A coupled hydrodynamic-ecological model of management options for restoration of lakes Onoke and Wairarapa

By David Hamilton and Mathew Allan, University of Waikato

Introduction

Approaches to assess water quality may be categorised into three main types; traditional in situ sampling, numerical modelling and remote sensing (Dekker et al., 1996). In situ methods using grab samples are generally suited to monitoring at low temporal resolution. By contrast autonomous water quality monitoring sensors allow for monitoring at high frequency and potentially in real time. However, neither of these methods is well suited to effectively capturing horizontal heterogeneity of water quality and temperature.

The synthesis of data derived from remote sensing, modelling and in situ sampling provides limnologists, scientists and engineers with an unparalleled opportunity for understanding ecosystem structure and function. Horizontal validation of three-dimensional (3-D) models with traditional point-based monitoring is often limited by the synoptic coverage and quantity of field data, and remote sensing has the potential to provide a cost effective method for synoptic validation. Modelling provides the opportunity for interpretation of remotely sensed imagery through the quantification of the physical and biological fluxes that redistribute variables and lead to spatial distributions observed through remote sensing.

This memo describes a modelling study of lakes Onoke and Wairarapa to address the following questions:

What determines the spatial distribution of optically active constituents and other key water quality variables within lakes Wairarapa and Onoke?

What are the likely water quality and ecological effects of specific management scenarios?

Methods

Lake Wairarapa study site

Lake Wairarapa is a shallow (max depth 2.6 m), isothermal, supertrophic (Perrie & Milne 2012; Perrie 2005) riverine lake (area 7737.4 ha) located in the Wairarapa, of the lower North Island. Due to the large shallow nature of Lake Wairarapa, it is very susceptible to sediment resuspension. Strong westerly winds can cause lake set-up on the eastern shore, and alter water levels by up to 1.2 m (Mitchell, 1989). The surficial lake sediments can be classified as medium to coarse silt (Trodahl, 2010), likely influenced by frequent exposure to orbitalmotions from wind waves.

