increased the TLI value by nearly 0.1 units. Both of these scenarios produced strong damping of water levels (Figure 37) compared with the other scenarios (Figure 36).

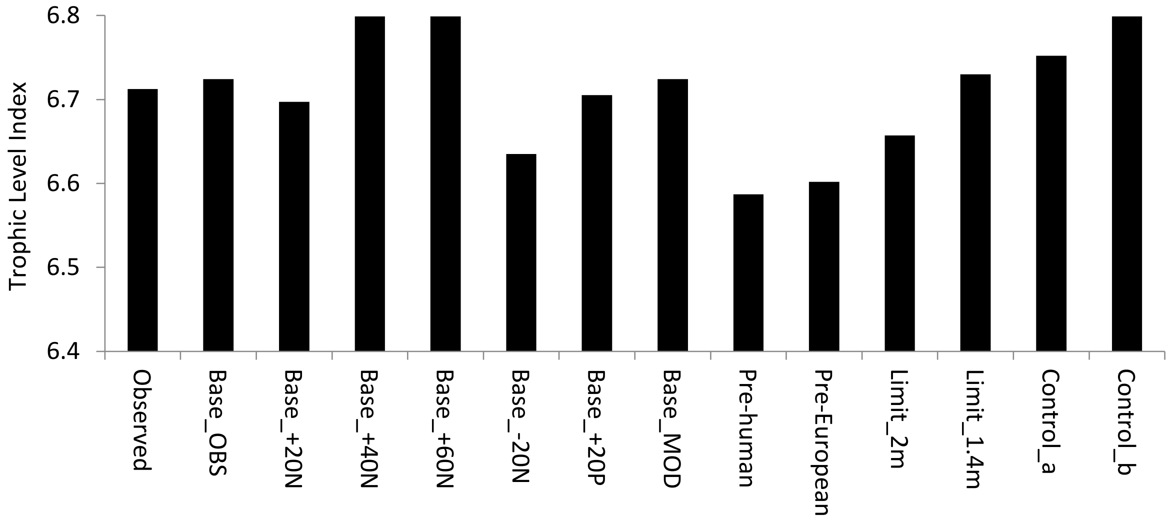

Figure 39. Summary of TLI4 results among all scenarios, Te Waihora/Lake Ellesmere, 2011 to 2015.

DISCUSSION

In this study an important advance on previous modelling work was an accurate mass balance for both water and salinity. Achieving this balance involved several assumptions which potentially point to knowledge gaps in boundary conditions used in the model. One of these assumptions relates to the increased volume of ungauged inflows compared with what has been used previously. Extended closing events were important in derivation of the total tributary inflows because of the simplification of not having the barrier open and therefore only needing to account for freshwater inflows, rainfall, evaporation and barrier seepage. For example, tributary discharges to the lake were estimated to be >2 $m^3 s^{-1}$ larger in the present study than those given in Horrell (1992), although the latter study had slightly lower rainfall (equivalent to 3.30 $m^3 s^{-1}$ vs 3.93 $m^3 s^{-1}$ on the lake itself). The nine major inflows are estimated to account for approximately 85% of the area of the catchment of the lake, yet in the water balance calculations contribute only around 60-70% of the discharge during periods of barrier closure. This difference between the hydrologically contributing land area and tributary inflows could be due to groundwater inputs direct to the lake, gauging inaccuracies, additional inflows below tributary gaugings, inaccurate bathymetry or errors in the water balance itself. These results point to a need to carry out additional hydrological studies in the catchment, particularly with changes in irrigation, groundwater levels and long-term rainfall. They also point to the need to update the bathymetry of the lake as sediment infill and re-working in recent decades may have reduced storage capacity of the basin. Some information about changes in the littoral and the varial zone of the lake to support the bathymetry analysis may be able to be obtained from time series of remote sensing (e.g., Landsat) images under different measured water levels.

Groundwater inflows were assumed to be negligibly different between the present study and that by Horrell (1992); 0.40 $m^3 s^{-1}$ in Horrell (1992) and 0.45 $m^3 s^{-1}$ in the present study. Additionally, barrier openings were calculated to discharge 3.75 $m^3 s^{-1}$ of marine water to the lake in the present study (vs. 2.60 $m^3 s^{-1}$ in Horrell (1992)), and barrier seepage from the lake was 1.15 $m^3 s^{-1}$ (vs. 1.20 $m^3 s^{-1}$ in Horrell (1992)). In order to match both salinity and water volumes in the lake, it was necessary to set the discharge from lake opening events to be 3.75 $m^3 s^{-1}$ (cf. 2.60 $m^3 s^{-1}$ in Horrell (1992)). The large difference in barrier outflows between the present study (17.9 $m^3 s^{-1}$) and Horrell (1992) (11.5 $m^3 s^{-1}$) was mostly due to a combination of larger tributary inflows and more water exported from the lake during opening events. It may also have been connected to longer openings which resulted in large marine intrusions into the lake. These intrusions and the resulting elevated levels of salinity in the lake enabled an increased degree of confidence in the salinity balance.

The barrier closure model was a useful way of developing criteria to predict opening and closing under a variety of water level thresholds, thus enabling a number of scenarios to be run using different water levels. The criteria for barrier opening and closing were based on Horrell (1992, 2009), but with the benefit of improved monitoring over recent years (i.e., ECAN's wave buoy). The optimisation process for parameters in the model provided a highly satisfactory outcome in terms of reproducing the dynamics of barrier opening and closing. In terms of refining the water balance, little recent work has focused on evaporation and this could represent another source of error for the water balance calculation.

Given the absence of a permanent outlet for Lake Ellesmere, it has been estimated that without human intervention the lake level would rise as high as 4 m a.s.l. and extend to an area of approximately 38,900 ha before breaching naturally and creating a temporary outflow to the sea (Samad, 2007; Horrell, 2011a,b). The current opening regime, as constrained by the Water Conservation Order (Section 1.5), has been set to reduce flooding of low-lying land around the lake while maintaining the quality of the lake environment for critical ecosystem services (WET, 2009). However, based on model simulations, there appears to be some opportunity to improve water quality by adopting an opening regime that maintains higher water levels. This is particularly evident in the pre-European scenario which had a water level threshold for barrier opening set to 3 m a.s.l. and a simulated decrease in TLI of 0.12 units. Neither of the hypothetical outflow control structures appeared likely to have a beneficial effect on the TLI. The control_a scenario of continuous outflow of 12 $m^3 s^{-1}$ for lake level between 0.75 and 0.9 m, and 50 $m^3 s^{-1}$ for lake level >0.9 m, had two breaches of the barrier, of total duration 24 days for the period 2011-2015.

Interestingly, water level changes (at least the pre-human and pre-European cases) had a larger impact on simulated TLI values in the lake than the assigned changes in nutrient loads. At first this might seem surprising, but it reflects to a large extent the enormous internal bottom-sediment fluxes of nutrients within the lake that are an important driver of concentrations within the water column. It is also worth pointing out some of the simplifications of the model. While the model could reasonably capture the internal nutrient fluxes (e.g., associated with sediment resuspension) for a few years when used in forecasting mode, this may not necessarily apply to extended periods (e.g., decades). In such cases, if external nutrient loads were to be consistently increased or decreased, the model currently does not have the capacity to simulate these effects as enrichment or decrease of nutrients, respectively, in the bottom sediments. In these circumstances the simulation results should not be regarded as a long-term, or equilibrium response to changes in nutrient loads. A similar logic could be applied to suspended sediment. Whilst there are high loads of suspended sediment entering the lake from tributaries, these sediments may be re-suspended during subsequent storm events, producing prolonged effects on the lake ecology (Burton and Pitt, 2002; Rossi et al., 2003). The pre-European and pre-human water level scenarios adopted catchment and internal (bottom-sediment) nutrient loads indicative of present-day conditions (i.e., representing a transition from present-day conditions to the new water level regime). The interpretation of these scenarios as 'pre-European' and 'pre-human' therefore refers specifically to the water level regimes and not to the nutrient regimes of these eras, as sediment and nutrient loads were likely to have been substantially smaller during these two eras.

This process–based modelling enables the simulation of a wide range of water quality variables at high temporal resolution and assists exploration to build more detailed understanding of major processes in the lake. Process based models typically offer greater confidence in the outcome of simulated scenarios that differ from current conditions, compared to the use of empirical (i.e., statistical) relationships which are generally invalid outside the bounds of the data used for model derivation (Abell et al., 2015). The process based models enable implicit links of stratification, dissolved oxygen, nutrients and biological response in terms of changes in phytoplankton chlorophyll *a* and major taxa. The observed stratification dynamics of Te Waihora/Lake Ellesmere can also now be examined in detail using buoy data to resolve sub-daily (15-minute) changes. The buoy data show occasional periods (a few hours) of thermal stratification that lead to rapid depletion of dissolved oxygen in bottom waters (Schallenberg and Cranshaw 2016). These dynamics are generally not captured in the DYRESM-CAEDYM model, which produces simulation output at daily frequency. While this model is well adapted to capture thermodynamics and the stratification regime of shallow lakes, the simulations with large increases in water level (e.g., the pre-European and pre-human cases) should nevertheless be viewed with some caution, and the model may not capture short-term stratification dynamics (notable those at sub-daily time scale). The importance of this relates to the potential for greater duration and extent of anoxia in water overlying the bottom sediments of the lake with higher water levels, in turn leading to increased rates of release of dissolved nutrients from the lake bed in the presence of anoxia. Because the lakebed nutrients are now strongly enriched (i.e., as a result of catchment development) the magnitude of the releases would be substantially higher than for the natural case. This point again emphasises that the pre-European and pre-human conditions pertain to water level regimes of an earlier era but to present-day nutrient and sediment pools in the lake.

