# Quantifying lake hydrological and isotopic responses to climate change: A coupled hydrologic-isotopic mass balance model applied to two Australian maar lakes

Thesis submitted in accordance with the requirements of the University of Adelaide for an Honours Degree in Geology.

Martin James Ankor
November 2015

THE UNIVERSITY
of ADELAIDE

# QUANTIFYING LAKE HYDROLOGICAL AND ISOTOPIC RESPONSES TO CLIMATE CHANGE: A COUPLED HYDROLOGIC-ISOTOPIC MASS BALANCE MODEL APPLIED TO TWO AUSTRALIAN MAAR LAKES

## LAKE HYDROLOGIC-ISOTOPIC MODELLING

## ABSTRACT

A hydrologic-isotopic mass balance model was developed and applied to Lakes Bullen Merri and Gnotuk in the Newer Volcanic Province, Australia to investigate the influence of basin morphometry upon a lake's hydrological and isotopic response to climate change. Model calibrations were successful from 1965 to 2001, however no calibration simulated an extreme lake level change from 1889 to 2006. This is interpreted to reflect that catchment flow to the lake is not proportional to catchment area, suggesting an additional influence from groundwater, and demonstrating the need for long-term lake monitoring documenting a range of lake conditions. The model broadly captures change in lake $\delta^{18}O$ and $\delta D$, based upon a sparse monitoring dataset. Both observed and modeled values indicate opposing trends in $\delta^{18}O$ and $\delta D$, which implies lake water re-equilibration to past climate change. Experiments were carried out to explore the influence of lake morphology on both the timing and extent of isotopic responses to changes in hydroclimate. Following a shift in precipitation, lake water isotope ratios underwent transient excursions opposite in sign to the precipitation change, before returning to an equilibrium value. Lakes with shallower basin slopes resulted in more rapid excursions with a lower magnitude. Lakes with longer residence times had longer and more subdued excursions. Applying a 1400 year hypothetical climate with both El Nino Southern Oscillation (ENSO) type cycles and hydroclimate shifts to the Gnotuk basin suggested that on the shallow slopes at lower lake levels, the seasonal isotopic cycle would obscure both ENSO cycles and hydroclimate shifts, while at higher lake levels and steeper basin slopes, the excursions following hydroclimate change may became identifiable. These results demonstrate that lake isotopic studies should target records that capture isotopic composition over several years, or during specific times of the year, so as to minimise the seasonal isotopic cycle.

## KEYWORDS

CHIMBLE, Model, Isotopes, Hydrology, Lakes, Victoria, Australia, Palaeoclimate

## TABLE OF CONTENTS

# LIST OF FIGURES AND TABLES

## INTRODUCTION

Lake sediments are important archives of past climate change, capturing the complex interaction between climate, geology, topography, ecology and hydrology (Cohen 2003). The palaeo-ecological and geochemical composition of lake sediments are important tracers of past climate and hydrological change, in particular recording changes in water depth and chemistry (Jones et al. 1998, Donders et al. 2007, Steinman et al. 2012, Van Boxel et al. 2013, Wilkins et al. 2013, Barr et al. 2014). Lakes are particularly sensitive to changes in hydroclimate, reflected in diatom assemblages (Fritz et al. 1991, Barr et al. 2014), and in the oxygen ($\delta^{18}O$) isotope composition of carbonates (Ricketts and Johnson 1996, Steinman et al. 2012). However, lake hydrology and chemistry respond non-linearly to hydroclimate changes and these responses differ between lakes (Battarbee 2000, Wigdahl et al. 2014). Consequently, lakes within close geographic proximity, perhaps even sharing the same climate, will rarely produce identical palaeo-records, undermining both the confidence in those records and efforts to synthesize composite regional palaeoclimates (Tierney et al. 2013, Tyler et al. 2015). Understanding and quantifying lake hydrological and chemical response to climate is an important step towards developing accurate records of past climate change.

Coupled hydrologic-isotopic balance models provide a method to resolve some of the uncertainties related to a lake's hydrological and chemical responses to climate by quantifying the various hydrologic fluxes and their isotopic composition through the lake and catchment. Several researchers have developed hydrologic-isotopic models, generally either for palaeoclimate studies (Jones et al. 2005, Steinman et al. 2012) or for determining source water contributions and tracing fluxes through a lake system

(Gibson et al. 2002, Shapley et al. 2008, Stets et al. 2010). These models range in complexity from lake only models (Hostetler and Benson 1994, Benson and Paillet 2002) to models that incorporate catchment areas, soil types and some groundwater effects (Jones et al. 2005, Steinman et al. 2010, Steinman et al. 2012). The history of hydrologic-isotopic lake models appears to show a lack of continuity in both the conceptual structure of the modelling and in the choice of programming language. Therefore, in addition to the ongoing development and application of hydrologic-isotopic models, there is a need for development of an open, extensible framework that can be updated as modelling methods are improved.

Australian lake records have global significance due to their location between the Pacific, Indian and Southern Oceans and accompanying climate systems and the sparsity of Southern Hemisphere palaeoclimate proxies (Neukom and Gergis 2012, Gouramanis et al. 2013). Hydrological balance models have been applied to some Australian lakes for both palaeoclimate reconstruction and lake level and salinity projections (Jones et al. 1998, Jones et al. 2001, Yihdego et al. 2014, Yihdego and Webb 2015), however, coupled hydrologic-isotopic models are yet to be applied to Australian lakes. The crater lakes of the Newer Volcanic Province in Victoria and South Australia are ideal for modelling as many have a long history of palaeoclimate research and monitoring data (Gouramanis et al. 2013). In particular, the neighbouring lakes Gnotuk and Bullen Merri share an identical climate while displaying different hydrological behaviour (Jones et al. 1998, Jones et al. 2001, Leahy et al. 2010), thereby providing an ideal testing ground for model development.

This study translates and expands upon the hydrologic-isotopic model of Steinman et al. (2010) to examine lake hydrological and isotopic responses to climate forcing in south eastern Australia. In particular, examining the following hypotheses:

- Hydrological and isotopic change within lakes of the Newer Volcanic Province can be accurately modelled as a function of basin morphology and climate, particularly using the model of Steinman et al. (2010).
- The hydrological and isotopic response of a lake to changes in hydroclimate is a predictable function of basin morphology.
- Lake oxygen and hydrogen isotope concentrations are correlated to the lake hydrology, and can be used to infer past lake conditions.
- A lake's hydrological condition and basin morphology determines the hydrological and isotopic sensitivity of the lake to climatic changes of differing frequencies and magnitudes.

# BACKGROUND

## Analysis of models

Hydrologic-isotopic mass balance modelling is a natural extension to hydrological mass balance modelling, a common technique used in many fields, ranging from lake (Jones et al. 2001, Yihdego and Webb 2015) and catchment studies (Boughton 2005), to agriculture (Panigrahi and Panda 2003), and global climate simulations (Neilson 1995). Hydrologic-isotopic models extend hydrological models by linking the hydrological mass balance to equations describing isotopic mixing and fractionation (Dincer 1968, Gat 1981, Gonfiantini 1986, Gibson et al. 2015). As the hydrological mass balance is a result of the sum of the inflows and outflows of a system, so too must the isotopic values balance (Jones et al. 2005).

From the models reviewed (Table 1), it is apparent that many different modelling approaches have been used for the investigation of lake hydrochemical behaviour. Models range from relatively simple spreadsheet models (Becht and Harper 2002, Yihdego and Webb 2012), to more complex models, capable of modelling stratification and lake isotopic evolution (Steinman et al. 2010). Generally speaking, lake models are developed for specific lakes, and often lack sub-routines needed for different lakes. Therefore, there is a need for a general model adaptable to different lakes and able to utilise datasets of varying completeness, without extensive recoding and with a modular framework that can be expanded upon in future studies. From the models reviewed (Table 1), the Steinman et al. (2010) model was chosen as the basis for this study, as it appeared most adaptable to future development and has demonstrated effectiveness in modelling evaporative lake systems in the North Western USA.

**Table 1: Models considered as a basis for the study.**

| Model | Purpose | Language | Evaporation | Isotope Modelling | Fractionation | Catchment & surface inflow | Soils & evapotranspiration | Groundwater aquifers | Snowpack | Bathymetry used in study. | Lake Stratification | Salinity | Deep lake heat storage | Other Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jones et al. 2001. Kirono et al, 2009 | Palaeoclimate | Fortran | CRLE (Morton 1983) | No | N/A | Percolation through soil to subsurface drainage (baseflow) | Single layer. CRAE (Morton 1983) | Darcy (1856) | No | Survey | No | Yes | Yes | Applied to lakes in Newer Volcanic Province. |
| Becht and Harper, 2002 | Safe yield/ abstraction | Spreadsheet | Meteorological records | No | N/A | Gauged river inflow | No | Hypothetical aquifer used as lake buffer | No | Survey | No | No | No | Lake Naivasha, Kenya. |
| Yihdego and Webb, 2012 | Hydrological and salinity budgeting | Spreadsheet | Meteorological records | No | N/A | Tanh method (Grayson et al, 1996) | No | Darcy (1856) & bucket model | No | Estimated from Landsat images | No | Yes | No | Applied to lakes in the Newer Volcanic Province. |
| Van Boxel et al, 2013 | Palaeoclimate |  | Penman, 1948. | No | N/A | Runoff & delayed percolation to subsurface drainage | Single layer. Penman 1948 + crop coefficient + linear relation to soil moisture | No | No | Estimated | No | No | No | Gridded lake model. Applied to Lake La Cocha, Colombia. |
| Hostetler & Benson, 1994 | Palaeoclimate (Benson & Paillet 1994) | Fortran | Brutsaert, 1982 | Yes | Benson & White, 1994 (based on Craig & Gordon, 1965) | Gauged river inflow | No | No (Can be included if fluxes are known). | No | Survey | Physically modelled (Hostetler & Bartlein 1990) | No | Yes | Applied to Pyramid, Owens, and Walker lakes, Nevada. |
| Gibson et al, 2002 | Throughflow, residence time and catchment runoff. |  | Interpolated from meteorological records | Yes | Craig & Gordon, 1965 | Model result | No | Model result | Yes | Survey/ Estimated | No | No | No | Uses isotopic observations to estimate difficult to measure water fluxes. |
| Jones et al, 2005 | Palaeoclimate |  | Penman, 1948. (Simplified, Linacre 1992) | Yes | Both Craig and Gordon, 1965, and Benson and White, 1994. | Runoff coefficient | No | Estimated during calibration. | No | Oblate Spheroid | No | No | No | Applied to Nar, Golu, Turkey, |
| Shapley et al, 2008 | Palaeoclimate, Groundwater influence | Visual Basic | Regional Penman calculations | Yes | Majoube (1971) Gonfiantini (1986), Benson & Paillet (2002) | Groundwater from solute basis analysis | No | As per catchment | No | Survey | Empirically specified | No | No | Applied to Evans Lake and Jones Lake, Montana, USA. |
| Steinman et al, 2010 | Palaeoclimate | Stella | Penman, 1948. (Simplified, Valiantzas, 2006) | Yes | Craig & Gordon, 1965 | Runoff and subsurface drainage | 2 layers. Penman, 1948 (Simplified, Valiantzas, 2006). | Outseepage estimated during calibration | Yes | Survey | Empirically specified | No | No | Applied to Castor and Scanlon Lakes, Washington State. |

## Geological setting

The Newer Volcanic Province is a region of Pliocene to Holocene basaltic plains unconformably overlying older igneous, metamorphic and sedimentary formations in the south east of South Australia and western Victoria (Dahlhaus et al. 2003). The basalt forms a 10-130 m thick unconfined aquifer, dotted with over 416 eruption centres, consisting of lava shields, scoria cones, tuff rings and maars (Boyce 2013, Yihdego et al. 2014).

Some of these eruptive centres have since formed significant lakes, which are of particular interest to palaeoclimate research due to their location between the Pacific, Southern and Indian Oceans and accompanying climate systems: the El Nino Southern Oscillation (ENSO), the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD) respectively (Fig. 1)(Gouramanis et al. 2013).