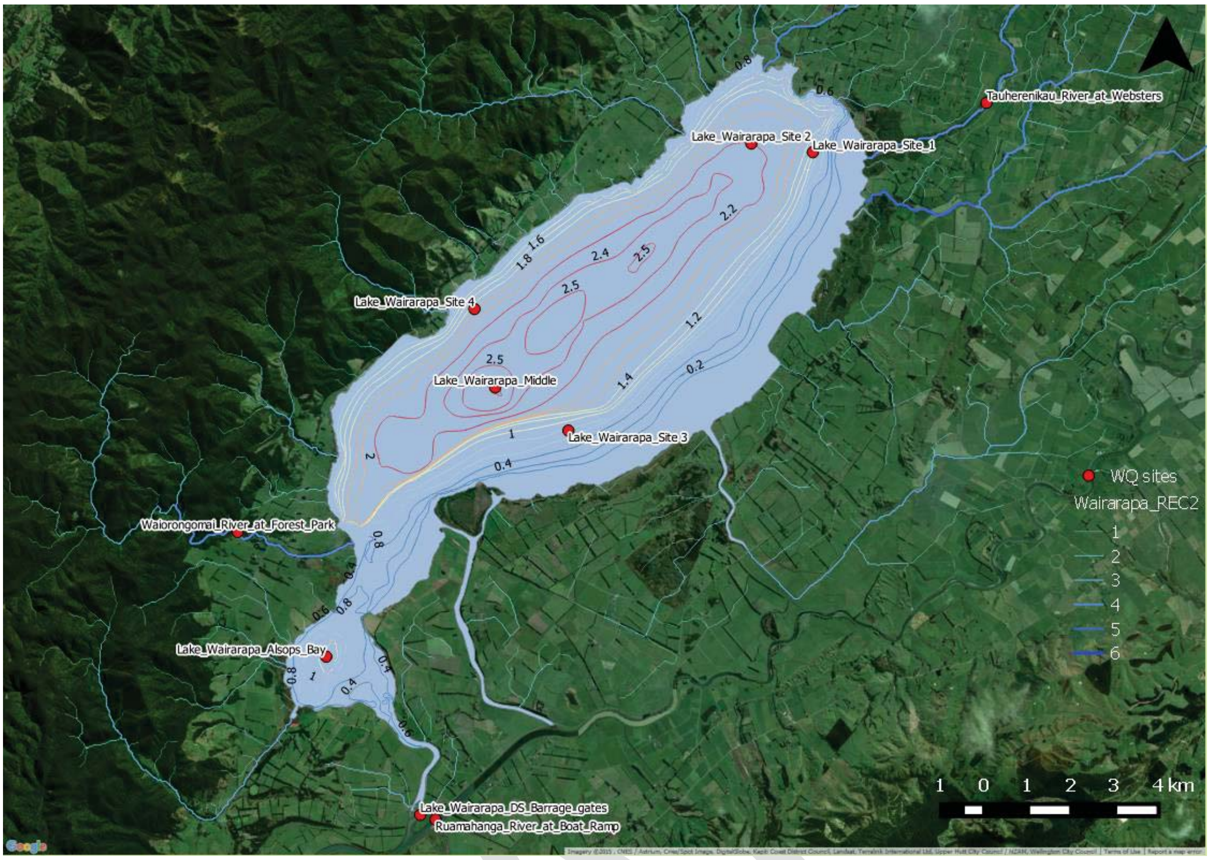

Figure 1. Lake Wairarapa study site with water quality (WQ) monitoring locations, River Environment Classification stream order (shades of blue), and bathymetric isobaths labelled by depth (m).

Inflows

Lake Wairarapa forms part of the lower Wairarapa groundwater system. The groundwater system is conceptually closed, with limited exchange between the groundwater system and the sea (Gyopari & McAlister, 2010). Most of the groundwater discharging into Lake Wairarapa originates from shallow unconfined aquifers (also discharging into inflowing streams and rivers), however near Lake Wairarapa groundwater becomes confined, with flow converging on the lake. Slow discharge may also occur from deep confined aquifers (Gyopari & McAlister, 2010). Groundwater discharge into the lake has been estimated at 0.4 $m^3 s^{-1}$, however it should be noted that this was derived as a model residual constituent of the Wairarapa Lower Valley groundwater model (Gyopari & McAlister, 2010).

The major inflows to the lake include the Tauherenikau River (northeast), Otukura stream (northwest), Waiorongomai River (south-western), the Ruamahanga River (during flooding via the Oporua floodway), and back-flow from the Barrage gates (southern).

Outflows

The outflow is via the barrage gates at the south-eastern end of the lake. The barrage consists of six gates that can be operated individually. Under normal operating conditions when the mouth of Lake Onoke is open and flood conditions are not present, the barrage gates operate to maintain consented levels, as stipulated by the resource consent, which targets lake levels of between 0.68 and 0.93 m asl (9.9 and 10.15 m Schemes datum). An automated alarm system is used to alert operators to high or low water level and the gates are adjusted in response. To allow for fish passage there are automated daily openings of two of the six gates (Thompson & Mzila, 2015). If the mouth of Lake Onoke becomes blocked the barrage gates are operated in order to raise the lake levels of Wairarapa to maximum consented level. The Onoke spit is then opened (via excavator) allowing floodwaters to drain and the level of the Ruamahanga River to return to normal. During large swells, opening is not possible, and under this scenario the barrage gates are opened to allow backflow into Lake Wairarapa. During a large flood event the barrage gates are closed to maintain Lake Wairarapa water level, and flood flows ideally drain through the Onoke spit.

The flow at the barrage gates has been monitored since August 2012, using a side-looking Acoustic Doppler Current Profiler (ADCP) (Thompson & Mzila, 2015). There are 11 consented abstractions with maximum daily abstraction of 39,635 m^3 day^{-1} (Thompson & Mzila, 2015).

Lake Onoke study site

Lake Onoke is a supertrophic (Perrie & Milne 2012), intermittently closed and open lake/lagoon (ICOLL) of moderate depth (max. depth 6.8 m) (Roy et al., 2001). It is located in the Wellington region and has an area of 622.3 ha (Fig. 2). The lake has a very high sedimentation rate, exceeding 10 mm $year^{-1}$ (Oliver & Milne, 2012).