The greatest departure between observed and model-simulated values occurred during or in the period following the major seawater intrusion into the lake in 2013. During the period of maximum salinity the model simulations overestimated concentrations of suspended solids, total N, total P and chlorophyll *a*, and underestimated Secchi depth. We hypothesise that the saline intrusion not only resulted in increased flushing of the lake (an effect we consider would have been captured by the model simulations) but also produced high levels of flocculation that reduced suspended solids and particulate nutrients directly, and indirectly led to greater nutrient limitation for phytoplankton, as well as conditions suitable for marine or brackish-water phytoplankton (as shown by the increase in the simulated estuarine/marine group at this time). Following this 'oligotrophication event' associated with the marine intrusion was some sort of rebound event (years 2014-15), which again was not captured well by the model simulations. The inability of the model to capture this change indicates that it was likely not driven by inflow- or weather-related changes (i.e., neither inflows nor weather were particularly distinct from previous years), leaving us to surmise that it may have been internally driven. Schallenberg and Cranshaw (2016) noted a major die-back of sediment infauna following the saline intrusion. These infauna perform important ecosystem-scale functions of aeration and processing and re-working of material in the sediments. We hypothesise that the elevated levels of total N and total P following the saline intrusion were internally driven and may have been related to the loss of infauna and their nutrient processing capabilities. Ultimately, this was reflected in exceptionally high levels of chlorophyll *a* (> 200 mg m^{-3}), which occurred in 2014.

Models are necessarily simplifications of reality and this may be recognised where there are periods of greatest discrepancy between simulation output and observations; specifically, in the case of Te Waihora/Lake Ellesmere, during and following the major saline intrusion of 2013. The lack of representation of flocculation and benthic infauna appears to have constrained model performance in terms of nutrients and chlorophyll predictions during and following the saline intrusion. This finding points to the potential importance of the saline intrusion to the ecological dynamics of the lake. Prolonged saline inundation will potentially lead to major improvements in water clarity and lower levels of nutrients and chlorophyll. Subsequent return to brackish or freshwater conditions may be problematic with the loss of benthic freshwater infauna from salinity stress (and the loss of their nutrient processing capacity), as well as substantial changes to any plant communities in the lake. While food web components such as fish were not included implicitly in the model, the combination of the barrier opening/closing model with DYRESM-CAEDYM allows for predictions of duration and timing of openings that may inform management decisions relating to migratory species (e.g., eels).

Sediment resuspension is a key process in the sediment, nutrient and ecological dynamics of Lake Ellesmere/Te Waihora. In this regard the 1-D DYRESM-CAEDYM model performed remarkably well in simulating concentrations of suspended solids, using two selected size classes for the sediment and without a directional component of the wind. By definition this 1-D model is representative of mid-lake conditions. A 3-D model combined with validation using remote sensing data could complement this approach and allow for assessments of the spatial variation of suspended sediment due to sediment resuspension in Te Waihora/Lake Ellesmere. This approach has been adopted by Allan (2015) and may be useful to complement output from the 1-D model as well as allowing consideration of locations for macrophyte re-establishment opportunities in the lake.

We have described the application of a range of hypothetical scenarios, used as a 'stress test' for the upgraded and improved lake model. These scenarios are not representative of specific management initiatives, or of real-world engineering designs targeted at lake restoration (for example, the control structure design presented in Gibbs and Norton 2014, and shown in Figure 40.

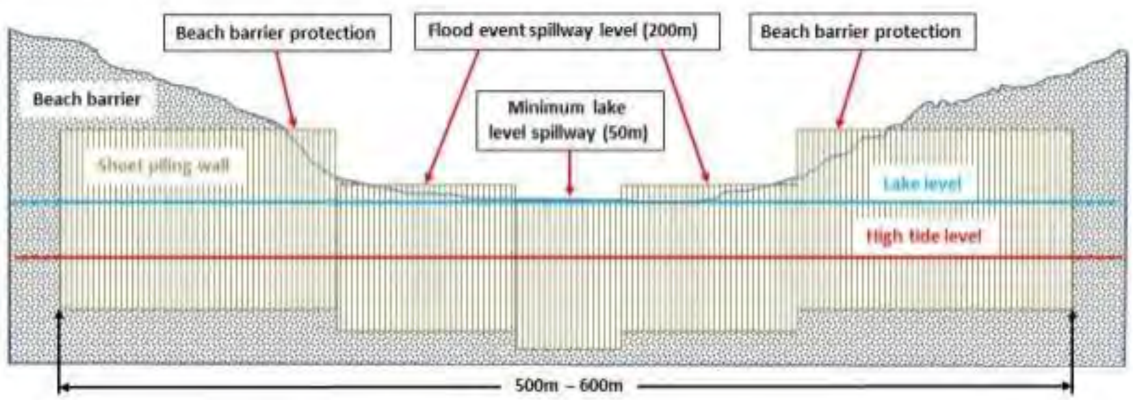

Figure 4-3: Schematic of lake level control wall. The width dimensions are indications only. The sheet piling may be much greater in some areas than others. Note that the elevation of the top of the sheet pilings can be adjusted up or down as required using the vibrating installation driver. Alternatively, a mechanically adjusted gate could be included to allow the minimum lake level to fall below high tide level on occasion to raise the salinity in the lake – see text. (Not to scale).

Figure 40. Diagram of lake outfall control structure conceptualised by Gibbs and Norton (2013), allowing for two-stage control of overflow from Ellesmere. Figure reproduced from Gibbs and Norton (2013).

CONCLUSIONS

The model application presented in this study has been developed using a comprehensive set of input data relating to the hydrological, meteorological and morphological aspects of Te Waihora/Lake Ellesmere. The model has then been calibrated with a small number of parameters that adjust the mixing dynamics of the model, and a larger number of parameters that influence the biogeochemical processes for multiple state variables (e.g., dissolved oxygen, five nutrient species, four representative phytoplankton taxa and two size classes of suspended sediments). The model accurately simulated the aggregated Trophic Level Index (TLI) and the four constituents of the TLI. As a result of inability to capture some of the dynamics associated with a sustained marine intrusion into the lake, and consideration of processes not represented in the model, this study has pointed to the potential ecological implications of the marine intrusion. These relate to flocculation and improvements in water clarity during marine inundation, followed by high nutrient concentrations that may be associated with reduced benthic processing from loss of freshwater benthic fauna due to salinity stress. The loss of benthic nutrient processing emphasises the importance of internal nutrient dynamics to the trophic status of the lagoon. It also indicates that sustained reductions in catchment nutrient loads will be required to ultimately reduce the pool of nutrients in the bottom sediments and reduce the current highly eutrophic state of the lake.

Technological advances can be expected to better inform the modelling process. Applications of three-dimensional models have become increasingly routine and are valuable where there is emphasis on variation across a lake, but due to prolonged run times they have limited scope for multi-year simulations. Remote monitoring sensors, which may be operated in situ, aerially or via satellite, have all been operated in some capacity in Te Waihora/Lake Ellesmere, and can provide rigorous data with which to calibrate models of the lake and increase confidence in model simulations.

The model scenarios presented in this report (relating to catchment nutrient loads and water level manipulations) are intended to be a forerunner to more detailed discussion and consultation with iwi and the community on additional scenarios to simulate with the model. Feedback on presentation methods, new scenarios for consideration using model simulations (e.g., barrier opening times) and refinements of existing scenarios (nutrient loads and water levels) will assist with a deeper understanding of the outcomes of different management regimes. This approach can be valuable when also informed by matauranga and oral histories, expert knowledge and observed data.

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APPENDIX

Appendix A. Summary statistics of meteorological data for the 2011-2015 simulation period

Statistics	Sol. rad.	Air temp.	Atm. Press.	Wind sp.	wind dir.	Rel. Hum.	Rain (m)
Minimum	0	-1.4	5	1.3	14	39	0
25% Percentile	76	8.4	8.9	4.8	166	73	0
Median	139	12	11	6.3	199	81	0
75% Percentile	240	15	13	8.3	238	87	0.0004
Maximum	408	28	24	24	342	100	0.065
5% Percentile	33	4.5	6.9	2.9	106	58	0
95% Percentile	355	19	16	12	302	95	0.0099
Mean	163	12	11	6.8	202	79	0.0016
Std. Deviation	103	4.4	2.8	2.8	58	11	0.0052

Sol. Rad = solar radiation (W/m2), Air temp. = air temperature (^{o}C), Atm. Press. = Atmospheric Pressure (hPa), wind sp.= wind speed (m/s), rain = total daily rainfall (m), wind dir. = wind direction (deg), Rel. Hum. = Relative Humidity (%)

Appendix B. ECAN Water quality data, Lake Ellesmere Inflows (raw, 2011-2015)

B 1. Kaituna River water quality data (raw) (2011-2015)