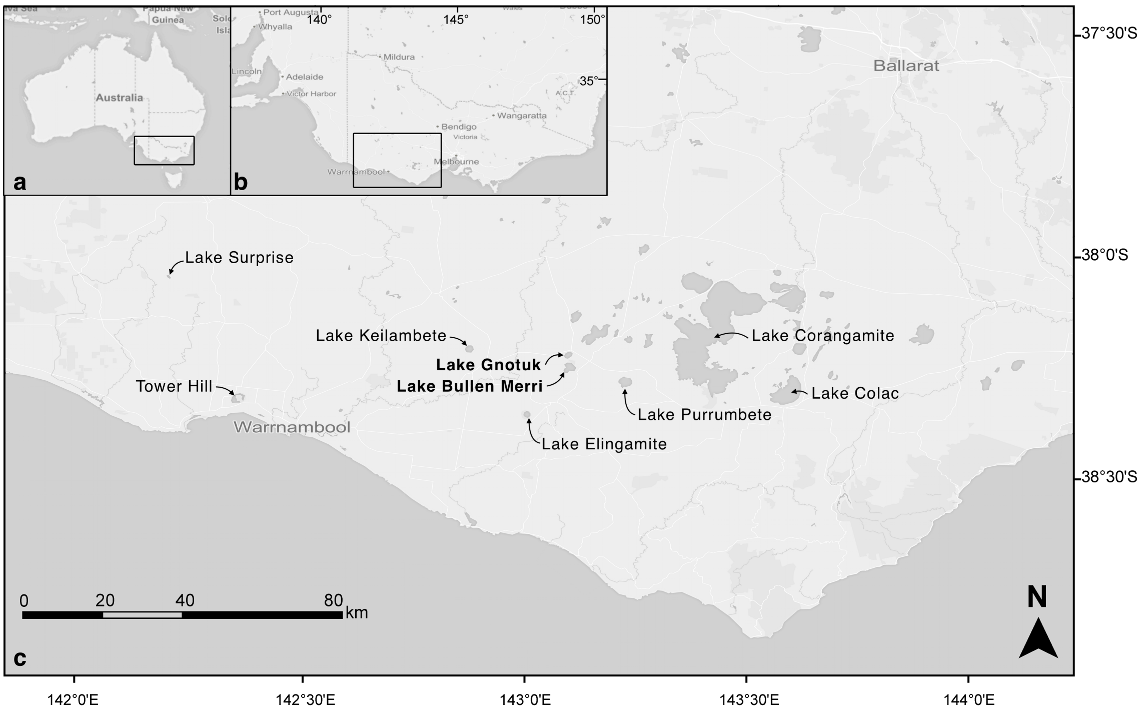

**Figure 1: (a) Global setting. (b) Regional setting. (c) Location of some key lakes of the Newer Volcanic Province, including the two modelled lakes (in bold). Sea is shaded grey in all figures. Adapted from Tyler et al. (2015).**

32 lakes in the Province were investigated to determine their suitability for modelling (Table 2). Of the 32 lakes over half were removed from consideration as they are susceptible to drying out. Of the remainder, only 5 were found to have water level data – a primary requirement for model calibration. These were Lakes Keilambete, Gnotuk, Bullen Merri, Purrumbete and Blue Lake. Of those, Blue Lake and Lake Keilambete are known to have significant or complex groundwater influence (Leaney et al. 1995, Jones et al. 2001). Lake Purrumbete has a complex catchment, consisting of between 30km$^2$ (Yihdego et al. 2014) to 52 km$^2$ of undulating plains, and has been subject to numerous alterations to surface hydrology and outflow in the last century (Yihdego et al. 2014). Lake Gnotuk and Bullen Merri however, provide an excellent testing ground for a new model, being in neighbouring craters, with straightforward geomorphology and differing responses to climate (Fig. 2).

**Table 2: Candidate lakes of the Newer Volcanic Province. Unticked boxes do not necessarily mean that a particular dataset is not available as once a lake failed to meet one criterion, no further investigation was carried out.**

| Lake Name | Latitude (GDA94) | Longitude (GDA94) | Susceptible to drying | Meteorological Data | Topographic Data | Soil Data | Salinity | Isotope Data | Water Temperature | Stratification Profiles | Bathymetry | Water Level Data | Geology/ Hydrogeology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Blue Lake** | 37°50'48.72" S | 140°46'39.79" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| **Lake Gnotuk** | 38°13'14.07" S | 143°06'08.41" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| **Lake Bullen Merri** | 38°14'54.34" S | 143°06'14.28" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| **Lake Purrumbete** | 38°16'54.24" S | 143°13'54.06" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ |
| **Valley Lake** | 37°50'24.42" S | 140°46'03.72" E | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☑ | ☑ | ☑ | ☑ |
| **Lake Keilambete** | 38°12'26.92" S | 142°52'49.33" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☐ | ☑ | ☐ | ☑ | ☑ | ☑ |
| **East Basin Lake** | 38°19'22.39" S | 143°26'52.03" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☑ | ☐ | ☑ |
| **West Basin Lake** | 38°19'41.35" S | 143°27'11.31" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☑ | ☐ | ☑ |
| **Lake Leake** | 37°36'47.21" S | 140°35'19.57" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☑ | ☐ | ☑ |
| **Lake Edward** | 37°37'27.12" S | 140°36'15.40" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☑ | ☐ | ☑ |
| **Lake Surprise** | 38°03'40.18" S | 141°55'20.10" E | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ |
| **Lake Elingamite** | 38°21'20.37" S | 143°00'33.93" E | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ | ☐ |
| **Lake Tooliorook** | 37°58'50.07" S | 143°16'16.01" E | ☐ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Mumblin** | 38°19'06.04" S | 142°54'49.26" E | ☐ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Lake Corangamite** | 38°11'02.72" S | 143°24'36.24" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☑ | ☐ |
| **Lake Colac** | 38°18'26.42" S | 143°35'55.60" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☑ | ☐ |
| **Lake Bolac** | 37°43'43.19" S | 142°51'34.25" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☑ | ☐ |
| **Lake Struan** | 38°00'54.93" S | 143°24'59.86" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Rosine** | 38°01'57.65" S | 143°34'14.25" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Gnarpurt** | 38°03'24.04" S | 143°23'41.74" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Cundare Pool** | 38°05'29.03" S | 143°35'12.52" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Kooraweera Lakes** | 38°05'50.70" S | 143°16'52.95" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Milangil** | 38°06'31.12" S | 143°12'54.30" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Terangpom** | 38°07'57.71" S | 143°19'35.06" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Cundare** | 38°09'17.38" S | 143°37'04.54" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Colongulac** | 38°10'24.68" S | 143°10'00.32" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Murdeduke** | 38°10'35.77" S | 143°54'03.80" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Modewarre** | 38°14'41.30" S | 144°06'34.88" E | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ |
| **Lake Weering** | 38°05'03.71" S | 143°41'07.59" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Lake Beeac** | 38°12'26.20" S | 143°37'19.56" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Lake Cartcarrong** | 38°14'35.55" S | 142°27'13.49" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Tower Hill** | 38°19'08.89" S | 142°21'31.24" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| **Lake Wangoom** | 38°20'40.30" S | 142°35'23.96" E | ☑ | ☑ | ☑ | ☑ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |

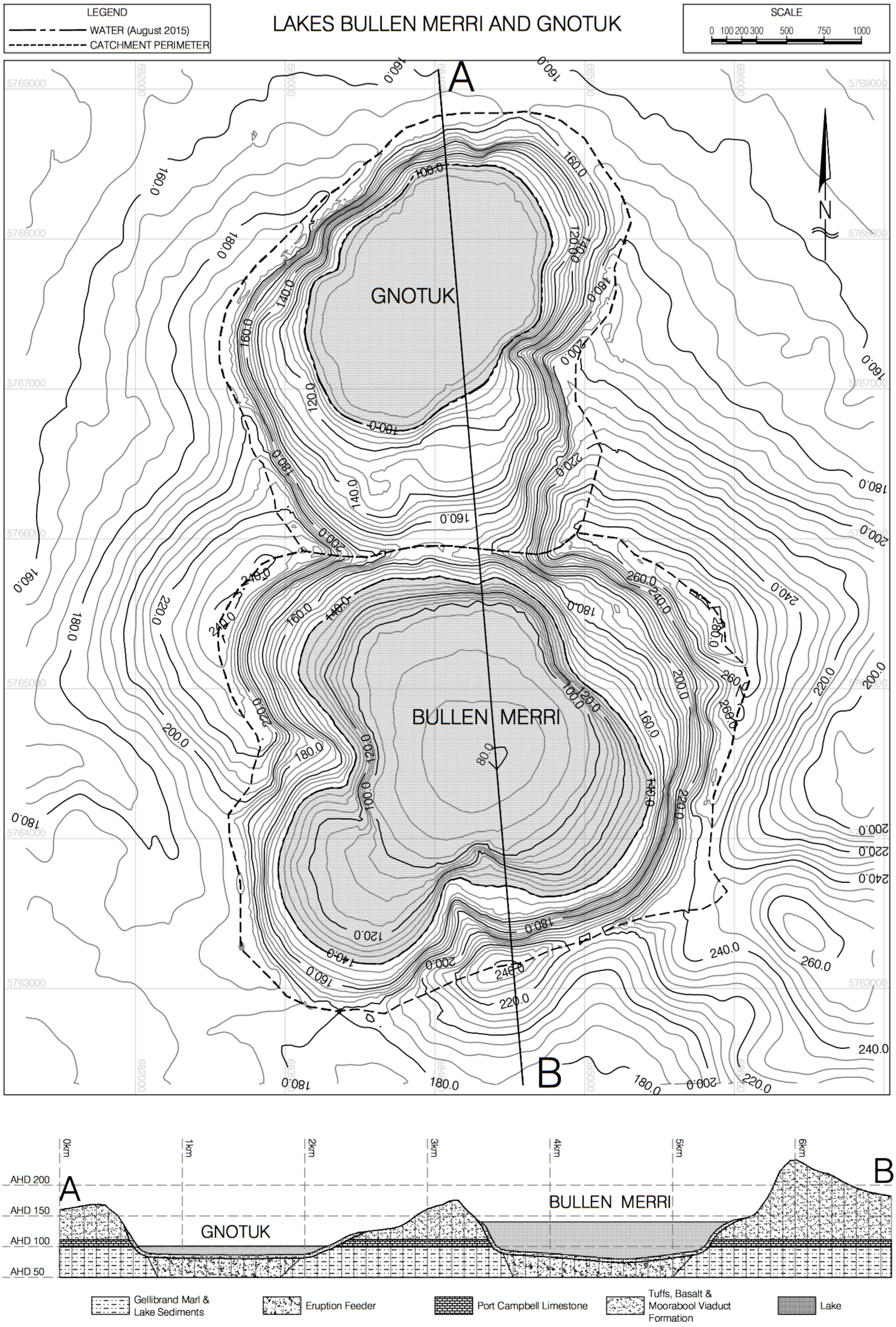

**Figure 2: Map and cross section of Lake Bullen Merri and Lake Gnotuk, showing catchment areas, current water levels and topopraphy. Subsurface structures and stratigraphy are indicative only, from Jones (1995) and Yihdego (2008). Coordinates shown: MGA, Heights: AHD.**

Lake Gnotuk is a flat bottomed, hypersaline lake, currently around 15 m deep (100.54 m AHD, August 2015), with a surface area of around 205 ha, and a catchment area of around 617 ha (Fig. 2). In contrast, Lake Bullen Merri is a conical, brackish, lake, with a current depth of around 60 m (140.04 m AHD, August 2015), a surface area of around 435 ha, and a catchment of around 886 ha. At both lakes water levels have dropped around 20 m since 1881 (Jones et al. 2001).

Surficial inflow to the lakes is derived solely from the catchment, with the exception of overflow from Bullen Merri to Gnotuk that occurs when Bullen Merri reaches a level of AHD 168.4 m (Jones et al. 2001), last observed in 1841 (Currey 1970). Both lakes are thought to have little groundwater input (Jones et al. 2001), and share similar geology. Both lakes lie within maars surrounded by, in sequence: younger tuffs at the surface, a basalt volcanic sequence, the Moorabool Viaduct Formation of fluvial and marine deposits, the Port Campbell Limestone, and the Gellibrand Marl (Fig. 2) (Jones et al. 2001, Leahy et al. 2010, Yihdego et al. 2014). Hydrogeologically the upper stratigraphic units – tuffs/basalt and the Moorabool Viaduct Formation – can be treated as one, as they share similar hydraulic conductivity ($10^{-2}$ to $10^{1}$ and $10^{-3}$ to $10^{2}$ m/day respectively) and are hydraulically connected (Dahlhaus et al. 2002, Yihdego et al. 2014). The Port Campbell Limestone is a regional aquifer, which is thought to have limited influence on the lakes, due to its low yield and slope away from the lakes (Jones et al. 1998, Jones et al. 2005, Yihdego et al. 2014). The bases of Lake Gnotuk and Bullen Merri lie in the Gellibrand Marl, an aquiclude preventing any interaction with deeper groundwater systems (Tweed et al. 2009, Leahy et al. 2010).

## Climatic setting

The Newer Volcanic Province is in a temperate climate, with a mean annual temperature of around 13º C, ranging from an average daily temperature of 18.9º C in summer to 8.4º C in winter. Annual rainfall is around 800 mm/year, predominantly from May to November, and yearly evaporation is around 1000-1100 mm/year (Jones et al. 2001, Kirono et al. 2009).

## Previous studies

Lake Gnotuk and Bullen Merri have a long history of palaeoclimatic research, and are of ecological and social significance (Kirono et al. 2009). Of particular relevance to this study is the hydrological modelling of Lakes Bullen Merri, Gnotuk and Keilambete by Jones et al. (2001). A hydrological mass balance model was developed to investigate changes in precipitation/evaporation ratio (P/E) in the past 16,000 years based on lake level changes. This model has also been used to develop projections for lake level and salinity up to the year 2100 (Kirono et al. 2009). The Jones et al. (2001) model links the evaporation model of Morton (1983), to lake water balance and a catchment soil model. Rainfall on the catchment undergoes evapotranspiration or percolates through the soil layer to subsurface drainage and then flows to the lake. A percolation coefficient, KQ, defined through model calibration, determines the rate of percolation. Jones et al. (2001) observed that calibrations starting from an earlier date required a lower KQ value than equivalent calibrations using only the more recent data, suggesting an increase in percolation as the lake levels dropped.

## METHODS

In this study a Coupled Hydrologic-Isotopic Mass Balance model for Lake Environments is developed, which for the sake of brevity will be called CHIMBLE. CHIMBLE is coded in R (Ihaka and Gentleman 1996) and is currently designed for use on lakes with limited groundwater interaction. CHIMBLE is based on the model introduced by Steinman et al. (2010), using the principle that any change in the hydrologic and isotopic mass balance of a lake is the sum of the input and output fluxes, as described in equations 1 and 2 (Dincer 1968, Gat 1981, Gonfiantini 1986, Steinman et al. 2010, Gibson et al. 2015).

$$\frac{\Delta V_L}{\Delta t} = \sum I - \sum O \qquad (1)$$

$$\frac{\Delta V_L \delta_L}{\Delta t} = \sum I\delta_I - \sum O\delta_O \qquad (2)$$

$\Delta V_L$ represents a change in lake volume, and $\sum I$ and $\sum O$ are the total inflow and outflow of the lake over a period of time. δ is the hydrogen or oxygen isotopic composition of the water within a certain hydrological component as denoted by subscripts (eg: $\delta_L$ is isotopic composition of the lake). The definition of δ follows standard practice: $\delta_X = 1000((R_X/R_{SMOW})-1)$, where R is $^{18}O/^{16}O$, or $^2H/^1H$, and SMOW refers to Vienna-standard mean ocean water.