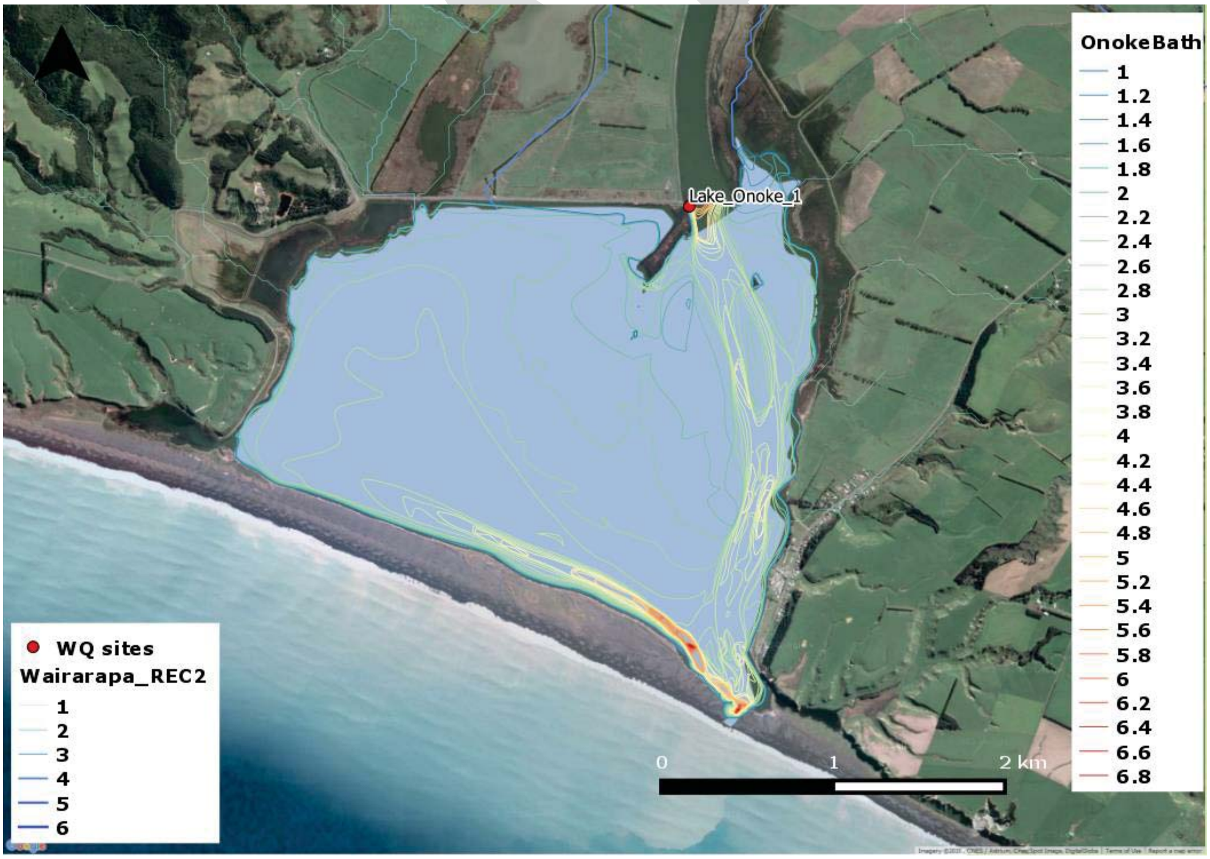

Figure 2. Lake Onoke study site with water quality (WQ) monitoring location shown (Lake_Onoke_1), and River Environment Classification stream order (shades of blue) and bathymetric isobaths, with depth (m) displayed in the legend.

Inflows

Lake Onoke's major inflow is via the Ruamahanga River entering in the north-east of the lake. Other inflows include the Turanganui River which enters directly to the west of the Ruamahanga River (the two inflows are separated by narrow spit) and Pounui Stream (via Pounui Lagoon) in the north-west. In addition, when open to the sea, saline intrusions occur.