Date	Mean Daily River flow (m3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11	0.103	19	8	7.9	1.7	0.017	0.007	0.005	0.08	0.042
15/03/11	0.102			7.8	3	0.027	0.01	0.008	0.25	0.049
12/04/11	0.187	12.7	11.1	7.8	3	0.022	0.01	0.017	0.19	0.028
04/05/11	0.226	12	10.3	7.7	3	0.32	0.01	0.02	0.22	0.029
09/06/11	0.109	10.1	10.1	8	5.4	0.013	0.027	0.028	0.08	0.046
07/07/11	0.446	6.9	11.9	7.7	3.3	0.013	0.03	0.12	0.23	0.026
04/08/11	0.34	5.5	13.6	7.7	3.5	0.012	0.013	0.092	0.28	0.023
08/09/11	0.251	8.2	12	7.9	3.3	0.014	0.016	0.092	0.2	0.022
18/10/11	0.31	10.5	11.1	7.9	2.4	0.011	0.018	0.048	0.08	0.028
09/11/11	0.24	14.6	8.3	7.8	1.3	0.014	0.022	0.11	0.24	0.041
08/12/11	0.825	10	10.7	7.7	5.3	0.018	0.024	0.09	0.17	0.047
10/01/12	0.142	17.9	10.9	7.8	1.4	0.021	0.009	0.021	0.08	0.038
22/02/12	0.077	17.3	9.7	8	1.9	0.018	0.008	0.019	0.08	0.048
08/03/12	0.267	12.7	11.4	7.9	3.2	0.016	0.017	0.014	0.08	0.032
04/04/12	0.144	12.4	10.5	7.9	4.9	0.024	0.017	0.011	0.11	0.055
22/05/12	0.132	8.1	11.9	7.5	1.8	0.027	0.009	0.025	0.08	0.037
26/06/12	0.651	6.3	12.3	7.7	3	0.013	0.011	0.1	0.29	0.059
12/07/12	0.265	5.8	12.9	7.8	1.8	0.01	0.008	0.079	0.32	0.015
16/08/12	5.271	9.9	10.9	7.5	19	0.022	0.009	0.42	0.56	0.27
06/09/12	0.362	11.2	10.6	7.8	4.8	0.018	0.023	0.22	0.31	0.027
10/10/12	0.189	11.4	11.5	7.9	2	0.021	0.009	0.074	0.09	0.026
14/11/12	0.495	10.5	11.2	7.8	3.4	0.018	0.008	0.065	0.21	0.031
06/12/12	0.185	16.3			4	0.018	0.01	0.036	0.165	0.046
10/01/13	0.09	18.6	10.4		3	0.028	0.01	0.002	0.118	0.038
11/02/13	0.066	20.1	9.9	7.8	9	0.03	0.01	0.007	0.145	0.066
12/03/13	0.052	15.6	9.7	7.9	4	0.048	0.017	0.01	0.121	0.42
22/04/13	0.858	11.3	10.15	7.34	11	0.018	0.01	0.083	0.38	0.048
23/05/13	1.481	9.7	10.8	7.4	10	0.018	0.018	0.087	0.29	0.03
28/06/13	3.744	7.2	11.48	7.3	33	0.019	0.023	0.26	0.61	0.066
16/07/13	4.056	7	11.85	7.62	13.2	0.018	0.01	0.29	0.54	0.039
15/08/13	0.354	8.8	11.6	6.97	3.6	0.012	0.016	0.107	0.25	0.022
18/09/13	0.2	9.4	12	7.8	2.2	0.017	0.017	0.086	0.182	0.028
15/10/13	0.513	10.1	10.1	7.66	5	0.023	0.01	0.077	0.23	0.039
21/11/13	0.128	19.8	8.63	7.74	1.4	0.025	0.024	0.03	0.155	0.041
11/12/13	0.088	18.6	9.7	7.85	0.7	0.023	0.015	0.013	0.177	0.036
22/01/14	0.075	17.4	9.58	7.76	4.1	0.029	0.015	0.008	0.123	0.036
12/02/14	0.072	18.9	10.7	8.08	4.1	0.042	0.021	0.037	0.29	0.103
20/03/14	0.73	14.1	9.57	7.52	3.6	0.0176	0.01	0.066	0.22	0.029
14/04/14	2.298	11	10.7	7.49	8.3	0.0163	0.01	0.152	0.38	0.04
22/05/14	0.378	9.4	10.6	7.61	3.2	0.0182	0.014	0.135	0.26	0.024
18/06/14	0.301	9.8	11.62	7.62	2.8	0.0145	0.012	0.074	0.199	0.022
24/07/14	4.954	7.6	12.02	7.18	25	0.0171	0.01	0.4	0.66	0.06
19/08/14	0.334	6	12.93	7.79	6	0.0141	0.014	0.132	0.23	0.019
17/09/14	0.256	8.7	11.41	7.69	7.1	0.0146	0.01	0.048	0.162	0.02
22/10/14	0.113	13.7	10.46	7.63	2.9	0.023	0.019	0.045	0.2	0.03
20/11/14	0.102	13.9	10.46	7.47	2.9	0.022	0.017	0.021	0.15	0.031
16/12/14	0.081	17.9	9.97	7.85	1.9	0.023	0.012	0.01	0.18	0.04
21/01/15	0.054	18.1	8	7.67	1.9	0.029	0.01	0.002	0.24	0.058
19/02/15	0.037	18.6	9.69	7.9	2.9	0.025	0.01	0.002	0.24	0.049
20/03/15	0.117	12	11.74	7.98	1	0.021	0.01	0.012	0.14	0.028
22/04/15	0.098	13.5	11.14	7.9	2.4	0.029	0.01	0.002	0.129	0.134
18/05/15	0.108		11.25	7.64	1.3	0.021	0.01	0.021	0.14	0.025
18/06/15	0.462	7.4	11.63	7.15	2.2	0.0166	0.01	0.17	0.3	0.018
22/07/15	0.556	7.1	12.26	7.36	1.5	0.0103	0.01	0.148	0.25	0.015
21/08/15	0.919	7.2	12	7.41	6.7	0.0121	0.01	0.36	0.58	0.018
24/09/15	1.489	9.2	11.62	7.54	6	0.0132	0.01	0.182	0.36	0.022
20/10/15	0.145	12.3	8.98	7.6	2.6	0.0163	0.016	0.038	0.17	0.025
19/11/15	0.085	14.4	10.58	7.88	1.8	0.021	0.012	0.025	0.16	0.029
21/12/15	0.076	19.3	9.75	7.52	1.4	0.0166	0.012	0.013	0.173	0.025

B 2. Selwyn River water quality data (raw) (2011-2015)

Date	Mean Daily River flow (m3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11	0.748	17.1	9.3	7.9	2	0.011	0.006	5.2	5.2	0.02
15/03/11	0.473			7.7	3	0.007	0.01	6.2	6.4	0.022
21/03/11	0.51	16.8	9.5	7.8	3	0.005	0.01	6.3	6.5	0.012
12/04/11	0.597	14.6	10.4	7.7	3	0.05	0.01	6.3	6.7	0.054
04/05/11	0.746	13	10.4	7.8	5	0.011	0.01	6.1	6.4	0.015
19/05/11	0.93	12.4	10.7	7.9	1	0.008	0.026	5.7	5.7	0.009
09/06/11	0.951	11.8	10.4	7.9	0.6	0.007	0.012	6.5	6.5	0.013
07/07/11	1.06	9.1	10.7	7.8	1.4	0.008	0.012	6.4	7	0.01
04/08/11	1.089	8.3	11.1	7.8	2	0.006	0.008	6.3	6.6	0.008
29/08/11	3.329	11.3	11.4	7.8	0.7	0.004	0.013	5.6	5.8	0.008
08/09/11	1.853	9.3	12.4	7.9	0.9	0.003	0.007	6	6.3	0.008
18/10/11	1.676	13	10.6	7.9	0.8	0.005	0.014	6.2	6.4	0.008
09/11/11	1.81	13.5	8.8	7.8	0.5	0.008	0.005	5.4	5.5	0.018
17/11/11	1.682	16.3	9.8	7.8	0.8	0.005	0.009	5.4	5.6	0.008
08/12/11	1.772	13.5	10	7.8	1.2	0.019	0.029	5.4	5.4	0.025
10/01/12	1.014	16.8	9.4	7.7	1.5	0.011	0.022	5.5	5.7	0.014
22/02/12	0.668	17.2	10	8	2	0.008	0.006	5.3	5.3	0.014
27/02/12	0.812	18.5	8.9	7.9	0.5	0.009	0.007	5	5.4	0.01
08/03/12	0.815	13.4	10.1	7.9	0.5	0.008	0.017	5.2	5.8	0.009
04/04/12	0.826	14	10.3	7.9	0.5	0.003	0.005	4.8	5.4	0.01
22/05/12	0.889	9.8	11.2	7.6	0.5	0.009	0.005	5.7	6	0.009
28/05/12	0.909	11.1	11	7.8	0.5	0.007	0.008	5.9	6.1	0.009
26/06/12	1.091	8.1	11.2	7.8	0.5	0.009	0.009	6.1	6.3	0.014
12/07/12	1.101	7.7	11.6	7.8	0.5	0.005	0.02	5.9	6.1	0.008
16/08/12	43.335	9.2	10.6	7.6	85	0.022	0.011	1.5	2.1	0.11
23/08/12	14.952	9.5	11	7.6	7	0.011	0.009	2.2	2.3	0.015
06/09/12	3.286	11.8	10.25	7.7	1.4	0.008	0.006	4.2	4.2	0.008
10/10/12	1.871	11.8	11.4	7.8	0.5	0.009	0.005	5	5.5	0.013
14/11/12	5.016	13.1	10.4	7.8	1.2	0.006	0.007	3.1	3.2	0.008
19/11/12	2.001	14.8	9.8	7.8	0.5	0.007	0.006	3.7	4	0.008
06/12/12	1.225	14			3	0.005	0.01	4.9	4.9	0.014
10/01/13	0.39	17.8	8.9		3	0.009	0.01	5	5	0.01
11/02/13	0.396	19.6	9	7.6	3	0.019	0.01	4.6	4.6	0.019
14/02/13	0.401	17.8	9.51	7.8	3	0.01	0.01	5.6	5.6	0.017
12/03/13	0.275	16.2	10.5	7.8	3	0.013	0.011	5.4	5.7	0.013
22/04/13	0.527	13	9.69	7.4	3	0.017	0.01	5.5	5.9	0.018
23/05/13	0.868	11.7	9.8	7.4	3	0.045	0.01	5.8	5.9	0.049
28/06/13	18.021	7.6	11.04	7.24	8	0.018	0.014	3.2	3.5	0.028
16/07/13	17.424	6.8	11.58	7.42	3.2	0.029	0.014	3.5	3.9	7.1
15/08/13	2.917	10.9	11.36	7.19	0.7	0.008	0.018	6.1	6.7	0.013
18/09/13	4.469	12.2	10.9	7.45	1	0.006	0.01	4.5	4.7	0.012
15/10/13	34.965	10.2	11.68	7.42	85	0.01	0.01	1.38	1.52	0.141
21/11/13	1.447	17.6	9.41	7.59	0.5	0.0102	0.011	5.4	5.6	0.015
11/12/13	1.19	16.4	9.48	7.67	0.8	0.041	0.01	5.5	6	0.05
22/01/14	0.91	17.4	8.81	7.56	0.6	0.027	0.012	5.2	6.2	0.028
12/02/14	0.749	17.1	9.15	7.56	0.7	0.0197	0.01	5.8	5.9	0.025
20/03/14	1.216	16.2	9.37	7.59	0.5	0.0178	0.01	5.7	5.7	0.019
14/04/14	1.649	12.7	10.07	7.58	0.6	0.033	0.01	5.9	6	0.036
22/05/14	3.539	10.8	10.37	7.75	4.5	0.0163	0.01	5.3	5.3	0.0163
18/06/14	8.842	10.2	11.2	7.33	2.5	0.023	0.01	3.7	4.2	0.026
24/07/14	3.029	8.8	11.64	7.56	1.2	0.0162	0.011	6.2	6.3	0.017
19/08/14	2.789	9.3	11.83	7.71	1.1	0.0066	0.01	5.9	6.3	0.009
17/09/14	2.06	11.6	10.28	7.66	4.4	0.0071	0.01	6.4	6.4	0.0071
22/10/14	1.438	13.5	10.1	7.43	0.7	0.0105	0.01	6.5	7.3	0.0105
20/11/14	1.04	14.6	9.34	7.59	0.5	0.05	0.01	6.7	6.7	0.052
16/12/14	0.678	16.4	8.99	7.53	0.5	0.0113	0.01	6.4	6.7	0.013
21/01/15	0.289	16.6	8.64	7.51	0.5	0.0154	0.01	6.5	6.5	0.02
19/02/15	0.164	15.8	9.04	7.43	0.7	0.0136	0.01	5.4	5.9	0.018
20/03/15	0.179	14.6	9.02	7.38	0.5	0.0162	0.01	5.9	6.2	0.0162
22/04/15	0.311	14	9.43		0.5	0.0133	0.01	5.2	5.2	0.014
18/05/15	0.382	11.3	10.1	7.43	0.5	0.0155	0.01	6.6	6.6	0.0155
18/06/15	0.529	8.9	10.69	7.2	0.5	0.012	0.01	6.9	6.9	0.012
22/07/15	0.685	8.1	11.15	7.25	0.5	0.0111	0.01	7.1	7.1	0.013
21/08/15	0.781	8.1	12.13	7.49	0.7	0.0063	0.01	6.9	6.9	0.0063
24/09/15	1.104	11.5	11.84	7.7	0.6	0.0068	0.01	6.8	6.8	0.012
20/10/15	0.961	12.7	10.28	7.58	0.5	0.0072	0.01	6.8	7.2	0.009
19/11/15	0.695	15	9.72	7.81	0.5	0.0075	0.01	6.7	6.7	0.011
21/12/15	0.277	18.6	8.65	7.35	3.6	0.0076	0.01	6.4	6.4	0.016