CHIMBLE is designed to model the lake hydrology and surface/subsurface flows of water in the upper layers of the soil as far as the perimeter of the catchment. Lake stratification and slower water flow paths, such as the containment of water in snowpack, or slower subsurface flows are also modelled (Fig. 3).

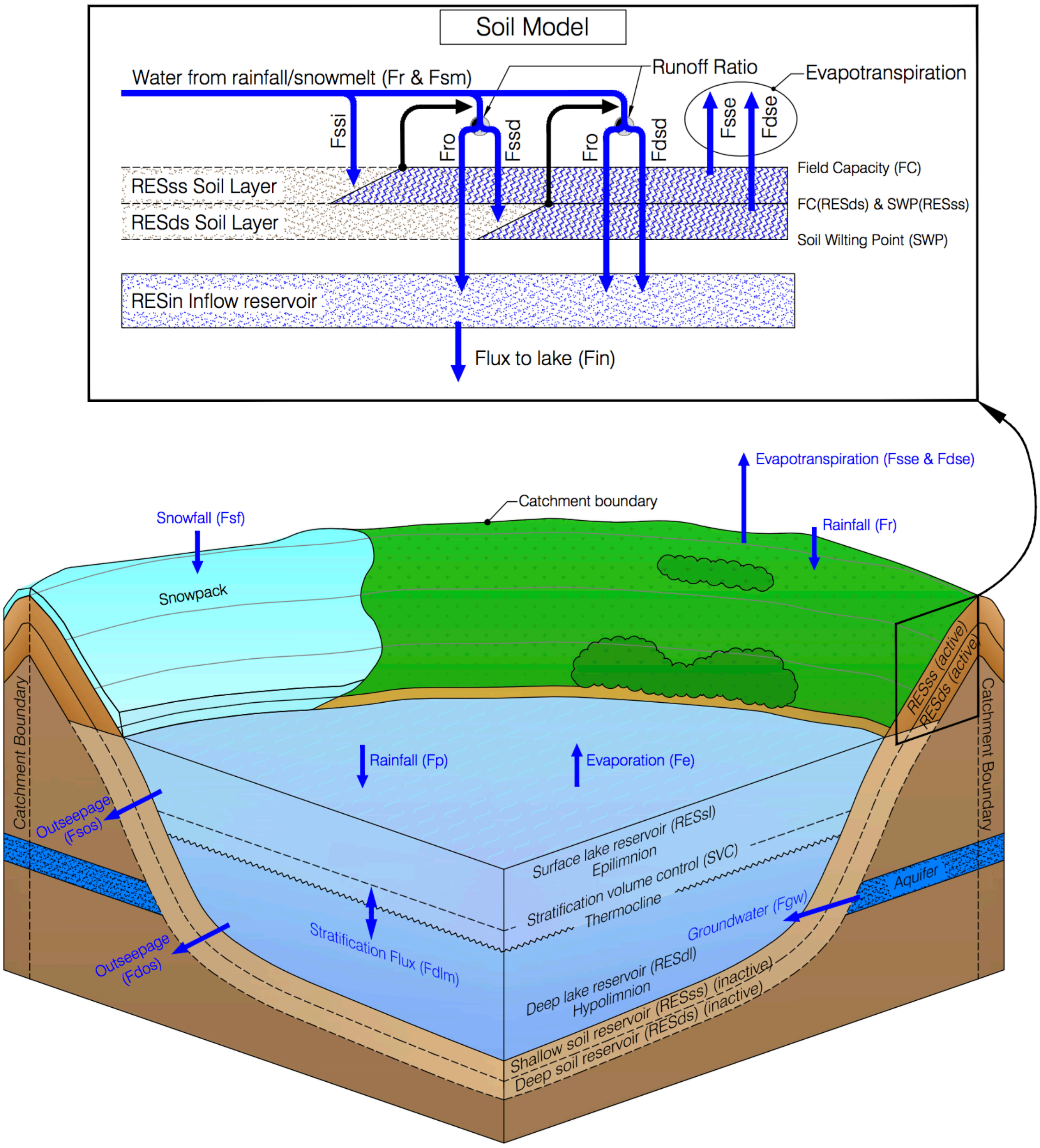

**Figure 3: Model schematic showing fluxes and reservoirs. The stratification flux represents the water that moves from the epilimnion to the hypolimnion or vice versa, as determined by observed lake stratification. In the soil model, water flux into the upper soil ($F_{SSI}$) occurs until the upper soil layer reaches field capacity. Then excess water is routed to the deep soil layer ($F_{SSD}$) until it reaches capacity, or as runoff ($F_{RO}$) depending on the specified runoff ratio. Once both soil layers are at field capacity, all incoming water is sent as runoff or deep drainage ($F_{DSD}$) to the inflow reservoir.**

CHIMBLE consists of multiple reservoirs and fluxes (Table 3, Fig. 3). For each time-step, reservoir volumes are determined from the addition and subtraction of incoming and outgoing fluxes respective to the previous reservoir volume, using Euler integration. CHIMBLE uses similar terminology to Steinman et al. (2010), with *RES* used to denote reservoirs and *F* used to denote fluxes (Table 3). A copy of the source code for CHIMBLE is included in the appendices.

**Table 3: List of key reservoirs, variables and fluxes used by CHIMBLE.**

Reservoirs (m$^3$)

| | |
|---|---|
| $RES_{SL}$ | Surface lake reservoir |
| $RES_{DL}$ | Deep lake reservoir |
| $RES_{SS}$ | Surface soil reservoir |
| $RES_{DS}$ | Deep soil reservoir |
| $RES_{IN}$ | Inflow reservoir |
| $RES_{SP}$ | Snowpack reservoir |

Fluxes (m$^3$ month$^{-1}$)

| | |
|---|---|
| $F_P$ | Precipitation over the lake |
| $F_{IN}$ | Catchment inflow to the lake |
| $F_E$ | Evaporation from lake surface |
| $F_{SOS}$ | Outseepage from surface lake |
| $F_{DOS}$ | Outseepage from deep lake |
| $F_{DLM}$ | Mixing between deep and surface lake |
| $F_R$ | Rainfall onto catchment area |
| $F_{SF}$ | Snowfall |
| $F_{SM}$ | Snow melt |
| $F_{SSI}$ | Surface soil infiltration |
| $F_{SSD}$ | Deep soil infiltration (from surface soil) |
| $F_{SSE}$ | Surface soil evaporation |
| $F_{SSD}$ | Deep soil evaporation |
| $F_{DSD}$ | Deep soil drainage |
| $F_{RO}$ | Surface runoff from catchment |

Meteorological variables

| | |
|---|---|
| $T_a$, $T_w$ | Air, water temperature (ºC) |
| RH | Relative humidity (%) |
| P | Precipitation (mm month/day$^{-1}$) |
| PET | Potential evapotranspiration(m month/day$^{-1}$) |
| E | Evaporation (m month$^{-1}$) |
| $ALB_L$ | Albedo for lake (unitless) |
| $ALB_E$ | Albedo for catchment (unitless) |
| au | Penman wind function (unitless) |
| WS | Wind speed (m s$^{-1}$) |
| $R_s$ | Solar radiation (MJ m$^{-2}$ d$^{-1}$) |
| $R_a$ | Extraterrestrial radiation (MJ m$^{-2}$ d$^{-1}$) |
| SL | Lake stratification depth (m) |

Catchment variables

| | |
|---|---|
| CAe | Catchment area (minus lake) (m$^2$) |
| $AWC_{SS}$ | Available water capacity of surface soil (m) |
| $AWC_{DS}$ | Available water capacity of deep soil (m) |
| $C_{IN}$ | Catchment inflow delay (unitless) |
| $C_{SR}$ | Lake outseepage rate (unitless) |
| SVC | Surface lake volume control (m$^3$) |
| $Kc_{SS}$ | Surface soil crop coefficient |
| $Kc_{DS}$ | Surface soil crop coefficient |
| $KcL_{SUM}$ | Lake maximum evaporation coefficient |
| $KcL_{WIN}$ | Lake minimum evaporation coefficient |

## Model developments

CHIMBLE is based on the hydrologic-isotopic model of Steinman et al. (2010) (hereby referred to as SRAB2010) however, there are numerous developments in both the structure and capabilities of the model.

- CHIMBLE is written in R (Ihaka and Gentleman 1996), an open source, statistical, programming language, making it more widely accessible and extensible, as well as compatible with a range of plotting and analytical scripts widely used in palaeo-environmental research. In contrast, SRAB2010 is written using Stella, a commercial modelling package.

- Hypsographic curves, linking a lake's volume, surface area and depth, are defined differently. CHIMBLE uses either loess smoothing (Cleveland 1981) or line segments to define the hypsographic curves, instead of the polynomial functions used by SRAB2010 and Benson and Paillet (2002). This technique allows for the formation of hypsographic curves of any complexity, derived from a simple table of height, area and volume for each lake.

- CHIMBLE can sample isotopic values from any specific depth, taking into account the stratification of the lake at that time.

- Thermal stratification – a climate controlled layering of lake waters (Imberger 2001) – is managed differently. In CHIMBLE, if the lake is fully mixed then fluxes are added or removed from the reservoir that currently represents the entire lake. This can occur during mixing events, when the hypolimnion reservoir ($RES_{DL}$) represents the entire lake volume, or when the lake is shallow, and the epilimnion reservoir ($RES_{SL}$) extends to the floor of the lake. Stratification is also interpolated from month to month to avoid sudden step changes in modelled lake isotopic values.

- The soil model used for the catchment differs significantly from that of SRAB2010. In SRAB2010 inflow to the catchment through rainfall and snowmelt infiltrates ($F_{SSI}$) the upper soil layer ($RES_{SS}$). In the subsequent time-step, if $RES_{SS}$ is saturated ($RES_{SS} > AWC_{SS}.CAe$), then any new inflow is divided, with 50% going to runoff ($F_{RO}$), and the remaining 50% as surface soil infiltration ($F_{SSI}$). From $RES_{SS}$ water is moved to the lower soil layer ($RES_{DS}$) as shallow soil drainage ($F_{SSD}$), and lost as evapotranspiration ($F_{SSE}$) based on the conditions of equation 3, 4 & 5.

$$F_{SSE} = \begin{cases} CAe.PET.dt^{-1} & RES_{SS} > CAe.PET \\ RES_{SS}.dt^{-1} & RES_{SS} \leq CAe.PET \end{cases} \tag{3}$$

$$F_{DSE} = \begin{cases} CAe.PET.dt^{-1} - F_{SSE} & RES_{DS} > CAe.PET - F_{SSE}.dt^{-1} \\ RES_{DS}.dt^{-1} & RES_{DS} \leq CAe.PET - F_{SSE}.dt^{-1} \end{cases} \tag{4}$$

$$F_{SSD} = (RES_{SS} - CAe.AWC_{SS}).dt^{-1} \tag{5}$$

$$F_{DSD} = \begin{cases} (CAe.PET.dt^{-1}) - F_{SSE} & RES_{DS} > CAe.PET - F_{SSE}.dt \\ RES_{DS}.dt^{-1} & RES_{DS} \leq CAe.PET - F_{SSE}.dt \end{cases} \tag{6}$$

In contrast, CHIMBLE incorporates components from many soil models (Palmer 1965, Black et al. 1969, Alley 1984, Allen et al. 1998, Panigrahi and

Panda 2003, Aydin 2008, Van Boxel et al. 2013). All fluxes are calculated in the current time-step, and are partitioned as each soil layer is saturated (Fig. 3). Runoff ratio can be set as a percentage of $F_{SSI}$ and evapotranspiration from the soil is determined as the product of potential evapotranspiration, a crop coefficient (Kc value), and linear interpolation between 0 at soil wilting point, and 100% at field capacity (equations 7 & 8).

$$F_{SSE} = \begin{cases} CAe.PET.Kc_{SS}.dt^{-1} & RES_{SS} > CAe.PET.Kc_{SS}.dt^{-1} \\ RES_{SS} & RES_{SS} \leq CAe.PET.Kc_{SS}.dt^{-1} \end{cases} \quad (7)$$

$$F_{DSE} = \begin{cases} CAe.PET.Kc_{DS}.dt^{-1} & RES_{DS} > CAe.PET.Kc_{DS}.dt^{-1} \\ RES_{DS} & RES_{DS} \leq CAe.PET.Kc_{DS}.dt^{-1} \end{cases} \quad (8)$$

Evapotranspiration occurs from both soil layers, but can occur at different rates using different Kc values, potentially enabling modelling of vegetation changes in a catchment.

- The evaporation equations of Penman (1948), and the simplified versions used in CHIMBLE and SRAB2010 do not take into account the heat storage capacity of large lakes, which absorb heat during summer, and release it during cooler months. For lakes the size of Bullen Merri this delays the annual peak in evaporation until mid to late autumn (Jones et al. 2001). CHIMBLE uses coefficients ($KcL_{SUM}$ & $KcL_{WIN}$) (Allen et al. 1998) to shift the peak evaporation using a sinusoidal, yearly wavelength.