Outflow

Lake Onoke is separated from Palliser Bay by a narrow spit. The outflow is in the southeast of the lake through the spit, and across a shallow gravel bar. This bar becomes closed approximately nine times per year, however it is opened (consented activity) to maintain a connection to the ocean and prevent water level rise. Factors that can lead to the closure of the outlet include low inflow volumes and large swells which deposit gravel. When the outflow is blocked the lake level can increase, leading to brackish backflow via the Ruamahanga River and through the barrage gates into Lake Wairarapa.

Water quality modelling - DYCD

DYRESM-CAEDYM (DYCD) is a 1-D water quality model that has been developed at the Centre for Water Research, University of Western Australia (Hamilton & Schladow, 1997). DYRESM simulates vertical distribution of temperature, salinity and density based using a horizontal Lagrangian layer approach. The horizontal Lagrangian layers are free to move vertically and can contract and expand based on changes in inflows, outflows and surface mass fluxes. The layer thicknesses also adjust during model simulations in order to more effectively represent vertical density gradients than with fixed grids. DYRESM is based on an assumption of one dimensionality where variations in the vertical dimension are assumed to be greater than variations in the horizontal dimension (Imerito, 2007). The DYRESM model coupled to CAEDYM (Computational Aquatic Ecosystem Dynamics Model) enables simulation of several biological and chemical variables broadly constituting 'water quality'. CAEDYM is a general biogeochemical model that can simulate specific ecological interactions between species or groups. A detailed description of the model can be found in Hamilton & Schladow (1997).

The model includes comprehensive process representations of carbon (C), N, P (Fig. 3), and dissolved oxygen (DO) cycles, and several size classes of inorganic suspended solids. Several applications have been made of DYRESM-CAEDYM to different New Zealand lakes (e.g., Burger et al., 2008; Özkundakci et al., Trolle 2011; Trolle et al., 2011) and these publications provide detailed descriptions of the model equations.

The biogeochemical variables in CAEDYM may be configured according to the goals of the model application and availability of data. In this study, two groups of phytoplankton were included in CAEDYM, representing generically diatoms and cyanobacteria. The interactions between phytoplankton growth and losses, sediment mineralisation and decomposition of particulate organic matter influence N and P cycling in the model as shown in Fig. 3. Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on temperature, nitrate and DO concentrations of the water layer immediately above the sediment surface.