B 3. Doyleston River water quality data (raw) (2011-2015)

Date	Mean Daily River flow (m3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11	0.013	17.800	7.800	7.900	2.000	0.062	0.045	0.390	0.530	0.100
15/03/11	0.013	15.100	2.000	7.400	3.000	0.130	0.061	0.120	0.850	0.150
12/04/11	0.076	13.300	8.700	7.600	3.000	0.039	0.010	1.800	2.400	0.047
04/05/11	0.133	13.700	11.200	7.800	3.000	0.052	0.010	1.600	2.100	0.056
09/06/11	0.129	11.200	10.100	7.900	5.300	0.032	0.021	2.300	2.700	0.058
07/07/11	0.168	7.200	11.600	7.800	4.900	0.015	0.026	1.900	2.200	0.039
04/08/11	0.154	5.300	14.000	7.800	2.400	0.011	0.014	2.300	2.500	0.023
08/09/11	0.2	7.600	13.400	7.900	1.700	0.011	0.015	3.900	4.900	0.020
18/10/11	0.18	12.400	11.900	8.000	7.500	0.008	0.048	5.800	6.300	0.036
09/11/11	0.196	13.000	10.500	8.000	2.600	0.022	0.014	6.600	6.800	0.044
08/12/11	0.362	13.600	10.700	7.900	5.700	0.069	0.047	5.900	6.200	0.110
10/01/12	0.047	17.000	12.100	7.900	3.800	0.026	0.017	3.600	4.000	0.050
22/02/12	0.009	16.400	7.000	7.800	2.800	0.110	0.050	0.150	6.000	0.150
08/03/12	0.086	12.300	9.800	7.800	1.100	0.038	0.019	0.470	0.780	0.055
04/04/12	0.041	13.200	7.800	7.800	0.900	0.035	0.029	0.530	0.590	0.042
22/05/12	0.066	7.000	10.000	7.600	0.500	0.026	0.013	1.900	2.300	0.032
26/06/12	0.193	6.300	11.100	7.800	9.900	0.024	0.050	3.200	3.600	0.060
12/07/12	0.148	5.900	11.800	7.800	9.100	0.012	0.046	3.400	3.500	0.024
16/08/12	0.989	9.400	10.000	7.700	10.000	0.110	0.057	3.700	4.500	0.170
06/09/12	0.248	11.500	15.500	8.600	1.600	0.010	0.012	5.100	5.300	0.024
10/10/12	0.289	10.200	13.400	8.100	6.300	0.074	0.180	4.900	5.600	0.091
14/11/12	0.282	11.000	11.700	8.000	7.400	0.010	0.012	4.900	5.400	0.021
06/12/12	0.111	13.200			4.000	0.016	0.010	5.000	5.000	0.042
10/01/13	0.001	18.100	6.600		8.000	0.103	0.114	0.193	0.860	0.155
11/02/13	0.002	20.000	7.800	7.500	3.000	0.042	0.010	0.011	0.390	0.048
12/03/13	0.004	14.700	4.300	7.400	3.000	0.020	0.022	0.002	0.340	0.024
28/06/13	0.789	8.400	10.160	7.300	5.000	0.053	0.073	6.200	6.700	0.076
18/09/13	0.334	11.300	14.800	8.500	5.700	0.007	0.013	6.300	6.900	0.021
11/12/13	0.094	16.400	11.270	8.360	8.000	0.027	0.023	5.400	6.300	0.042
20/03/14	0.304	15.900	9.530	7.530	1.200	0.043	0.011	3.900	4.200	0.054
18/06/14	0.629	10.300	10.650	7.490	18.500	0.046	0.061	4.600	5.400	0.090
17/09/14	0.262	9.800	11.100	7.660	23.000	0.009	0.014	6.200	6.500	0.040
16/12/14	0.012	14.000	8.570	7.290	4.300	0.750	0.041	0.380	1.330	0.790
20/03/15	0.004	14.500	7.910	7.180	0.500	0.034	0.010	0.004	0.350	0.038
18/06/15	0.038	8.600	9.020	7.220	0.600	0.025	0.019	0.340	0.580	0.034
24/09/15	0.141	10.900	13.410	7.970	2.600	0.010	0.010	1.280	1.720	0.018
21/12/15	0.004	21.000	13.630	8.770	8.400	0.013	0.011	0.151	0.530	2.500

B 4. Halswell River water quality data (raw) (2011-2015)

Date	Mean Daily River flow (m3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11	0.848	16.900	8.500	7.900	11.000	0.018	0.038	3.600	3.700	0.051
15/03/11	0.7			7.600	5.000	0.024	0.019	3.600	4.000	0.047
12/04/11	0.692	13.100	9.600	7.700	3.000	0.020	0.010	3.800	4.000	0.024
04/05/11	0.804	12.900	8.900	7.700	4.000	0.030	0.021	3.600	3.900	0.035
09/06/11	0.753	11.600	9.300	7.900	30.000	0.017	0.058	3.700	3.900	0.061
07/07/11	0.9	9.900	9.400	7.800	71.000	0.018	0.130	3.700	4.100	0.099
04/08/11	0.978	9.700	9.900	7.800	36.000	0.021	0.083	3.600	3.800	0.063
08/09/11	0.992	10.800	10.100	7.900	28.000	0.030	0.072	3.600	3.800	0.068
18/10/11	1.011	13.500	9.900	8.000	20.000	0.022	0.046	3.700	3.900	0.054
09/11/11	0.975	14.800	7.100	7.800	24.000	0.030	0.089	3.500	3.700	0.074
08/12/11	1.156	12.400	7.900	7.700	25.000	0.041	0.120	2.700	3.100	0.098
10/01/12	0.618	16.900	9.700	7.700	2.200	0.025	0.037	3.100	3.300	0.041
22/02/12	0.483	16.100	10.400	8.000	4.300	0.027	0.021	3.000	3.000	0.044
08/03/12	0.519	13.500	10.000	7.900	2.900	0.022	0.037	3.400	3.500	0.032
04/04/12	0.472	13.100	9.900	7.900	3.400	0.027	0.039	3.000	3.200	0.036
22/05/12	0.653	9.600	10.500	7.800	2.300	0.023	0.028	3.300	3.500	0.031
26/06/12	0.703	8.600	10.100	7.800	2.500	0.020	0.038	3.200	3.500	0.045
12/07/12	0.724	8.300	10.400	7.800	2.900	0.012	0.041	3.300	3.300	0.050
16/08/12	5.247	10.000	6.700	7.400	38.000	0.160	0.110	2.000	3.800	0.310
06/09/12	0.997	12.700	9.400	7.900	5.300	0.031	0.064	3.100	3.300	0.060
10/10/12	0.963	12.500	11.700	8.000	1.500	0.025	0.014	3.000	3.200	0.026
14/11/12	0.985	11.100	13.200	8.000	3.100	0.020	0.016	2.800	2.900	0.028
06/12/12	0.914	15.700		0.000	3.000	0.020	0.010	2.700	2.700	0.044
10/01/13	0.621	17.500	8.000	0.000	3.000	0.027	0.010	2.600	2.800	0.039
11/02/13	0.517	17.900	8.500	7.600	3.000	0.025	0.010	2.300	2.500	0.034
12/03/13	0.478	14.900	7.600	7.600	4.000	0.031	0.051	2.700	2.900	0.041
22/04/13	0.593	12.500	7.900	7.240	4.000	0.028	0.048	2.700	3.100	0.039
23/05/13	0.939	11.600	7.600	7.300	20.000	0.043	0.096	2.700	2.900	0.101
28/06/13	2.932	7.500	7.490	6.960	42.000	0.108	0.199	1.760	2.800	0.230
16/07/13	2.569	7.500	9.500	7.130	78.000	0.054	0.147	2.100	3.400	0.210
15/08/13	1.509	11.500	9.320	6.800	76.000	0.017	0.065	3.300	3.900	0.122
18/09/13	1.418	12.100	10.700	7.500	39.000	0.014	0.032	3.400	3.600	0.057
15/10/13	1.515	12.400	9.320	7.310	39.000	0.032	0.060	2.900	3.100	0.086
21/11/13	1.214	16.900	9.840	7.600	46.000	0.009	0.019	3.200	3.600	0.021
11/12/13	0.995	15.600	9.530	7.580	40.000	0.011	0.023	3.300	3.800	0.030
22/01/14	0.825	16.000	8.890	7.390	6.000	0.033	0.061	3.300	4.000	0.060
12/02/14	0.82	16.700	8.570	7.840	4.100	0.026	0.037	3.800	4.000	0.040
20/03/14	0.968	15.500	8.500	7.450	6.600	0.037	0.030	3.800	3.800	0.062
14/04/14	1.271	11.900	7.470	7.320	23.000	0.066	0.084	2.800	3.600	0.148
22/05/14	1.596	11.000	8.150	7.340	37.000	0.048	0.121	3.800	4.100	0.121
18/06/14	1.77	11.300	9.030	7.130	34.000	0.041	0.103	3.400	4.400	0.120
24/07/14	2.056	8.500	9.670	7.130	38.000	0.039	0.081	3.000	4.100	0.138
19/08/14	1.592	10.100	9.890	7.520	41.000	0.014	0.043	3.700	4.100	0.044
17/09/14	1.548	11.500	9.500	7.550	16.300	0.018	0.024	3.600	4.100	0.032
22/10/14	1.182	13.500	9.730	7.420	14.900	0.017	0.029	3.700	4.500	0.027
20/11/14	0.981	14.400	8.720	7.490	12.600	0.021	0.029	3.900	3.900	0.038
16/12/14	0.875	15.700	8.590	7.630	6.100	0.025	0.039	3.600	3.900	0.037
21/01/15	0.561	15.900	8.610	7.550	4.200	0.021	0.026	3.400	3.700	0.039
19/02/15	0.493	15.800	8.500	7.260	2.700	0.020	0.025	3.300	3.700	0.031
20/03/15	0.533	12.200	9.910	7.390	1.100	0.018	0.010	3.600	3.700	0.024
22/04/15	0.619	13.300	8.300	7.400	1.200	0.021	0.016	3.600	3.600	0.025
18/05/15	0.688	10.600	8.730	7.400	11.900	0.031	0.034	4.100	4.100	0.047
18/06/15	0.772	9.200	9.880	7.220	3.700	0.024	0.053	3.900	4.300	0.034
22/07/15	0.806	9.000	10.330	7.120	3.900	0.023	0.053	3.700	4.200	0.036
21/08/15	0.801	9.200	10.600	7.620	4.400	0.018	0.030	3.500	4.100	0.034
24/09/15	0.989	11.900	8.610	7.320	7.600	0.024	0.039	2.700	3.300	0.067
20/10/15	0.686	13.600	10.770	7.860	1.000	0.017	0.015	3.400	3.500	0.023
19/11/15	0.561	14.700	11.470	8.440	1.100	0.023	0.034	3.300	3.700	0.030
21/12/15	0.484	16.200	9.730	7.510	0.600	0.021	0.019	3.100	3.300	0.023