## Data sources.

Catchment topography was digitised from 1:30K Vicmap (2014) topographic maps inside the catchments, and SRTM DEM-H DEMs (Gallant et al. 2011) outside the catchment perimeter. Bathymetry was digitised from surveys by Timms (1976), then scaled and aligned to best fit within the topography. The digitised contours were processed in 12D Model (www.12d.com) to form a topographic surface, and volumes, surface areas and heights were calculated from lake floor to the overflow at 0.2 m intervals. Catchment areas were defined by the direction of surficial flow, typically the crater rim.

SILO (Jeffrey et al. 2001) meteorological data was chosen for the climate data, providing continuous daily climate records from 1889 to present, covering Australia on a 0.05° grid. Daily average temperature was calculated as the mean of the maximum and minimum daily temperature. The average relative humidity was derived by determining the daily dewpoint temperature using the August-Roche-Magnus Approximation (Magnus 1844, Alduchov and Eskridge 1996) from the daily minimum and maximum humidity, then calculating the average humidity based on the average daily temperature. Wind data was extracted from 2m wind run grids developed by McVicar et al. (2008) covering the time period from 1975 to current. For data prior to 1975, the long-term average was used. Average monthly stratification data was determined from 3 years of observations by Timms (1976).

Lake water temperature has a correlation with both maximum monthly air temperature (Tibby and Tiller 2007) and average monthly air temperature. The relationship between lake temperature and average monthly temperature was derived from lake temperature data of Tibby and Tiller (2007) for Bullen Merri ($R^2 = 0.84$, n=179, 16 years) and Timms (1976) data for Gnotuk ($R^2 = 0.92$, n = 38, 3 years). These relationships were used to establish water temperatures for the duration of climate data (Fig. 4). The isotopic composition of precipitation was acquired from the Online Isotopes in Precipitation Calculator (OIPC) (Bowen and Revenaugh 2003, Bowen 2015), an interpolated isotope dataset derived from the Global Network of Isotopes in Precipitation (GNIP) data (Schotterer et al. 1996). Climate datasets for morphology experiments used the average temperature and precipitation deciles (http://www.bom.gov.au/climate/enso/) for El Niño, La Niña and neutral years to establish a hypothetical, average year for each ENSO mode.

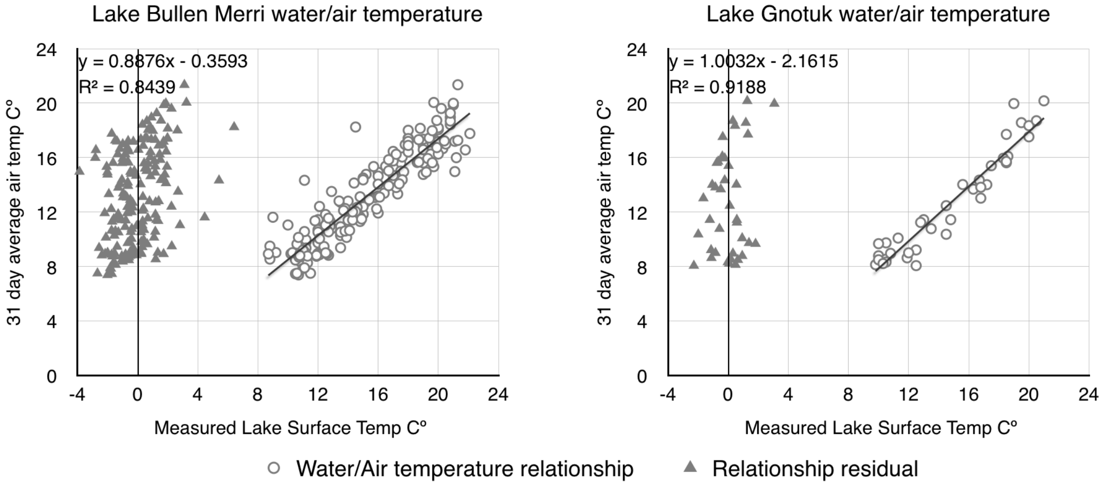

**Figure 4: Correlations between 31 day average air temperatures and observed water surface temperatures for Lake Bullen Merri and Gnotuk. Linear regression of temperature correlation (line), and residuals from the linear regression (triangles) also shown.**

## Model validation and calibration

To examine the effects of the different approaches between CHIMBLE and SRAB2010 the two models were compared using identical input data from Castor Lake, Washington, to achieve a steady yearly seasonal cycle. SRAB2010 is typically calibrated using outseepage ($C_{SR}$) and catchment inflow ($C_{IN}$) rates. As the primary difference between the models lies in the soil layer structure, for the model comparison, those variables were held constant between both models and the Kc values in CHIMBLE for the soil layers were changed in a stepwise fashion (Table 4: Steinman) to decrease evapotranspiration from the catchment until the equilibrium lake level matched that of SRAB2010.

Calibration of CHIMBLE for Lake Gnotuk and Bullen Merri required a different approach, as the hydrological flux through the catchment is quite different to that of the lakes studied by Steinman et al. (2010). Calibrations (Table 4) are named by the year that they began, and a suffix, defining how the $RES_{IN}$ value was determined: B – jump-start, E - estimated, D - daily data. “Jump-start” refers to a technique used to validate the estimated $RES_{IN}$. Calibrations were performed between key historical observations – 1889 to 1949, 1949 to 1965 and 1965 to 2006 – and the final value determined for $RES_{IN}$ used as a boundary condition for later calibrations, thereby giving those calibrations a “jump-start”. The rationale and implications of this method of calibration will be covered in the discussion.

**Table 4: Parameters for CHIMBLE model runs. Calibrations are defined as B/G = Bullen Merri/Gnotuk, year = calibration start year, J/E/D = jump-start method/estimation method/daily climate data. Last 4 rows provide parameters for the model runs used to jump-start calibrations. All model runs use monthly data unless otherwise specified.**

| Model Run | Catchment Area ($m^2$) | $AWC_{SS}$ (m) | $AWC_{DS}$ (m) | $C_{IN}$ | $C_{SR}$ | $RES_{SL}$ ($m^3$) | $RES_{DL}$ ($m^3$) | $RES_{IN}$ ($m^3$) | $RES_{SP}$ ($m^3$) | PWF | Runoff Ratio | $KCL_{SUM}$ | $KCL_{WIN}$ | KcSS | KcDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Steinman | 858000 | 0.023 | 0.023 | 0.21 | 0.016 | 50000 | 300000 | 20000 | 15000 | 1 | 50 | 1 | 1 | 0.347 | 0.347 |
| B 1889J | 8860412 | 0.12 | 0.12 | 0.01 | 0 | 72920033 | 183968729 | 500000 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1949J | 8860412 | 0.055 | 0.055 | 0.01 | 0 | 58188172 | 127750354 | 437344 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1965J | 8860412 | 0.035 | 0.035 | 0.01 | 0 | 60174241 | 121487836 | 3229721 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1965JD | 8860412 | 0.118 | 0.118 | 0.01 | 0 | 60174241 | 121487836 | 3229721 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1965ED | 8860412 | 0.105 | 0.105 | 0.01 | 0 | 60174241 | 121487836 | 2000000 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 2006JD | 8860412 | 0.04 | 0.04 | 0.01 | 0 | 52893291 | 108608578 | 2957666 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| G 1889J | 6174407 | 0.12 | 0.12 | 0.01 | 0 | 32983225 | 35039670 | 500000 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 1949J | 6174407 | 0.065 | 0.065 | 0.01 | 0 | 25864762 | 7841446 | 318536 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 1965J | 6174407 | 0.055 | 0.055 | 0.01 | 0 | 22217168 | 11047245 | 2785130 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 1965JD | 6174407 | 0.107 | 0.107 | 0.01 | 0 | 22217168 | 11047245 | 2785130 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 1965ED | 6174407 | 0.098 | 0.098 | 0.01 | 0 | 22217168 | 11047245 | 2200000 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 2006JD | 6174407 | 0.03 | 0.03 | 0.01 | 0 | 27641725 | 0 | 1969224 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G ENSO | 6174407 | 0.04 | 0.04 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1889-1949 | 8860412 | 0.23 | 0.23 | 0.01 | 0 | 72920033 | 183968729 | 500000 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| B 1949-1965 | 8860412 | 0.09 | 0.09 | 0.01 | 0 | 58188172 | 127750354 | 437344 | 0 | 0.3 | 100 | 0.65 | 1.25 | 0.7 | 0.8 |
| G 1889-1949 | 6174407 | 0.23 | 0.23 | 0.01 | 0 | 32983225 | 35039670 | 500000 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |
| G 1949-1965 | 6174407 | 0.09 | 0.09 | 0.01 | 0 | 25864762 | 7841446 | 318536 | 0 | 1 | 100 | 0.6 | 1.15 | 0.7 | 0.8 |

Both lakes were assumed to be terminal lakes and the $RES_{IN}$ reservoir considered as the unconfined aquifer. Outseepage ($C_{SR}$) of both lakes was set to zero, as the water table in the surrounding catchment is above lake level, and the Port Campbell Limestone shows no indication of recharge from the lakes based on salinity (Jones et al. 2001). Initial calibrations (B1965ED & G1965ED) were for the time period of monthly historical lake level data from 1965 to 2006 (Leahy et al. 2010). Then monthly data calibrations from 1889 to 2006 and 1949 to 2006 were performed to assess the usefulness of CHIMBLE over longer time periods during a significant change in lake water levels. The isotopic evolution of the lakes was also modelled with a short calibration from 2006 to 2015.

## Model experiments

To investigate the effects of catchment morphology, several hypothetical lake basins were constructed (Fig. 5). These basins were designed to allow lakes of similar volumes and surface areas to have differing basin slopes, ranging from 2% to 20%, and to investigate the effect of changing lake residence time (defined as total lake volume divided by total outgoing fluxes) through changing the lake volume while maintaining similar surface areas. A single, neutral year, repeated for 1200 years was used for climate data for the morphology experiments, with a stepped increase in rainfall of 5% between years 100 to 800.

Following the model experiments on the hypothetical lakes, another experiment was run using the Gnotuk catchment data and 1400 years of constructed climate data with every 5th year being an El Nino, and every 10th year a La Nina year (Table 3: G ENSO). Stepped increases in rainfall of 5% above average for years 200 to 400, and 10% above average for years 400 to 800 simulated long-term changes in precipitation.

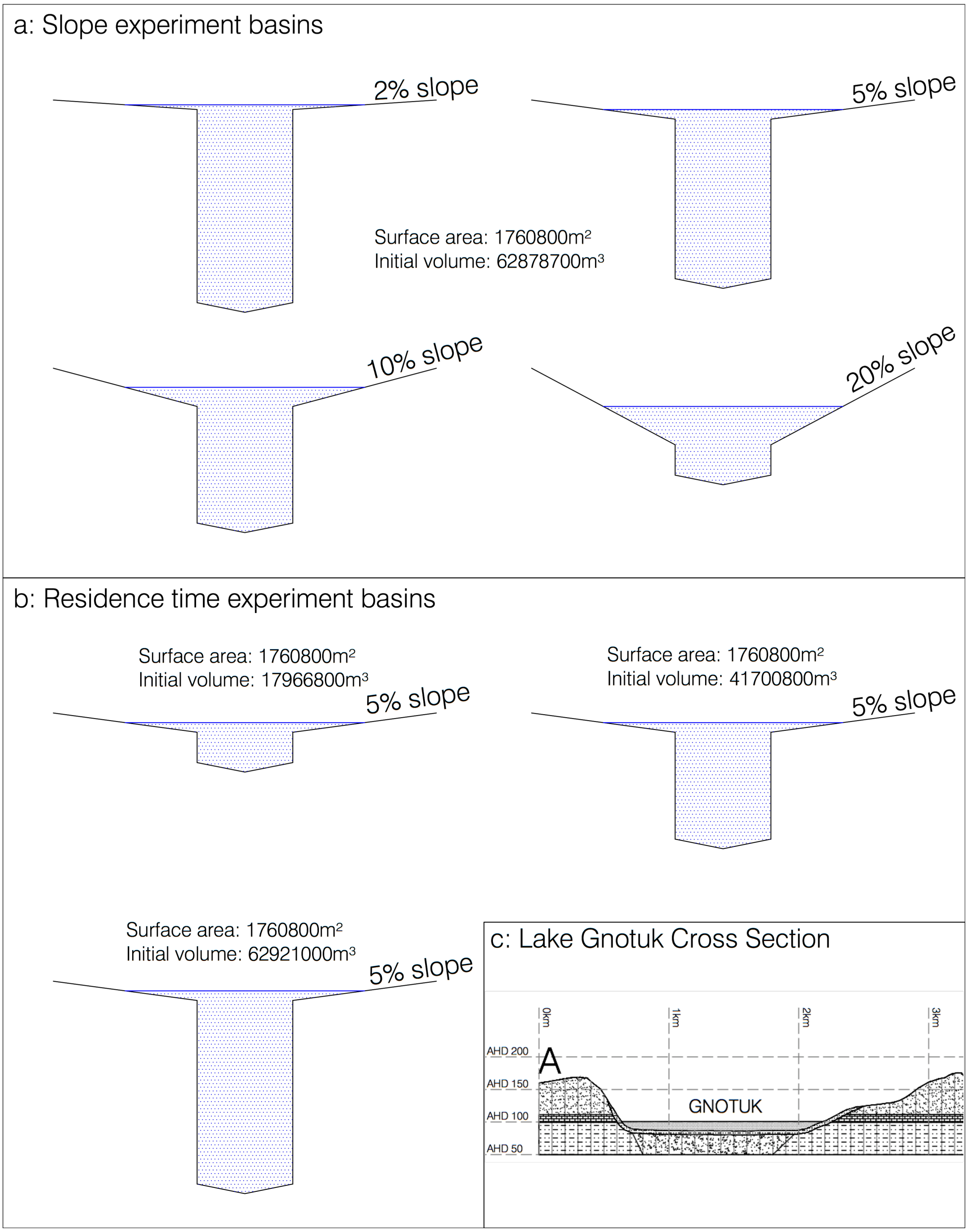

**Figure 5: Morphological experiment basin shapes (Not to scale). (a) Slope experiment basins share similar initial volumes and surface areas. (b) Residence time experiment basins share identical slopes and initial surface areas. (c) Lake Gnotuk basin used for the transient climate morphological experiment (See also Fig. 2).**