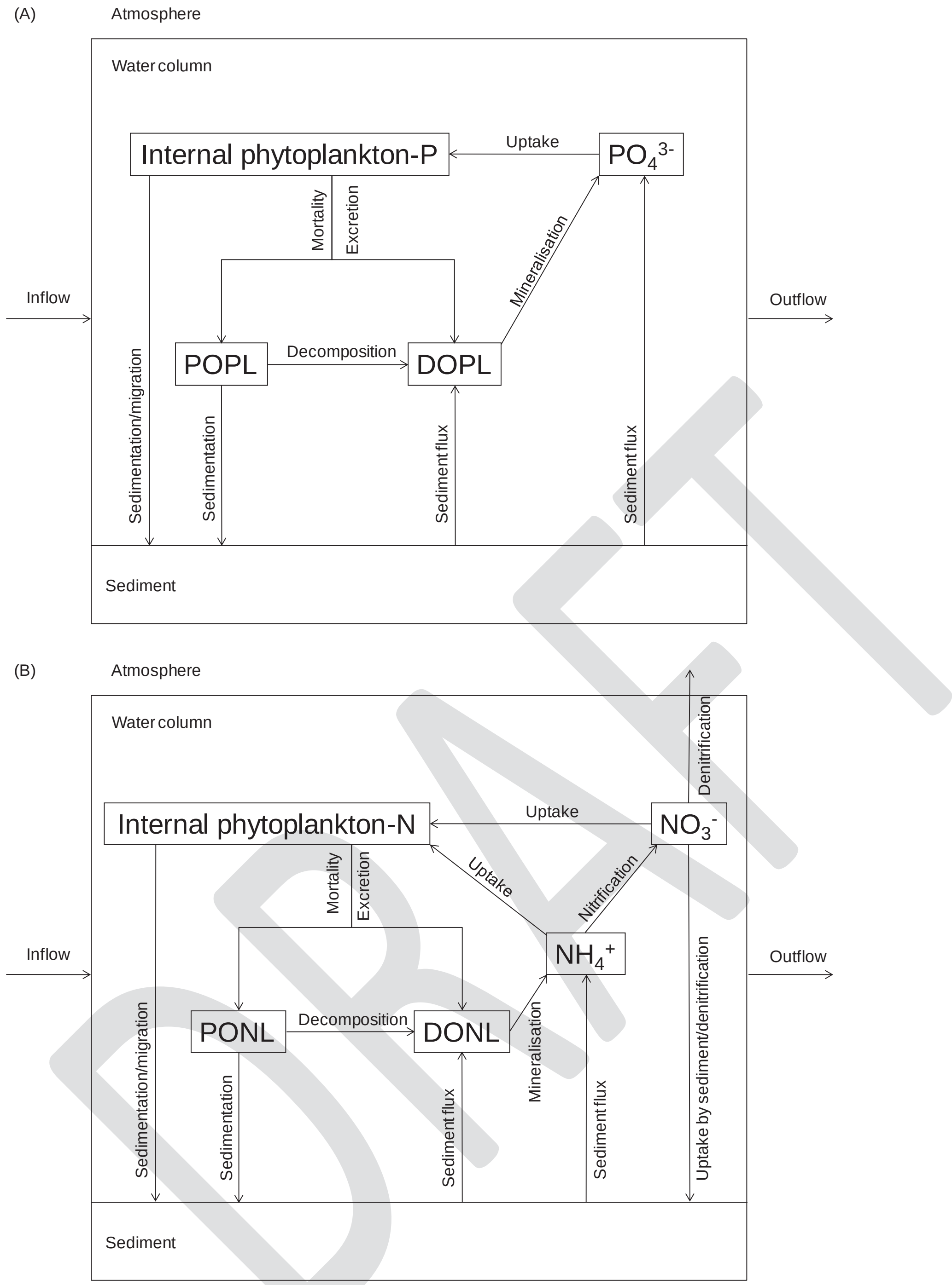

Figure 3. Conceptual model of the (A) phosphorus and (B) nitrogen cycles represented in DYRESM-CAEDYM for the present study. POPL, PONL, DOPL and DONL represent particulate labile organic phosphorus and nitrogen, and dissolved labile organic phosphorus and nitrogen, respectively.

Water quality modelling - ELCOM

ELCOM (Estuary, Lake, Coastal Ocean Model) is a three-dimensional (3-D) numerical model (Hodges & Dallimore, 2001) that uses hydrodynamic and thermodynamic models in order to predict velocity, salinity and temperature in waterbodies. The hydrodynamic model solves the unsteady, viscous Navier-Stokes equations for incompressible flow using the hydrostatic assumption for pressure. A Euler-Lagrange method is used for advection of momentum with a conjugate-gradient solution for the free-surface height (Casulli & Cheng, 1992). Passive and active scalars are advected using a conservative Ultimate Quickest discretization (Leonard, 1991). ELCOM was also coupled to CAEDYM for the purpose of resolving horizontal distributions of biological and chemical variables.

E. coli modelling

For modelling of *E. coli*, the following assumptions were used:

- Bacteria are present in the water column and do not accumulate in the sediment;
- Bacteria do not grow in the lake;
- Mortality can be modelled using a temperature dependent function according to first-order kinetics;
- Higher mortality rates are associated with higher salinity and UV radiation.

Forcing variables for modelling

Lake inflow volumes and nutrient concentrations were derived from a linked combination of specialised catchment models. The specific details of this modelling are not covered in this report. Briefly, hill country flows are modelled with top TopNet (NIWA), which is a semi-distributed hydrological model for simulating catchment water balance and flow. This flow is then assimilated by the United States Geological Survey (USGS) model ModFlow, which is a 3-D finite difference coupled groundwater/surface water model. Groundwater contaminant flow was modelled using the Modular 3-D Multi-Species Transport Model (MT3DMS) for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems. The model eSource was used to model surface water contaminant flow. The resulting flow and nutrient concentrations entering the lakes were input to 1-D and 3-D lake models at daily time-step.