B 5. LII River water quality data (raw) (2011-2015)

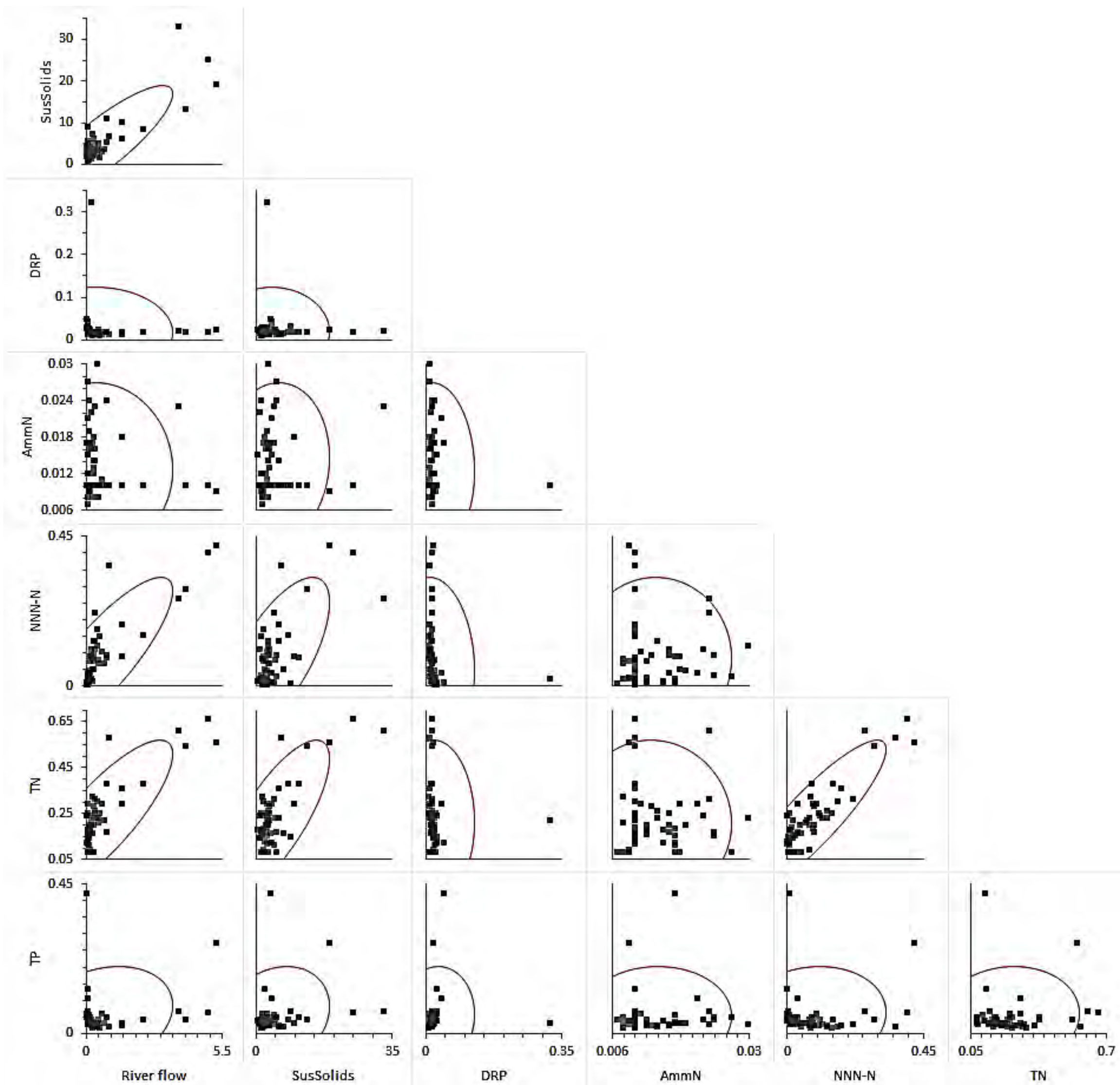
Date	Mean Daily River flow (m3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11	1.819	17.100	7.000	7.700	0.600	0.009	0.023	3.800	3.800	0.023
15/03/11	1.8			7.400	3.000	0.020	0.010	4.500	4.800	0.026
12/04/11	2.139	12.800	9.200	7.500	3.000	0.015	0.010	4.400	4.600	0.017
04/05/11	2.396	12.900	8.100	7.600	3.000	0.020	0.010	4.100	4.300	0.021
09/06/11	2.286	12.000	8.580	7.800	2.300	0.010	0.014	4.200	4.600	0.023
07/07/11	2.365	10.600	8.500	7.700	1.900	0.011	0.014	4.200	4.300	0.016
04/08/11	2.571	10.100	9.600	7.700	1.500	0.010	0.011	4.100	4.200	0.014
08/09/11	2.396	11.000	8.500	7.700	2.700	0.010	0.006	4.000	4.000	0.017
18/10/11	2.545	12.400	10.100	7.800	1.600	0.010	0.010	3.800	4.000	0.013
09/11/11	2.509			7.700	1.200	0.016	0.006	3.800	3.900	0.026
08/12/11	2.482	12.100	5.600	7.600	2.400	0.056	0.075	3.300	3.700	0.083
10/01/12	1.867	14.600	8.500	7.600	0.700	0.017	0.015	3.800	4.000	0.026
22/02/12	1.853	14.300	9.200	7.900	2.600	0.017	0.011	3.800	3.800	0.029
08/03/12	2.047	12.900	10.200	7.800	5.500	0.014	0.029	3.800	4.100	0.020
04/04/12	2.094	12.800	9.500	7.800	2.700	0.011	0.008	3.700	3.800	0.017
22/05/12	2.037	10.700	10.300	7.500	1.500	0.013	0.005	3.800	3.900	0.016
26/06/12	2.433	9.800	9.400	7.700	2.100	0.012	0.009	3.600	3.700	0.022
12/07/12	2.166	9.900	9.600	7.700	1.700	0.009	0.017	3.400	3.600	0.012
16/08/12	4.599	10.700	5.700	7.500	11.000	0.210	0.055	2.400	3.800	0.290
06/09/12	2.537	12.200	9.600	7.800	2.900	0.016	0.007	3.400	3.400	0.018
10/10/12	2.439	12.000	10.000	7.800	1.500	0.017	0.005	3.400	3.400	0.023
14/11/12	2.311	12.800	10.300	7.800	1.600	0.013	0.007	3.100	3.100	0.017
06/12/12	1.834				3.000	0.011	0.010	3.300	3.300	0.026
10/01/13	1.245	16.300	7.500		3.000	0.025	0.010	3.300	3.300	0.025
11/02/13	1.92	16.000	6.200	7.400	4.000	0.016	0.011	3.200	3.500	0.017
12/03/13	1.289	13.600	7.900	7.800	12.000	0.015	0.025	3.700	4.000	0.028
22/04/13	1.972	12.600	7.650	7.160	8.000	0.020	0.029	3.300	3.600	0.038
23/05/13	2.417	11.900	8.100	7.300	3.000	0.053	0.027	3.300	3.400	0.067
28/06/13	3.486	10.100	6.910	7.030	4.000	0.156	0.056	3.000	3.300	0.200
16/07/13	3.621	9.300	7.820	7.070	10.300	0.076	0.053	2.900	3.700	0.128
15/08/13	2.891	11.700	10.540	6.970	3.900	0.010	0.010	3.600	3.900	0.018
18/09/13	2.722	12.100	13.800	7.800	2.200	0.007	0.010	3.500	3.900	0.015
15/10/13	2.908	12.100	9.970	7.270	2.900	0.026	0.010	3.400	3.400	0.032
21/11/13	1.955	15.800	11.350	7.580	1.500	0.005	0.010	3.500	3.800	0.016
11/12/13	1.872	15.300	8.780	7.320	1.900	0.011	0.010	3.600	4.100	0.022
22/01/14	1.428	15.100	8.330	7.270	5.800	0.017	0.017	4.000	4.600	0.026
12/02/14	1.684	14.900	8.160	7.460	3.900	0.017	0.016	4.500	4.700	0.027
20/03/14	2.179	14.300	9.810	7.390	1.000	0.016	0.010	4.100	4.100	0.019
14/04/14	2.722	12.000	5.590	8.170	2.400	0.107	0.059	3.400	3.900	0.132
22/05/14	2.762	11.400	8.990	7.420	3.900	0.029	0.016	4.100	4.100	0.032
18/06/14	3.219	11.700	8.540	7.150	6.600	0.035	0.028	3.900	4.400	0.055
24/07/14	3.552	9.900	8.800	7.150	8.800	0.040	0.035	3.700	4.200	0.062
19/08/14	2.812	10.800	9.270	7.450	6.600	0.011	0.011	4.000	4.300	0.017
17/09/14	2.949	11.800	10.270	7.430	2.900	0.011	0.010	3.900	4.200	0.011
22/10/14	2.374	12.700	12.700	7.670	2.000	0.007	0.010	4.100	4.900	0.012
20/11/14	1.981	13.200	10.870	7.590	1.800	0.013	0.010	4.600	4.600	0.023
16/12/14	1.699	14.600	8.620	7.300	2.500	0.011	0.010	4.400	4.600	0.015
21/01/15	1.194	15.100	7.040	7.130	1.100	0.010	0.010	4.100	4.500	0.022
19/02/15	1.016	15.300	7.400	7.220	2.400	0.010	0.010	4.400	4.600	0.017
20/03/15	1.56	13.100	10.550	7.320	0.900	0.013	0.010	3.900	3.900	0.016
22/04/15	2.071	13.300	7.670	7.210	7.700	0.018	0.025	3.700	3.700	0.026
18/05/15	1.993	11.600	8.230	7.260	10.200	0.016	0.023	4.100	4.100	0.021
18/06/15	2.051	10.800	8.510	7.120	3.900	0.011	0.012	3.800	3.900	0.012
22/07/15	2.387	10.300	9.650	7.000	2.200	0.010	0.010	3.700	3.800	0.013
21/08/15	2.087	10.300	10.980	7.560	1.900	0.005	0.010	3.500	4.000	0.005
24/09/15	2.592	12.300	10.700	7.430	1.500	0.008	0.010	3.300	3.500	0.013
20/10/15	1.698	12.900	12.240	7.790	1.800	0.006	0.010	3.500	3.600	0.008
19/11/15	1.336	14.600	12.830	8.480	2.000	0.013	0.010	3.500	4.000	0.020
21/12/15	1.328	15.700	8.050	7.310	0.800	0.005	0.010	3.400	3.500	0.009