# RESULTS

## Model validation

To validate CHIMBLE against previous research, duplicate model runs were made with both CHIMBLE, running in R, and SRAB2010, in Stella. A Kc value of 0.347 for both upper and lower soil layers resulted in a similar equilibrium lake depth for both models of ~11.55 m (Fig. 6). The seasonal cycle was broadly similar between the two models, but had a larger amplitude in the CHIMBLE model run, resulting in lake level maxima and minima ~5 cm higher in June, and ~3 cm lower in November. A range of other Kc values for upper and lower soil layers (eg: 0.2 & 0.86, 0.45 & 0.16) produced similar results, with only minor monthly variations, so long as the flux through both soil layers to the inflow reservoir was similar. Initial runs produced very different seasonal cycles of $\delta^{18}$O between the models, being similar when the lake was stratified, but differing by up to ~ 9‰ when the lake was fully mixed during the winter months (Fig. 7). This occurred because SRAB2010 does not fully mix the lake, instead retaining a very thin surface lake reservoir. This thin surface reservoir does not represent the main lake isotopic composition, instead resulting from the remainder of the addition and subtraction of fluxes in each time-step and thereby acquiring an isotopic value close to runoff. To emulate this effect the minimum stratification depth in CHIMBLE was changed from 0 to 0.04 cm, which prevented the surface lake reservoir from being fully mixed back into the lake. The resulting seasonal cycle for $\delta^{18}$O was broadly similar between the two models, with similarly timed maxima and minima, however the CHIMBLE $\delta^{18}$O values were typically around ~ 1‰ lower through most of the season, excepting the months of April and May, where CHIMBLE produced higher $\delta^{18}$O values than SRAB2010 following a greater increase in $\delta^{18}$O during March (Fig. 7).

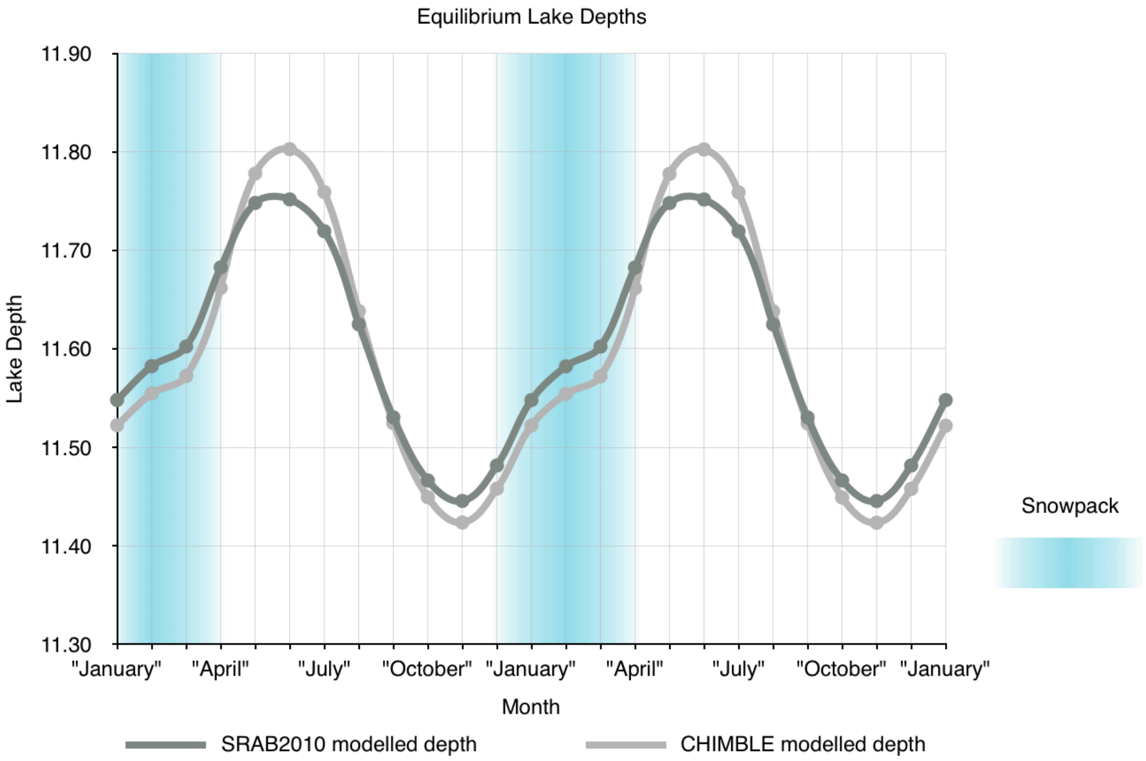

Figure 6: Modelled lake depths for SRAB2010 and CHIMBLE for Lake Castor, Washington.

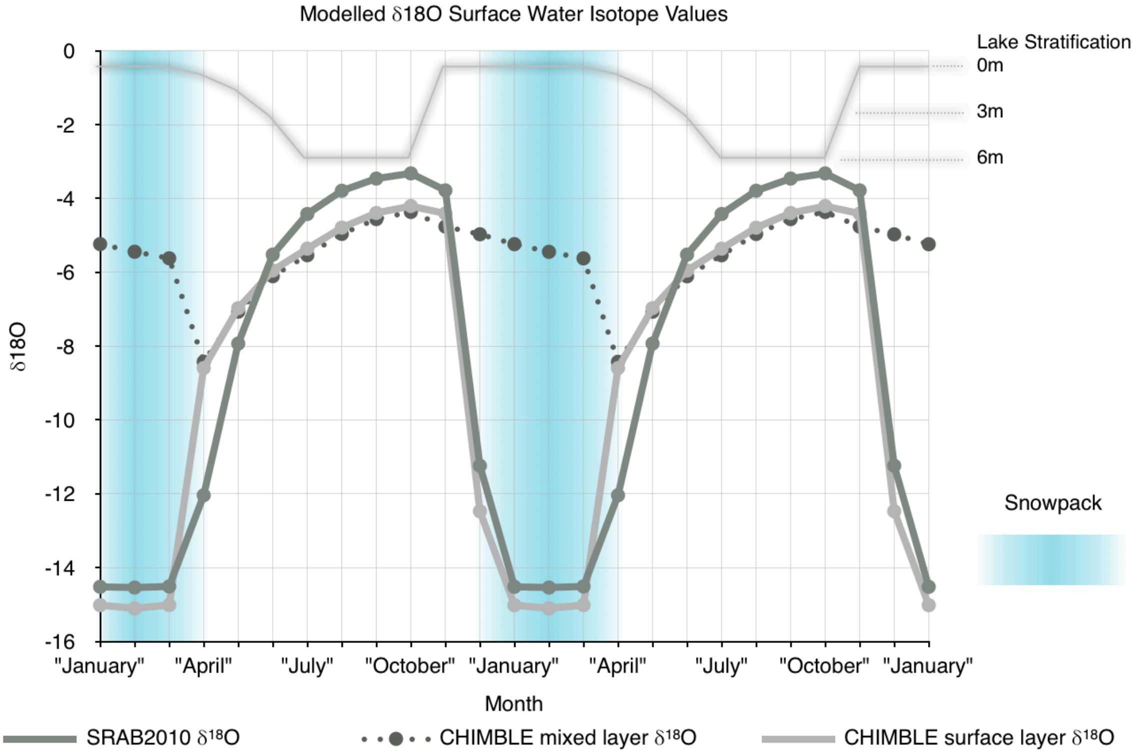

Figure 7: Modelled isotopic concentrations for SRAB2010, CHIMBLE with complete mixing, and CHIMBLE retaining a thin surface water layer. Lake stratification is shown at top of graph.

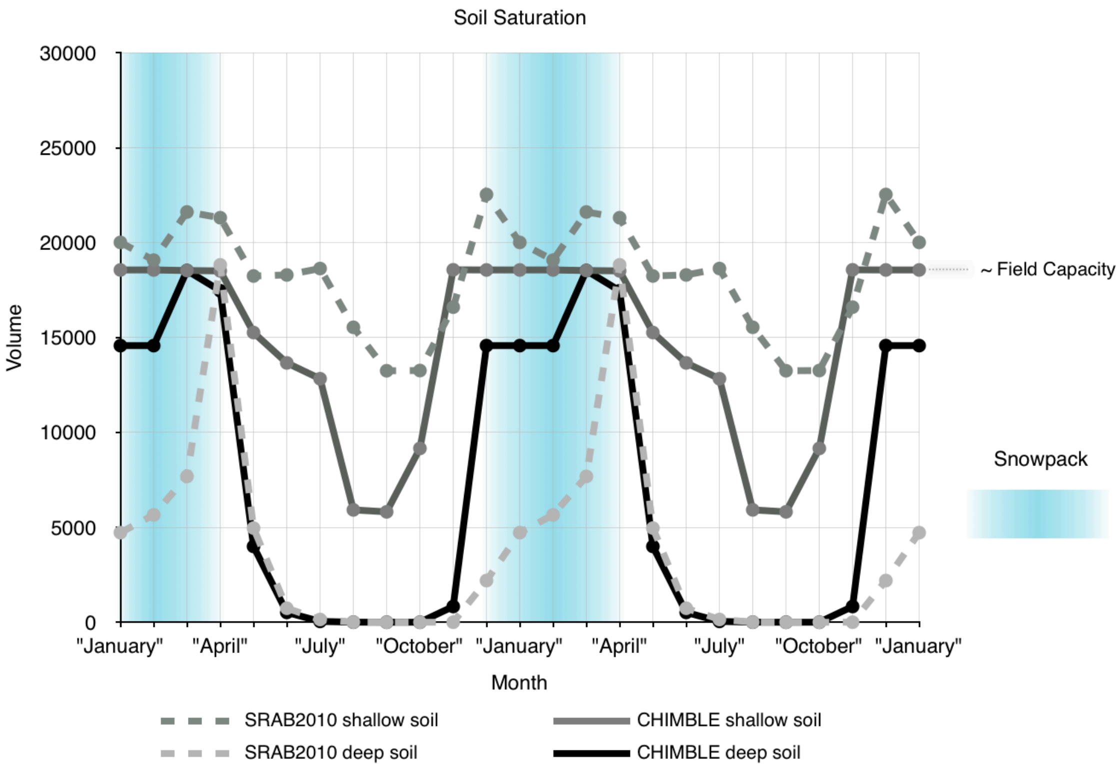

**Figure 8: Volume of water stored in soil layers in SRAB2010 (dashed lines) and CHIMBLE (solid lines). Approximate field capacity volume for soil (at equilibrium lake depth) shown on right hand side.**

## Lake Gnotuk and Bullen Merri calibrations

Calibrations of both lakes from 1965 to 2006 using both jump-start and estimated $RES_{IN}$ boundary conditions were able to simulate the observed lake depth between 1965 and 2002, with a distinct deviation from historical levels from 2002 onwards, where CHIMBLE significantly underestimated lake depth (Fig. 9 & 10, Table 5). The seasonal cycle was modelled well, with similar amplitudes to the historical water levels. Calibrations that used monthly climate data required a decrease in the available soil water (AWC) to allow for the distribution of sporadic rainfall events observed in daily data over a month. For example, if a month had a single significant rainfall event over just a few days, then both soil layers could be filled on the first day of rain, letting subsequent rainfall percolate to the inflow reservoir. Using monthly data, that event would be spread over the course of the month, which may result in insufficient rain during each time-step to saturate the soil. All soil water would then be lost through evapotranspiration, and none would percolate to the inflow reservoir. Monthly calibrations used the same parameters as the jump-start, daily calibrations (Table 4), and AWC decreased in a stepwise fashion until calibration was achieved. Lake Gnotuk required an AWC decrease, relative to the daily data runs, from 0.107m to 0.055m, and 0.118m to 0.035m for Lake Bullen Merri (Fig. 11 & 12). All daily and monthly calibrations from 1965 to 2006 tended to have greater variability early in the model run, with some occasional differences from historical values of ~0.5 m (B1965ED, B1965J, year 1972) and overestimated levels of ~0.4 m between 1989 and 1993. Monthly calibrations also tended to have a shallower trend in lake fall than daily calibrations due to different integration rates, typically being ~0.1-0.2 m lower in level in the early years and ~0.1 m higher at the end of each run.