A daily water balance was determined for each lake, which included inflows, estimates of groundwater inflow, rainfall and calculated evaporation from estimates of the evaporative heat flux (Fischer, 1979) and the saturation vapour pressure, together with water-level induced (Fig. 5) changes in lake volume. Where outflow measurements were unavailable (i.e., for Lake Onoke and before ADCP flow data were available for Lake Wairarapa), a residual term in the water balance was used to derive a daily outflow.

Meteorological forcing of DYRESM included daily average air temperature (ºC), shortwave radiation (W m^{-2}), cloud cover (fraction of whole sky), vapour pressure (hPa), wind speed (m s^{-1}) and rainfall (m) (Fig. 6). Meteorological forcing of ELCOM included daily average wind speed (m s^{-1}), direction (degrees), air temperature (ºC), shortwave radiation (W m^{-2}), atmospheric pressure (Pa), relative humidity (% fraction), rainfall (m) and cloud cover (fraction of whole sky).

Lake bathymetry data was sourced from GWRC, and originated from ADCP soundings collected in 2010.

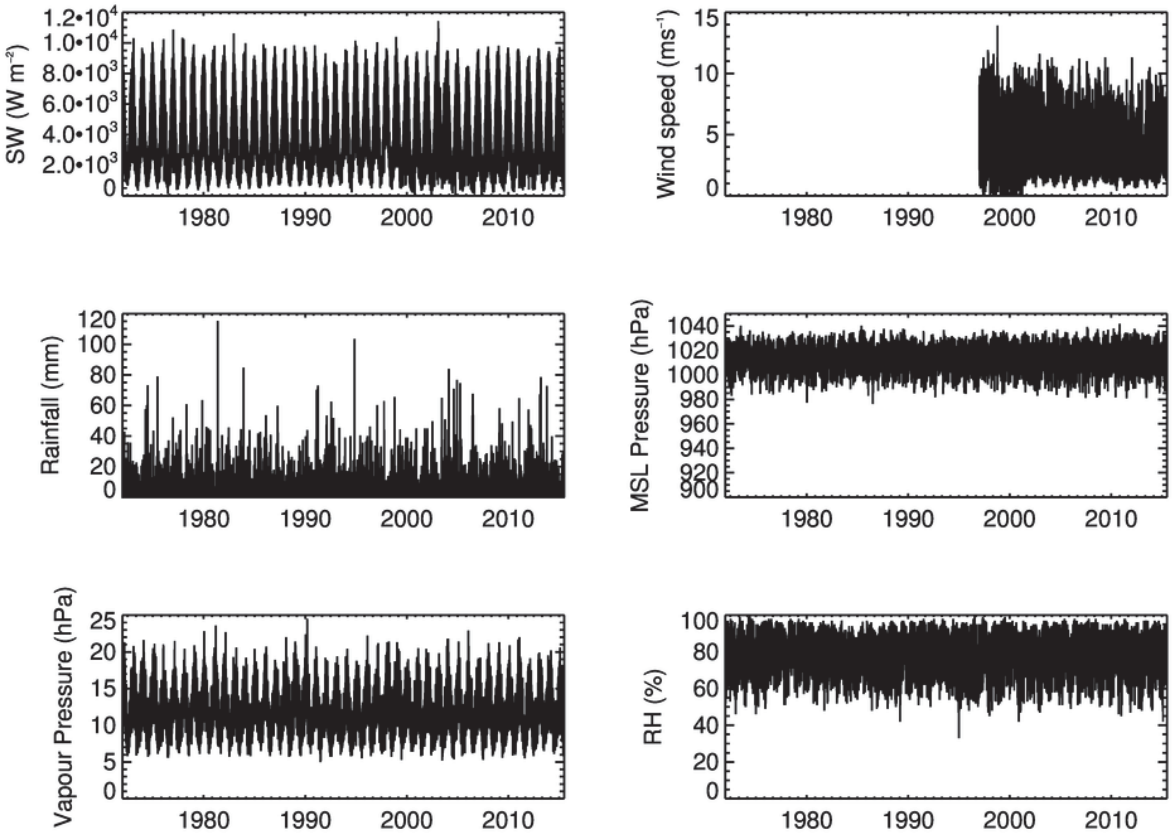

Fig. 4. Meteorological data used as input to DYRESM. SW is shortwave radiation. Data were obtained from the NIWA Virtual Climate Station data. Wind speed data was not available in the VCN until 1997.