B 6. Harts Creek water quality data (raw) (2011-2015)

Date	Mean Daily River flow (m^3/s)	Temp (degC)	DO	pH	SusSolids (g/L)	DRP (g/L)	AmmN (g/L)	NNN-N (g/L)	TN (g/L)	TP (g/L)
18/01/11		13.100	9.300	7.800	2.500	0.007	0.006	3.900	5.900	0.011
15/03/11		13.200	7.900	7.700	3.000	0.006	0.010	6.900	7.000	0.007
12/04/11	1.502	12.100	9.000	7.600	3.000	0.004	0.012	7.100	7.400	0.004
04/05/11	1.553	12.500	10.100	7.600	3.000	0.007	0.010	6.900	7.100	0.010
09/06/11	1.673	11.900	9.160	7.800	4.500	0.008	0.011	6.500	6.900	0.013
07/07/11	1.649	10.400	9.100	7.700	5.500	0.007	0.018	6.300	7.600	0.020
04/08/11	1.58	9.500	10.400	7.700	6.300	0.005	0.013	6.500	6.600	0.009
08/09/11	1.684	10.400	10.400	7.800	8.300	0.005	0.007	6.000	6.500	0.008
18/10/11	1.53	11.600	9.900	7.800	3.500	0.003	0.017	6.600	6.800	0.009
09/11/11	1.64	12.000	9.900	7.700	2.700	0.006	0.012	6.600	6.600	0.020
08/12/11	1.448	11.900	9.800	7.800	3.500	0.013	0.022	6.400	6.400	0.035
10/01/12	1.44	12.900	9.000	7.500	4.000	0.006	0.013	5.900	6.400	0.012
22/02/12	1.238	13.000	9.400	7.800	5.100	0.010	0.006	5.800	6.000	0.013
08/03/12	1.357	11.900	10.900	7.800	6.300	0.007	0.013	6.200	6.800	0.012
04/04/12	1.374	12.300	9.700	7.800	4.300	0.013	0.016	5.600	6.300	0.015
22/05/12	1.406	10.300	9.800	7.700	4.700	0.010	0.014	6.300	6.500	0.013
26/06/12	1.516	10.100	9.800	7.700	6.300	0.007	0.015	6.400	6.600	0.016
12/07/12	1.51	10.100	10.100	7.800	8.400	0.005	0.025	1.700	3.700	0.008
16/08/12	2.248	10.800	9.100	7.700	12.000	0.034	0.033	6.300	6.700	0.059
06/09/12	1.696	11.600	9.700	7.800	8.100	0.008	0.011	5.900	6.500	0.012
10/10/12	1.644	11.000	10.100	7.700	5.300	0.009	0.011	5.800	6.300	0.013
14/11/12	1.692	11.400	9.700	7.700	3.900	0.006	0.021	5.500	5.900	0.008
06/12/12	1.45	11.800		0.000	5.000	0.004	0.010	6.600	6.600	0.018
10/01/13	1.035	13.700	8.400	0.000	5.000	0.009	0.010	6.100	6.100	0.017
11/02/13	0.916	13.700	8.900	7.700	7.000	0.010	0.013	5.600	5.900	0.014
12/03/13	0.914	12.400	9.200	7.700	7.000	0.010	0.012	6.000	6.300	0.030
22/04/13	1.115	11.900	8.940	7.350	8.000	0.007	0.017	6.100	6.500	0.010
23/05/13	1.301	11.500	8.900	7.400	8.000	0.011	0.017	6.400	6.500	0.013
28/06/13	2.466	10.500	8.970	7.260	8.000	0.024	0.027	6.600	6.600	0.030
16/07/13	2.769	9.600	9.230	7.280	12.200	0.021	0.021	6.700	6.700	0.046
15/08/13	2.343	11.100	9.900	6.960	7.100	0.005	0.010	7.400	7.400	0.012
18/09/13	2.343	10.500	10.800	7.400	3.800	0.005	0.010	7.900	8.400	0.014
15/10/13	2.285	10.800	10.460	7.360	3.300	0.008	0.010	7.800	7.800	0.012
21/11/13	1.593	12.700	9.730	7.420	2.700	0.005	0.010	7.200	7.200	0.012
11/12/13	1.392	12.800	9.400	8.000	3.200	0.007	0.010	6.800	6.800	0.010
22/01/14	1.228	12.800	9.260	7.300	1.900	0.008	0.010	6.400	6.700	0.080
12/02/14	1.158	13.100	8.910	7.460	1.800	0.006	0.010	7.000	7.000	0.010
20/03/14	1.409	12.800	8.930	7.260	2.000	0.010	0.010	7.300	7.300	0.012
14/04/14	1.672	11.700	8.380	7.430	2.500	0.020	0.012	7.000	7.000	0.022
22/05/14	1.908	11.100	9.680	7.810	2.300	0.010	0.010	7.800	7.800	0.010
18/06/14	2.342	11.500	9.740	7.780	3.100	0.013	0.015	7.700	8.300	0.015
24/07/14	2.271	10.000	10.130	7.670	4.300	0.010	0.010	8.000	8.100	0.013
19/08/14	1.992	10.400	10.030	7.580	4.000	0.006	0.010	7.600	7.900	0.007
17/09/14	1.904	10.900	10.220	7.470	3.500	0.005	0.010	7.500	7.500	0.005
22/10/14	1.669	10.700	10.610	7.820	2.200	0.004	0.010	7.300	8.100	0.006
20/11/14	1.251	11.200	9.550	7.690	1.800	0.006	0.010	7.400	7.400	0.007
16/12/14	1.13	12.300	8.890	7.390	2.300	0.007	0.010	6.900	6.900	0.009
21/01/15	0.79	12.300	8.680	7.040	4.800	0.005	0.014	6.500	6.700	0.014
19/02/15	0.713	12.400	9.170	7.090	10.500	0.010	0.018	6.400	6.700	0.020
20/03/15	0.82	11.700	9.390	7.280	7.600	0.010	0.010	6.400	6.400	0.016
22/04/15	0.835	12.500	9.580	7.380	4.600	0.012	0.010	6.600	6.700	0.015
18/05/15	0.974	11.300	9.070	7.450	3.500	0.010	0.010	7.100	7.100	0.010
18/06/15	1.004	10.900	9.210	7.310	3.100	0.008	0.010	6.900	6.900	0.012
22/07/15	1.13	10.400	9.830	7.060	5.100	0.009	0.010	7.200	7.200	0.014
21/08/15	1.19	10.100	10.120	7.560	3.600	0.006	0.010	6.700	7.500	0.007
24/09/15	1.265	11.300	10.000	7.600	2.500	0.006	0.010	7.200	7.200	0.008
20/10/15	1.001	11.000	9.840	7.540	1.200	0.004	0.010	6.700	7.000	0.007
19/11/15	0.773	11.700	9.710	7.640	1.600	0.008	0.010	6.600	6.600	0.009
21/12/15	0.648	12.900	9.210	7.090	2.600	0.007	0.010	6.700	6.700	0.013