**Table 5: Lake Bullen Merri and Lake Gnotuk model calibration results.**

| Calibration | Average error between modelled and historical (m) | Standard Deviation (m) | Figure reference |
|---|---|---|---|
| B 1889J | -1.264 | 0.79 | Fig. 13 |
| B 1949J | -0.143 | 0.274 | Fig. 13 |
| B 1965J | -0.003 | 0.202 | Fig. 11, 13 |
| B 1965JD | 0.035 | 0.275 | Fig. 9, 11 |
| B 1965ED | -0.011 | 0.228 | Fig. 9 |
| B 2006JD | n/a | n/a | n/a |
| G 1889J | -1.613 | 1.119 | Fig. 14 |
| G 1949J | -0.165 | 0.226 | Fig. 14 |
| G 1965J | 0.042 | 0.189 | Fig. 12, 14 |
| G 1965JD | 0.004 | 0.215 | Fig 10, 12 |
| G 1965ED | 0.024 | 0.185 | Fig. 10 |
| G 2006JD | n/a | n/a | n/a |

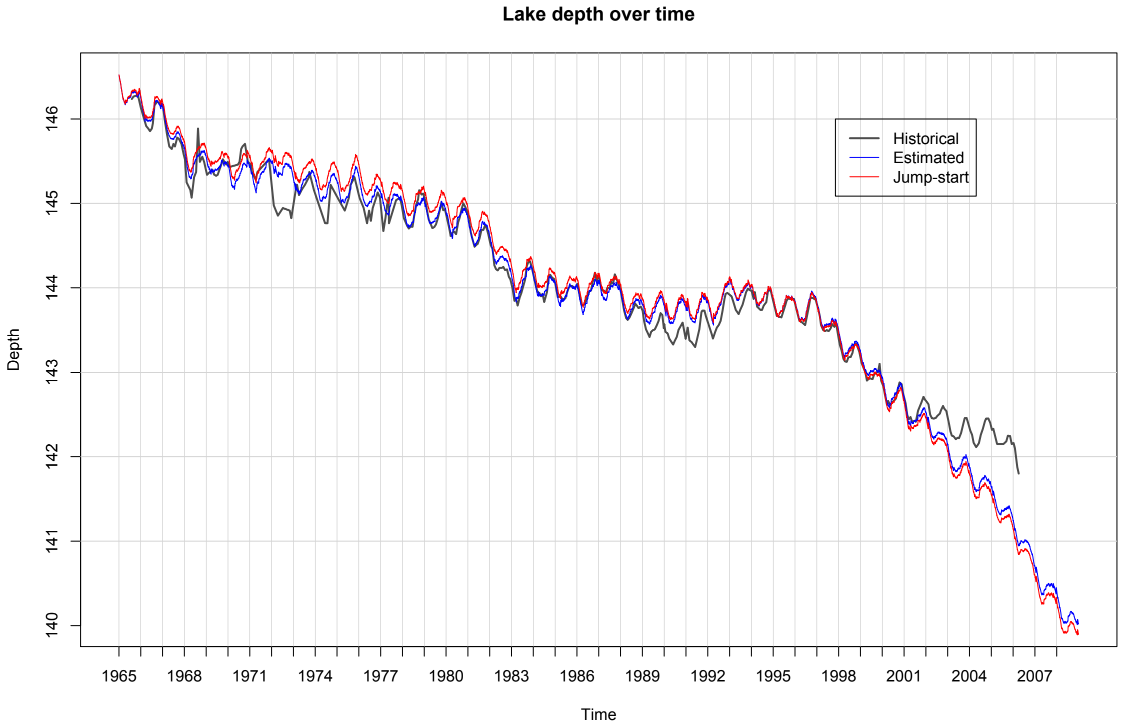

**Figure 9: Comparison between model runs for Lake Bullen Merri using jump-start and estimated values for $RES_{IN}$. X axis ticks show the beginning of each year.**

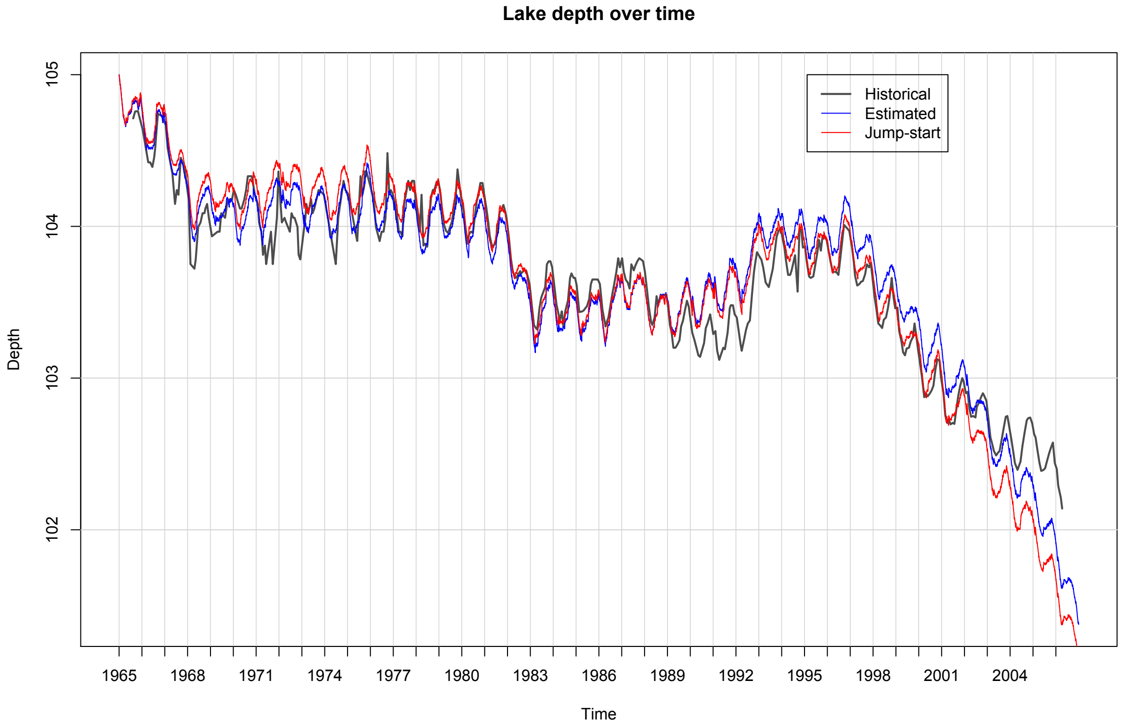

**Figure 10: Comparison between model runs for Lake Gnotuk using jump-start and estimated values for $RES_{IN}$. X axis ticks show the beginning of each year.**

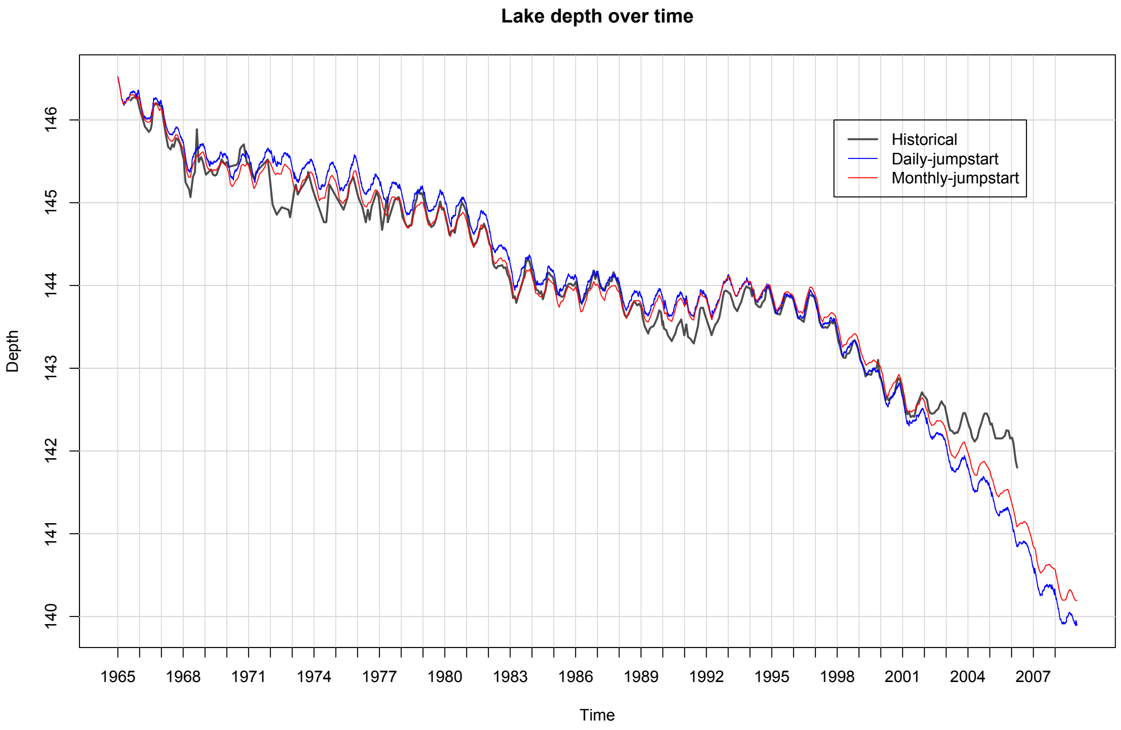

**Figure 11: Comparison between model runs for Lake Bullen Merri using daily and monthly climate data. X axis ticks show the beginning of each year.**

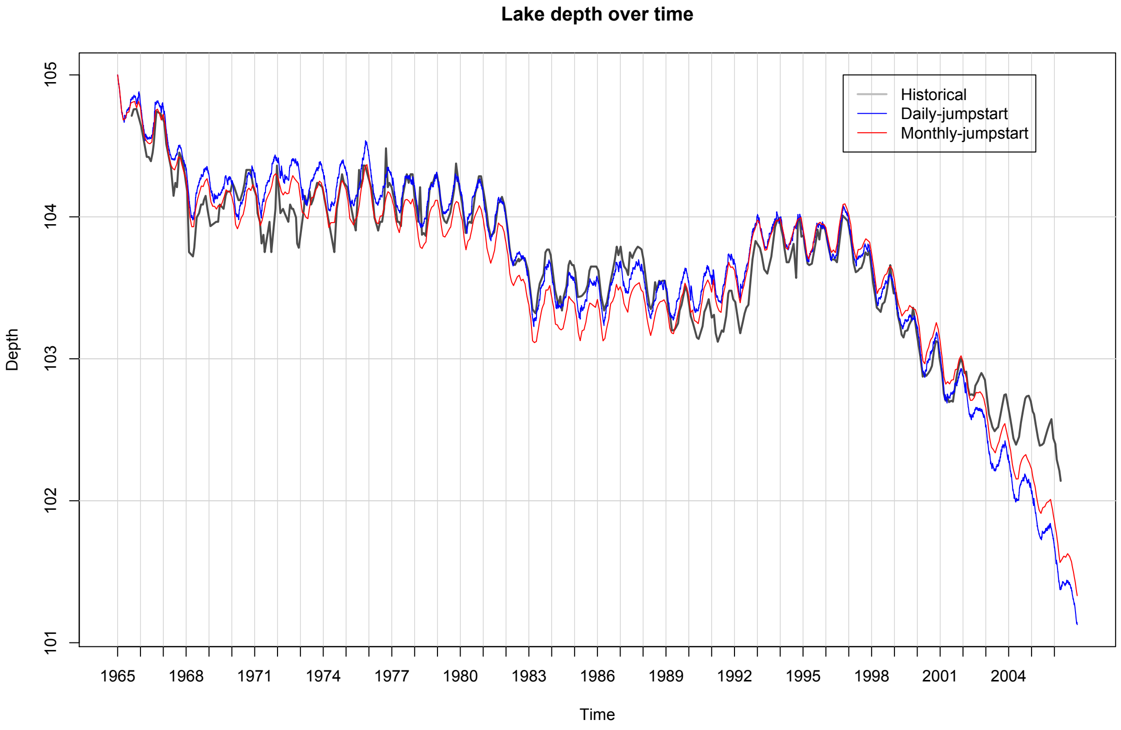

**Figure 12: Comparison between model runs for Lake Gnotuk using daily and monthly climate data. X axis ticks show the beginning of each year.**

Calibrations were also performed on the lakes from 1889 and 1949 to test the effectiveness of CHIMBLE over longer time frames. Following the observation that the 1965 calibrations failed to model the observed levels after ~2002 the lakes were considered calibrated if they matched the observed lake level around 2001-2002. Using the parameters from the 1965 calibrations and beginning the model run in 1889, the modelled lake levels were significantly overestimated, being around 5.5m too high in 2001. No calibration was able to match the observed lake levels between 1889 and 2001, with runs that started earlier (1889 and 1949) needing a greater AWC value (and hence less inflow from the catchment to the lake) to achieve the 2001 lake level (Fig. 13 & 14).