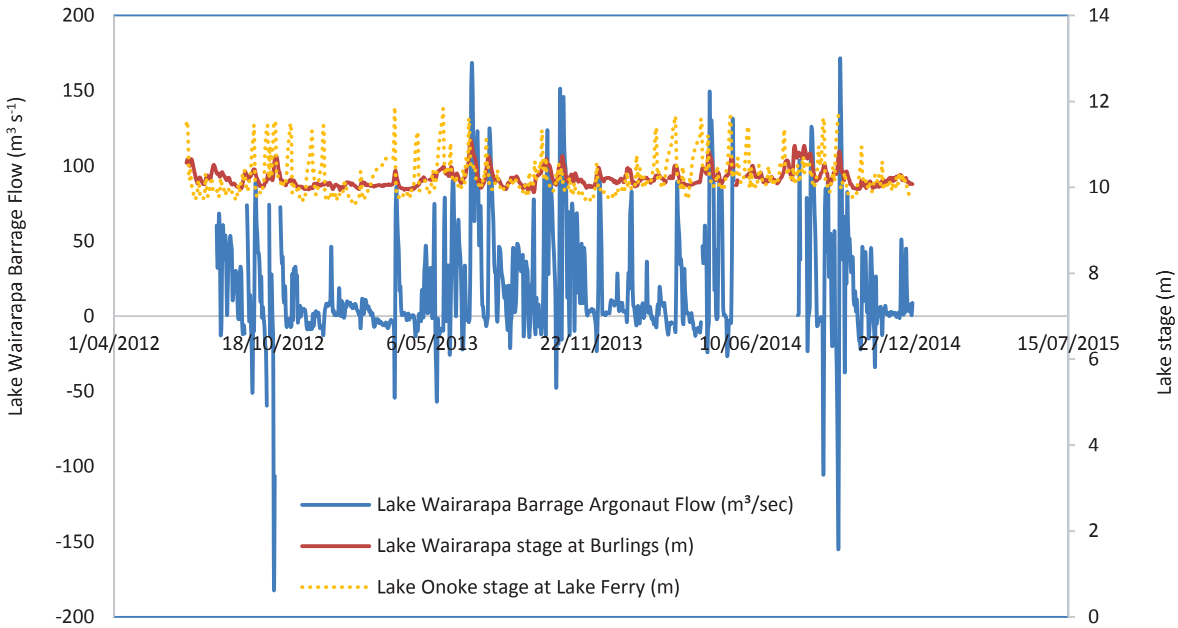

Figure 5. The stage of Lake Wairarapa (red line, right axis) and Lake Onoke (orange dashed line, right axis), and Lake Wairarapa barrage flow (blue line, left axis).

Progress to date one-dimensional and three-dimensional

One-dimensional and three-dimensional ecologically coupled hydrodynamic models have been created for lakes Onoke and Wairarapa. The modelling includes generating inputs for bathymetry (1D hypsography, 3D cells), formatting meteorological forcing data inputs, and initial testing of models (without inflow data).

Future work

A large component of the work will involve calibration/validation of 1D and 3-D models using in situ water quality data measured by the Greater Wellington Regional Council. Ideally, the parameterisations will be identical for the two model types but not necessarily so since there may be numerical factors that will necessitate individualised calibrations for at least some parameters in the models.

Calibrated models will then be used to determine the likely water quality and ecological effects of specific management scenarios. The selection of these scenarios and the number of them will need to be carefully considered alongside GWRC, other contractors, and stakeholders.

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