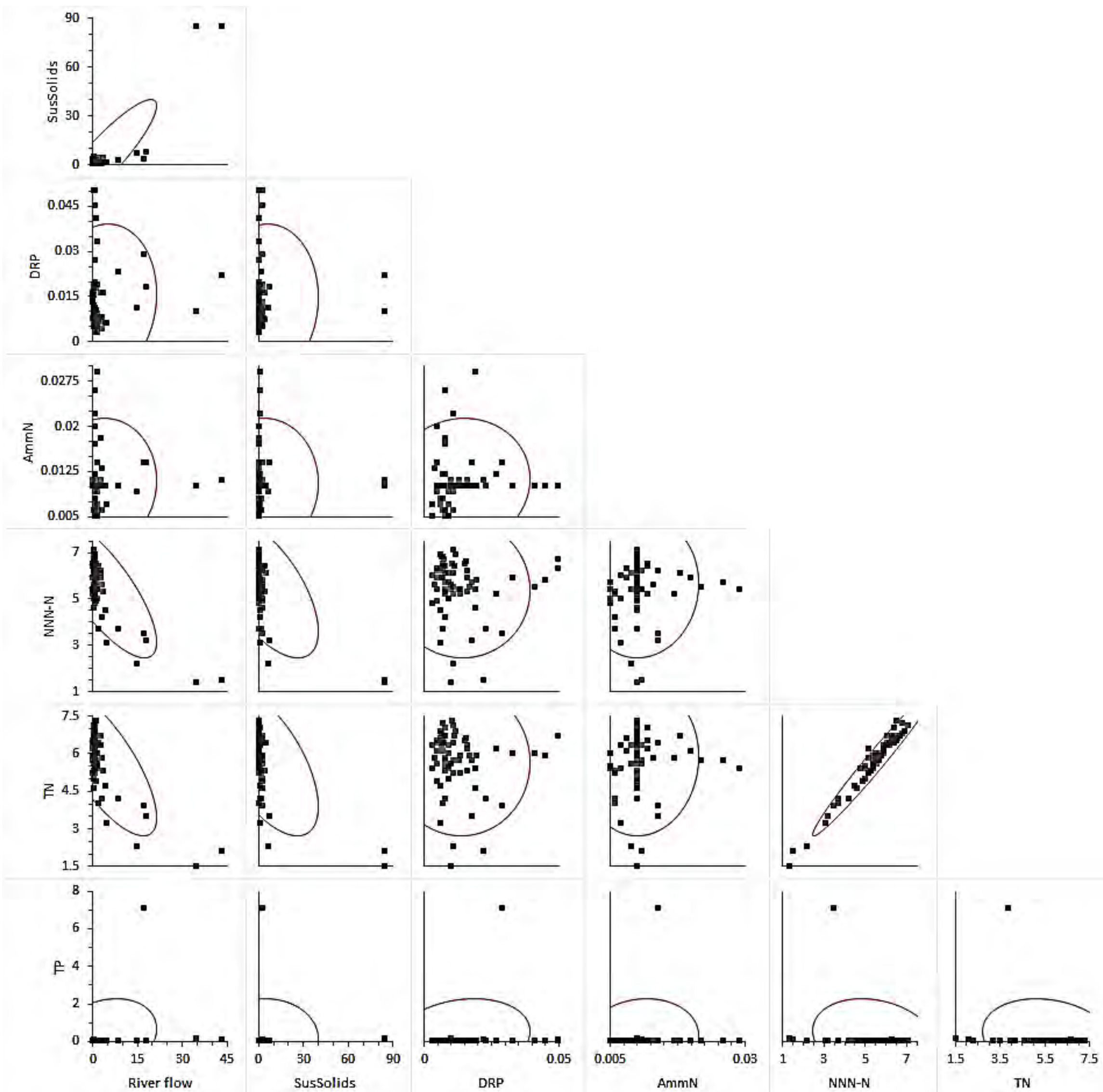
Appendix C. Scatter plots of Te Waihora/Lake Ellesmere Inflow water quality data (2011-2015).

C 1. Scatter plot of Kaituna River water quality data (2011-2015).



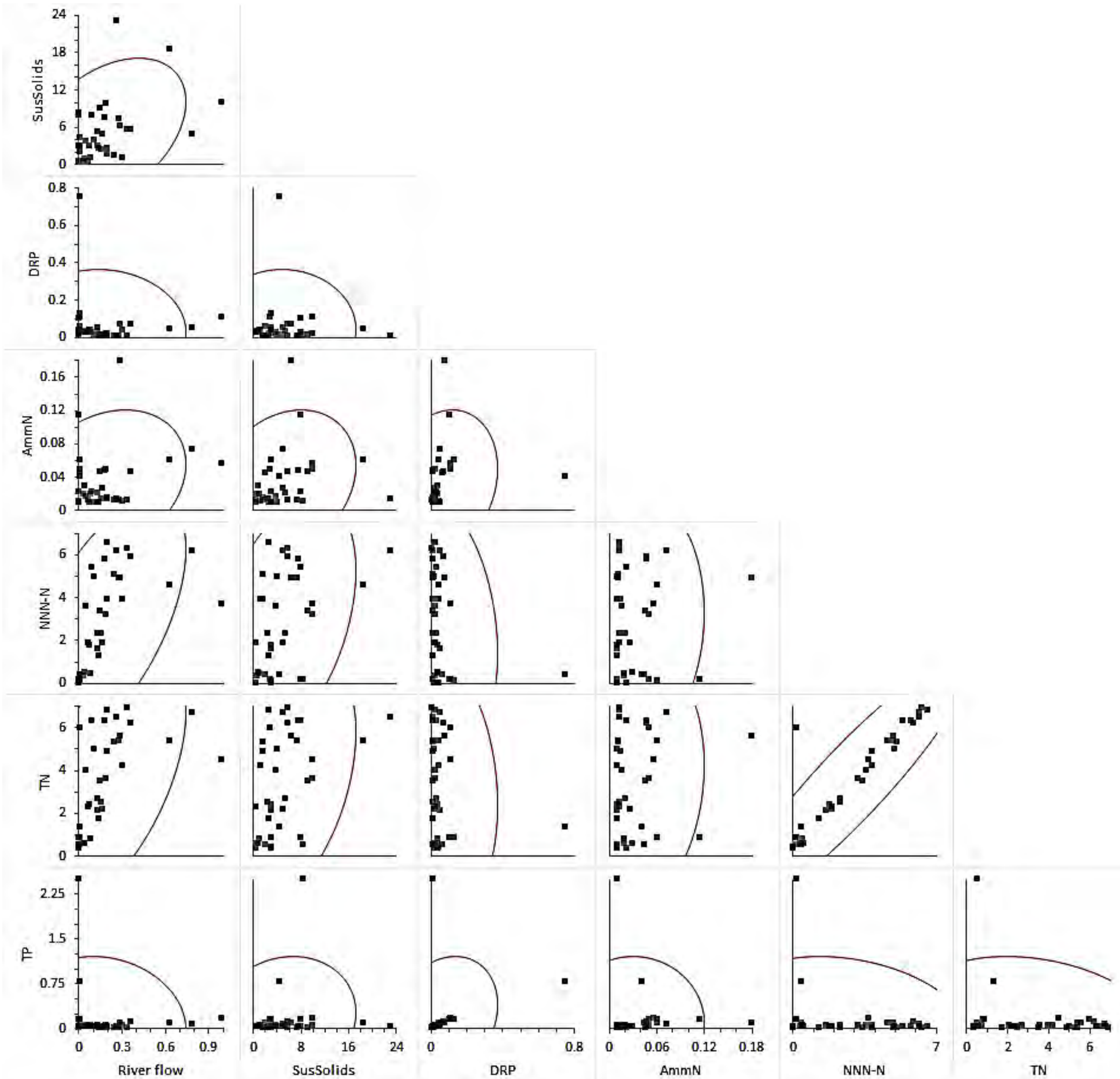
TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.

C 2. Scatter plot of Selwyn River water quality data (2011-2015).



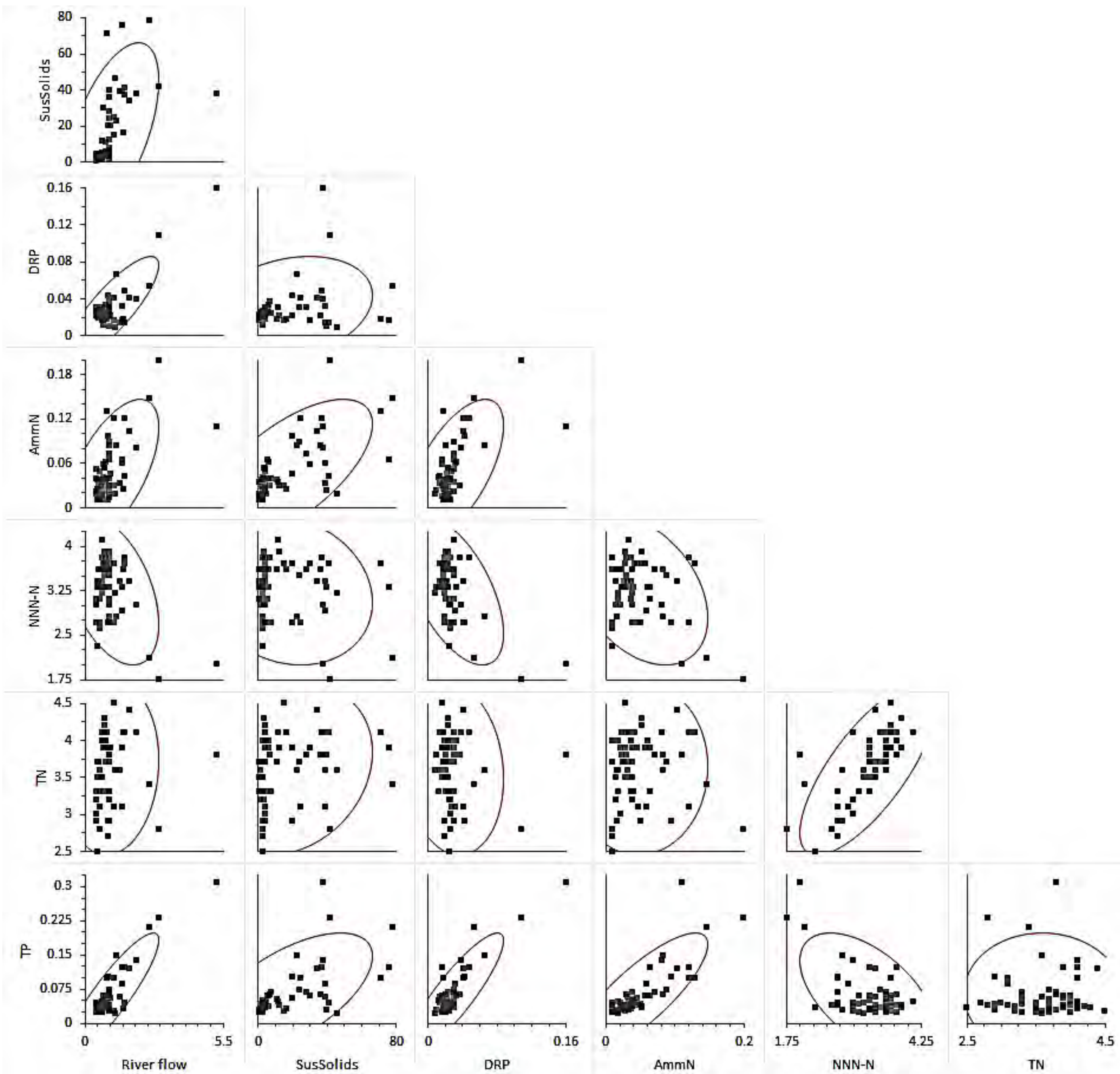
TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.