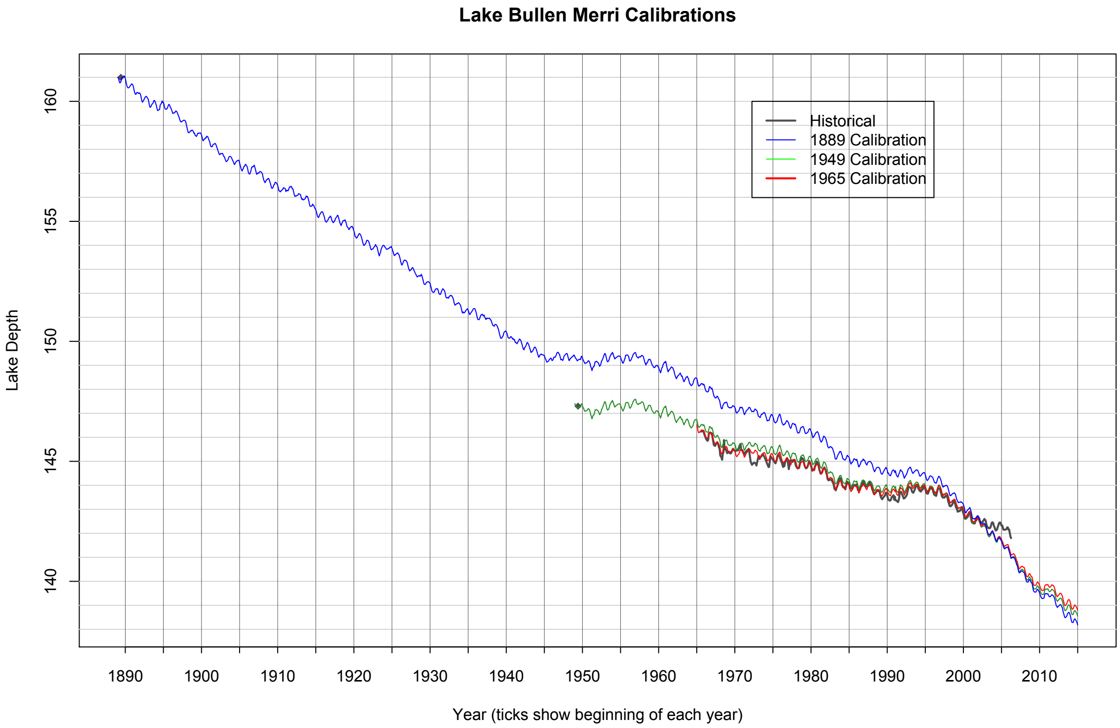

**Figure 13: Comparison between model calibrations and historical data for Lake Bullen Merri from 1889, 1949 and 1965, using different values for AWC$_{SS}$ and AWC$_{DS}$. (1889 – 0.12, 1949 – 0.055 and 1965 – 0.035) and jump-start RES$_{IN}$ values. X axis ticks show the beginning of each year.**

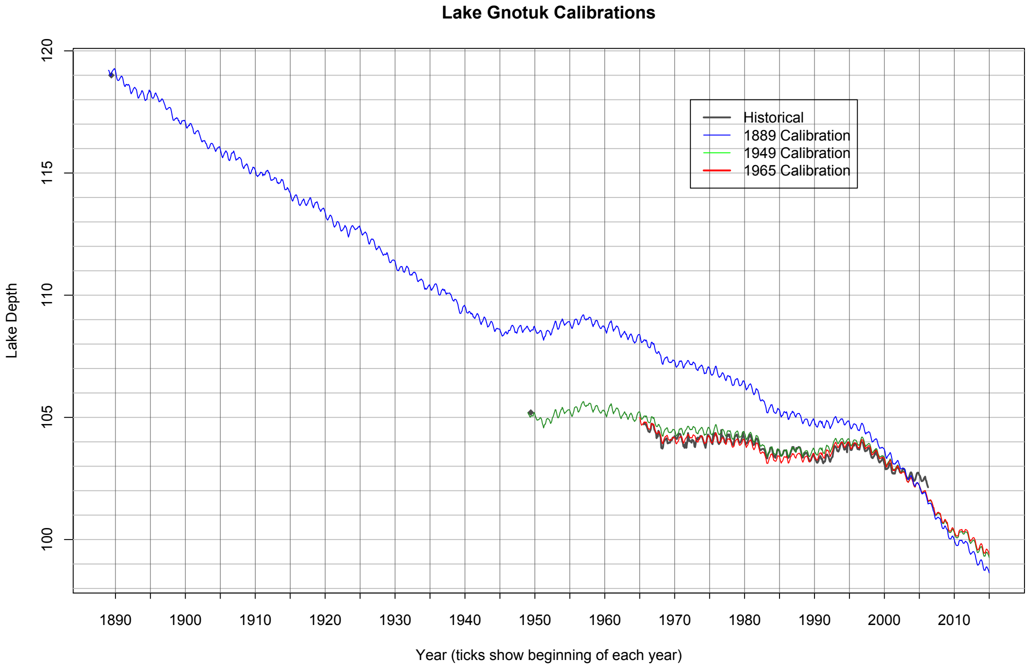

**Figure 14: Comparison between model calibrations and historical data for Lake Gnotuk from 1889, 1949 and 1965, using different values for $AWC_{SS}$ and $AWC_{DS}$. (1889 – 0.12, 1949 – 0.065 and 1965 – 0.055) and jump-start $RES_{IN}$ values. X axis ticks show the beginning of each year.**

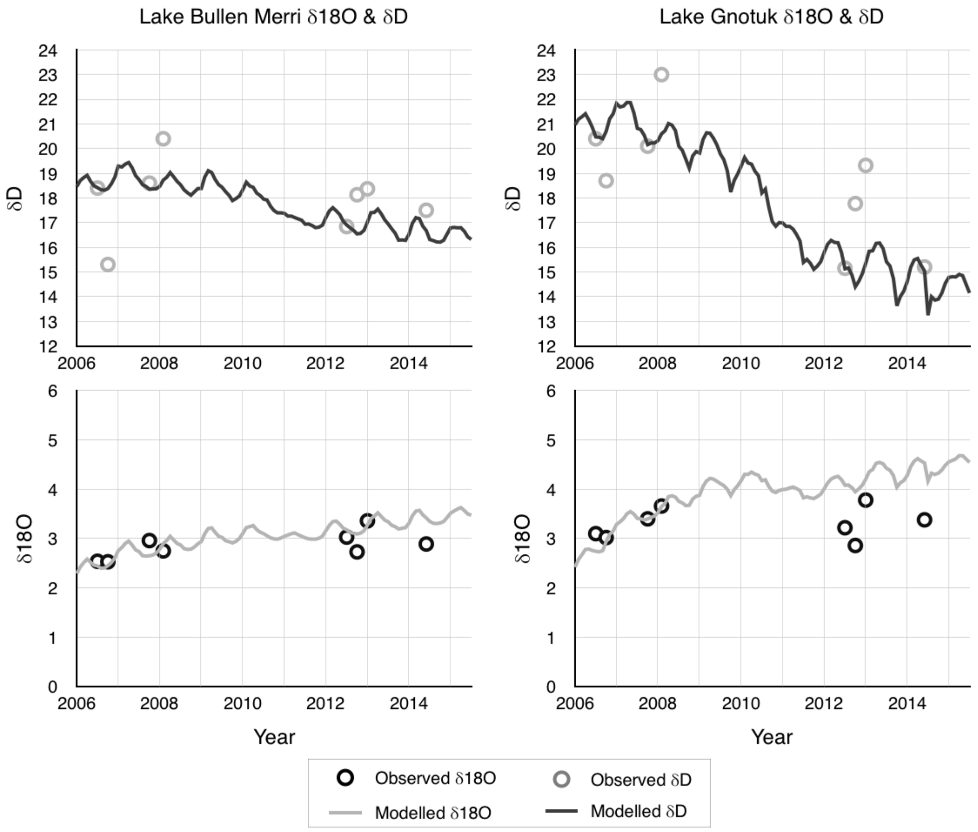

**Figure 15: Modelled and observed isotope values for Lake Bullen Merri and Lake Gnotuk, showing opposing trends for $\delta^{18}O$ and δD. X axis grid-lines show the beginning of each year.**

To investigate lake isotopic behaviour a calibration was performed between 2006 and 2015 with a final lake level based on August 2015 lake levels. Although there is little isotopic data available for Lake Gnotuk and Bullen Merri, the modelled isotopic values had a comparable trend to the observed readings, collected between August 2006 and May 2015 (Dahlhaus P. & Currell M., unpublished data) with deviations from -0.3 to 0.56‰ $\delta^{18}$O and -1.63 to 3.09‰ δD for Bullen Merri and from -0.39 to 0.97‰ $\delta^{18}$O and -4.42 to 1.9‰ δD for Gnotuk. $\delta^{18}$O and δD did not change proportionally. While lake level decreased over the calibration, modelled δD decreased ~2‰ and ~7.4‰, while $\delta^{18}$O increased by ~1.1‰ and ~2‰ in Lake Bullen Merri and Gnotuk respectively (Fig. 15 & 16).

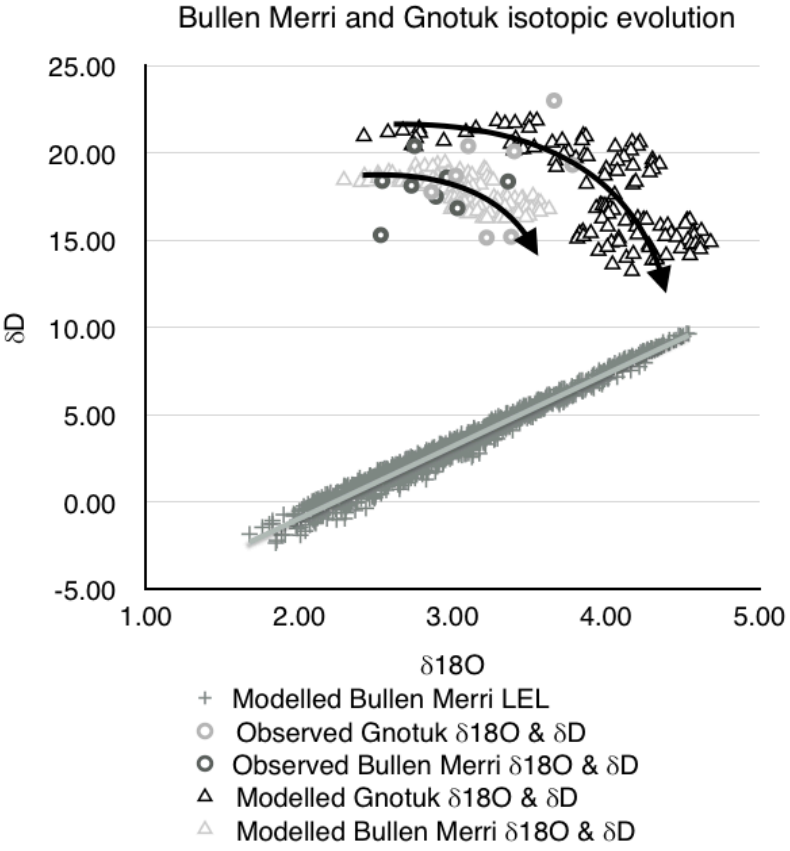

**Figure 16: Modelled isotopic evolution of Lake Gnotuk and Bullen Merri, showing trend (arrows) from 2006 to 2015 towards modelled local evaporation line (LEL). LEL generated using a model run letting Lake Bullen Merri fill from empty.**

## Basin morphology

Hypothetical basins and climate data were used to investigate the influence of differing basin slopes and residence times (Fig. 5). In all cases (Fig. 17 & 18), a change in the hydroclimate, achieved through a 5% step change in the monthly precipitation at model year 100 resulted in a change in hydrological equilibrium and a transient isotopic excursion observable in the yearly average lake isotope concentrations. The lake basin slope had a strong effect on the time a lake took to achieve hydrological equilibrium, with the 2% basin slope lake reaching an equilibrium level (< 1 mm change per year) at year 188, while the 20% slope lake failed to reach hydrological equilibrium even after 700 years. All lakes achieved an initial isotopic equilibrium value before model year 100 of 3.85‰ $\delta^{18}$O and 7.00‰ δD, with the exception of the lake with 2% slope, which achieved equilibrium at 3.86‰ $\delta^{18}$O and 7.05‰ δD probably due to an increased seasonal lake surface area change. A change in precipitation and corresponding change in lake level resulted in a transient isotopic excursion of opposing sign before a slow return towards an equilibrium isotopic composition. In all cases, the maximum isotopic excursion occurred before the lake achieved hydrological equilibrium. Lakes with shallow slopes had excursions of smaller amplitude, with their peak occurring sooner than in more steeply sloped lakes. Following an increase in precipitation of 5% in year 100, the 2% slope lake had a peak excursion of -0.12‰ $\delta^{18}$O and -0.49‰ δD at year 117, while the 20% slope lake had a peak of -0.22‰ $\delta^{18}$O and -0.95‰ δD at year 142. The initial excursion slope was similar for all basins at -0.01 to -0.02‰ $\delta^{18}$O and -0.04 to -0.05‰ δD per year. The isotopic equilibrium for all lakes that reached hydrologic equilibrium was around 3.87‰ $\delta^{18}$O and 7.15‰ δD by model year 800.