C 3. Scatter plot of Doyleston River water quality data (2011-2015).



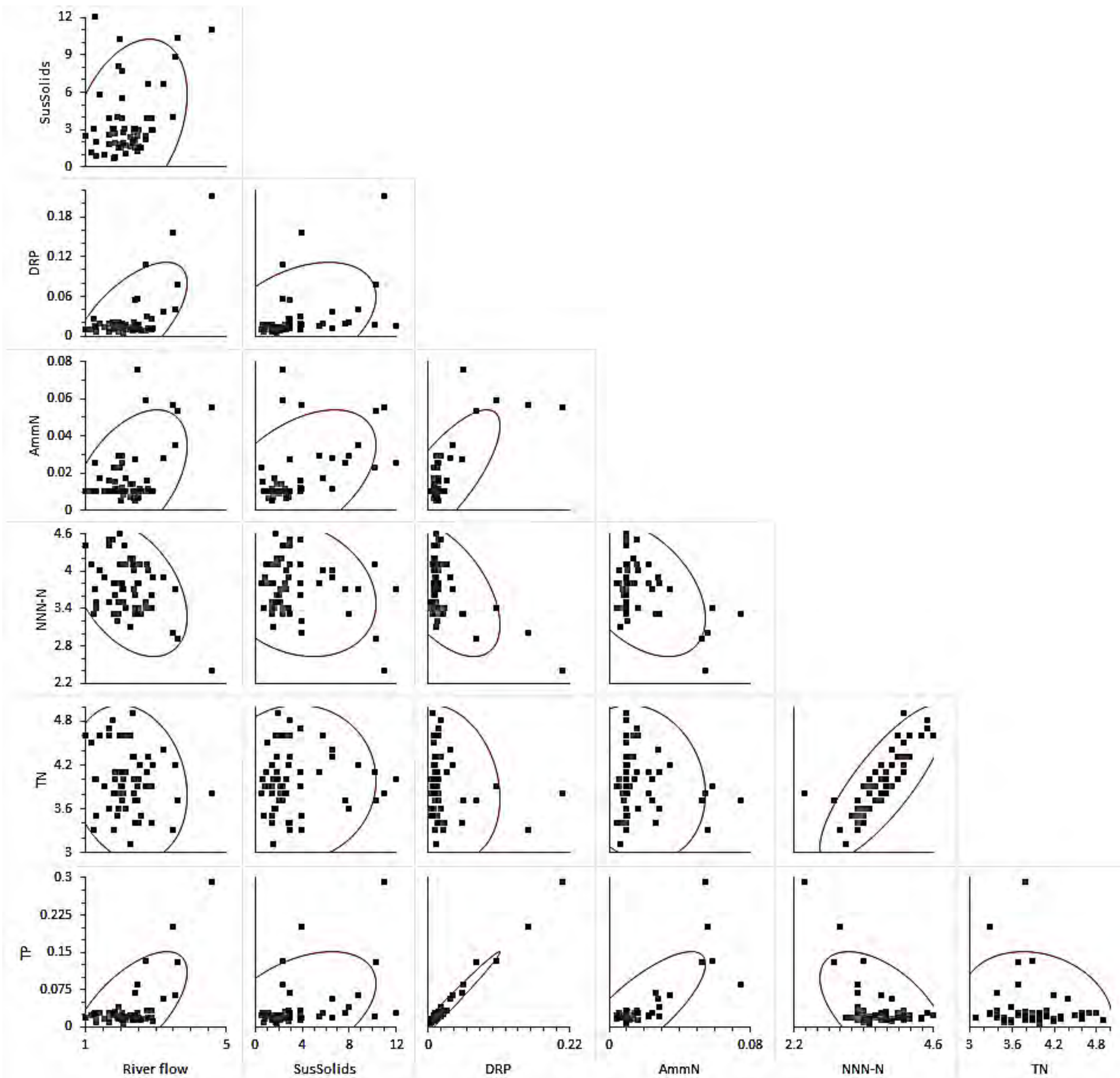
TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.

C 4. Scatter plot of Halswell River water quality data (2011-2015).



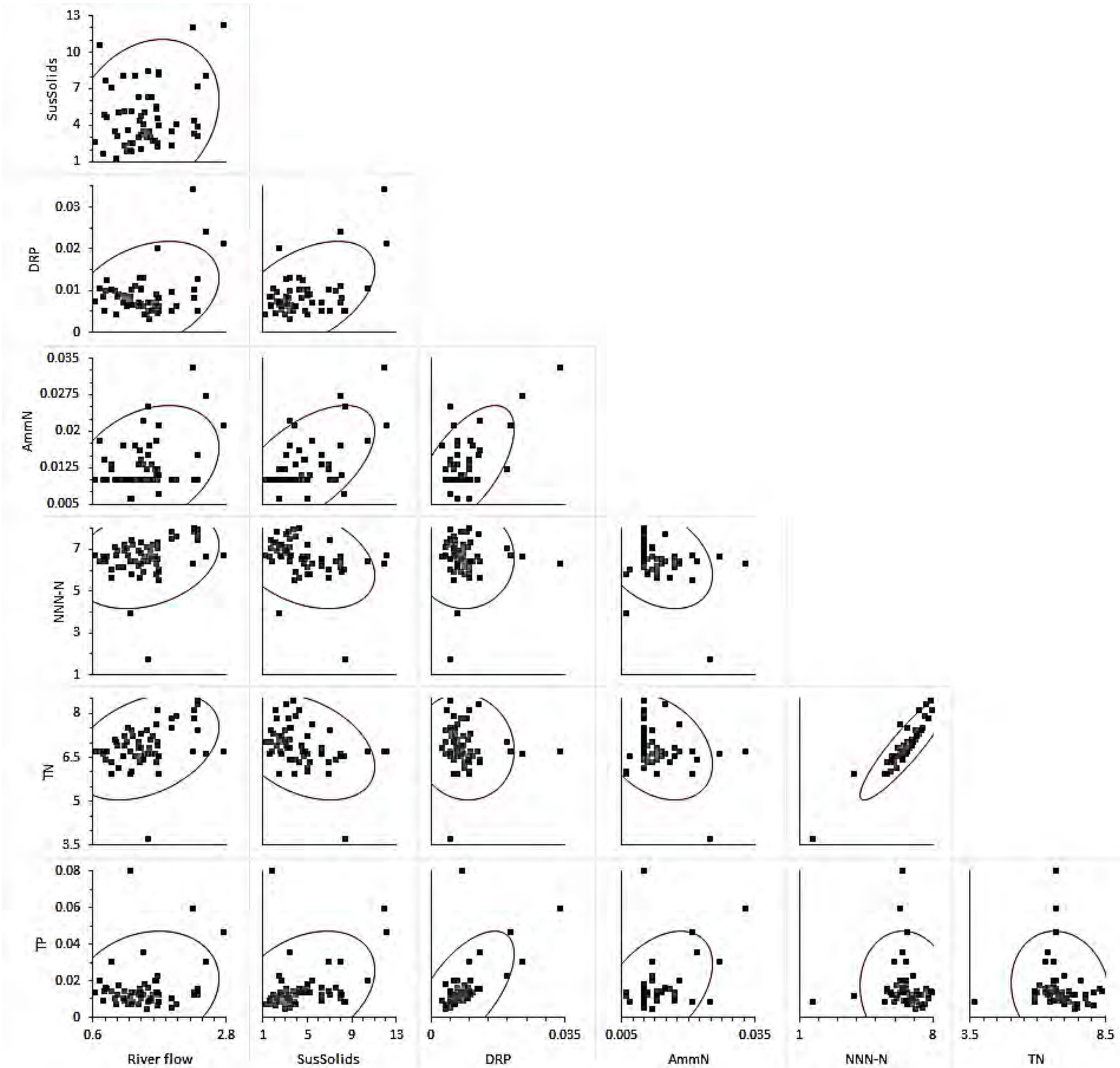
TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.

C 5. Scatter plot of LII River water quality data (2011-2015).



TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.

C 6. Scatter plot of Harts Creek water quality data (2011-2015).



TP, TN, NNN-N, AmmN, DRP, and SusSolids represent respectively, total phosphorus (mg/L), total nitrogen (mg/L), nitrate nitrogen (mg/L), ammonium nitrogen (mg/L), dissolved reactive phosphorus (mg/L), suspended solids (mg/L) based on grab sampling. River flow depicts mean daily river flow (in $m^3 s^{-1}$) for the day samples were collected.