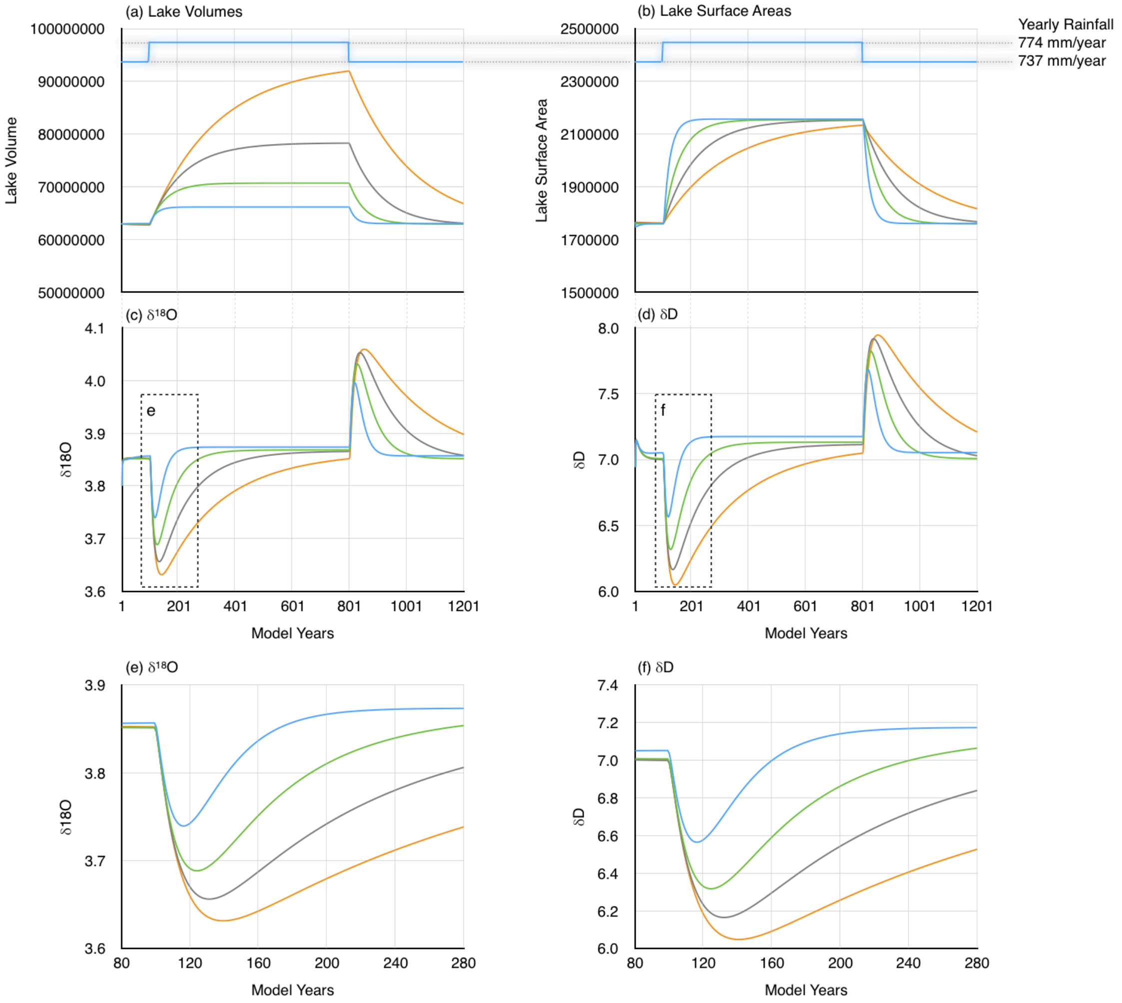

**Figure 17: Isotopic response in lakes with differing basin slopes due to a 5% change in precipitation. (a) Lake Volumes. (b) Lake Surface Area. (c) & (d) $\delta^{18}$O and δD concentrations over the full model run. (e) & (f): Expanded view showing $\delta^{18}$O and δD concentrations from model year 80 to 280. Blue : 2% slope. Green: 5% slope. Grey: 10% slope. Orange: 20% slope.**

In contrast, the initial slope of the isotopic excursion for the residence time experiments (Fig. 18) decreased as the residence time increased. The largest lake, with volume around 3 times the smallest, and therefore a residence time 3 times greater, had an initial excursion slope of around -0.01‰ $\delta^{18}$O and -0.05‰ δD per year, compared with around -0.03‰ $\delta^{18}$O and -0.15‰ δD per year of the smallest lake.

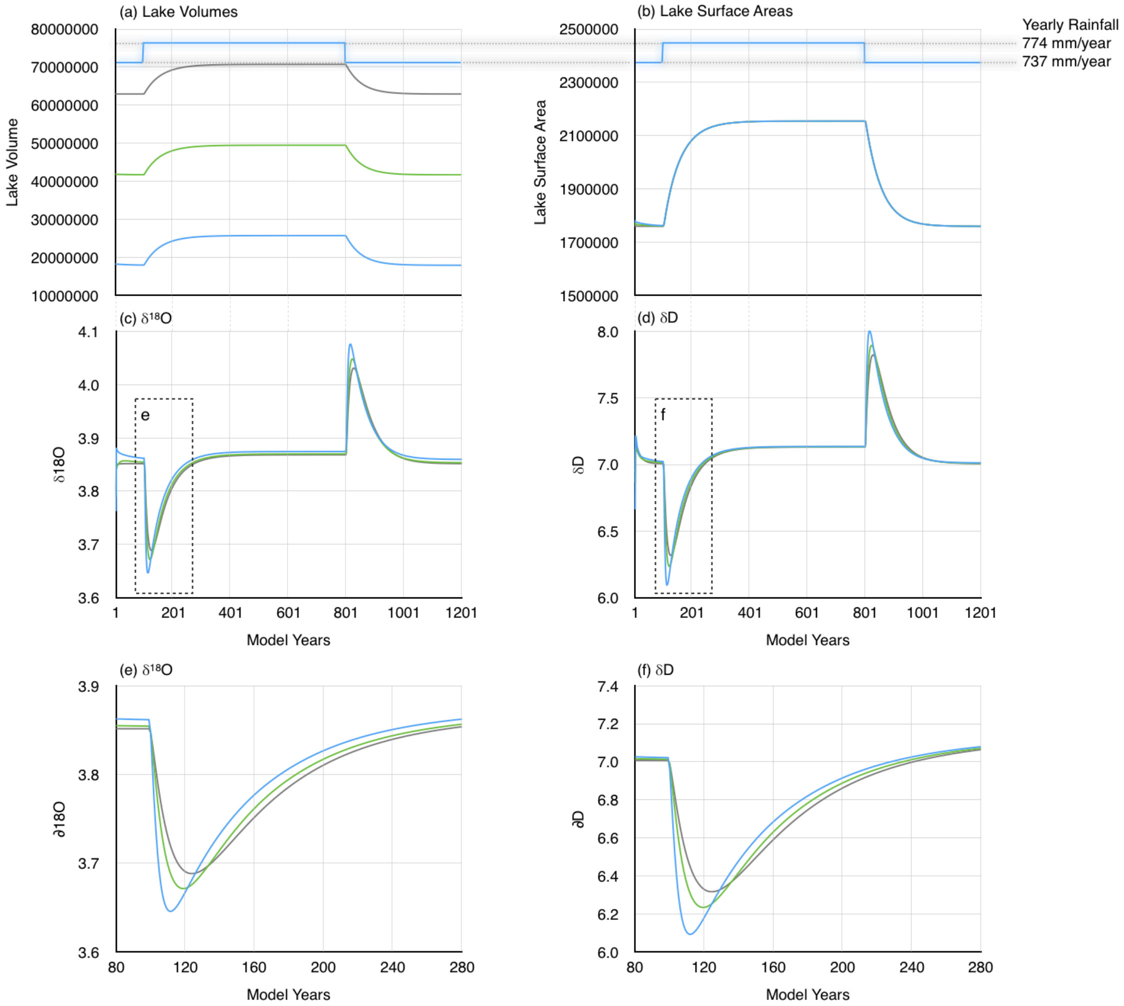

**Figure 18: Isotopic response in lakes with differing residence times due to a 5% change in precipitation. (a) Lake Volumes. (b) Lake Surface Area. (c) & (d) δ$^{18}$O and δD concentrations over the full model run. (e) & (f) Expanded view showing δ$^{18}$O and δD concentrations from model year 80 to 280. Blue: short residence time. Green: medium residence time. Grey: long residence time.**

Lakes with greater volumes and longer residence times had more subdued but longer excursions, while all lakes took equal time to achieve hydrological equilibrium. The lake with the smallest residence time had a peak excursion of -0.22‰ δ$^{18}$O and -0.95‰ δD at year 112, while the largest volume lake had a peak of -0.16‰ δ$^{18}$O and -0.69‰ δD, at year 124.

## Basin morphological influence during transient climate change

To investigate how the isotopic behaviour observed in the morphology experiment might appear in lake sediments a hypothetical ENSO climate was applied to the Lake Gnotuk catchment (Table 3:G ENSO, Fig. 5 & 19). The lake initially reached hydrological equilibrium at around 90.2m (4.7m depth) and was nearing isotopic equilibrium, with yearly averaged values of 3.86‰ $\delta^{18}O$ and 6.9‰ δD. The effect of the ENSO cycle was identifiable as minor isotopic excursions around 0.1‰ $\delta^{18}O$ and 0.25‰ δD on a decadal cycle. Following a 5% increase in precipitation in year 1200, lake level increased to 96.54 (11.04 m depth) by the year 1400, with a longer isotopic excursion of around -0.2‰ $\delta^{18}O$ and -0.75‰ δD peaking around year 1215, overprinted by the decadal ENSO cycle. By year 1400 the model had not achieved hydrological or isotopic equilibrium. Isotopic values were 3.81‰ $\delta^{18}O$ and 6.8‰ δD, trending towards the earlier equilibrium values, and the ENSO excursions had decreased to around 0.05‰ $\delta^{18}O$ and 0.14‰ δD. A second 5% increase in precipitation was used to force the model at year 1400, resulting in a negative isotopic excursion peaking around -0.2‰ $\delta^{18}O$ and -0.9‰ δD around year 1421. By year 1800 the lake had not reached hydrological equilibrium with a water level of 110.6 m (25.1 m depth), while the isotopic concentrations had almost returned to equilibrium, at 3.83‰ $\delta^{18}O$ and 6.98‰ δD. At this lake depth the ENSO signal was very weak, with decadal excursions of -0.01‰ $\delta^{18}O$ and -0.025‰ δD. The decrease in precipitation at year 800, generated a positive isotopic excursion of around 0.4‰ $\delta^{18}O$ and 1.8‰ δD centred around year ~1835.

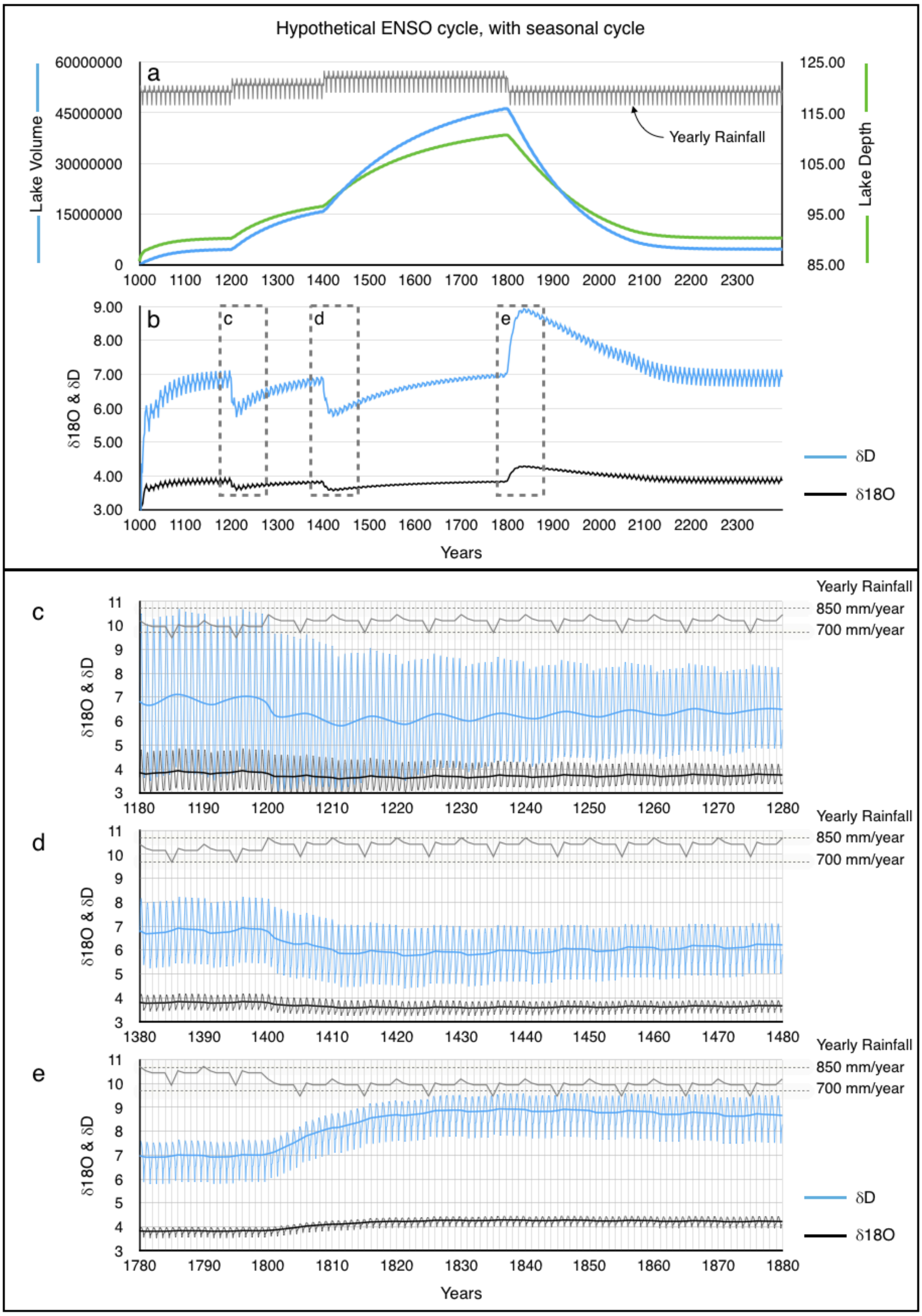

**Figure 19: (a) Lake volume, depth and precipitation over the full model run. (b) $\delta^{18}O$ (black) and $\delta D$ (blue) yearly averaged isotopic concentrations over full model run. (c), (d) & (e) Expanded views of isotopic concentrations, showing precipitation and both seasonal cycle and yearly averaged $\delta^{18}O$ and $\delta D$ concentrations.**

The seasonal isotopic cycle (Fig. 19) typically saw excursions of 0.9‰ $\delta^{18}O$ and 3.6‰ δD at low lake level (9m depth, year 1200), decreasing to 0.25‰ $\delta^{18}O$ and 0.8‰ δD at the lake's maximum depth (25.1 m, year 1800). At lower lake levels the seasonal isotopic cycle obscured both the ENSO cycle and excursions caused by the shifts in precipitation, but became more subdued as lake depth, residence time and basin slope increased. At the maximum lake depth, the isotopic response to precipitation change was around double the seasonal cycle.

# DISCUSSION

## Model validation

Most of the differences between CHIMBLE and SRAB2010 can be traced back to the differences in the soil model. SRAB2010 uses concepts from the soil layer structure of Palmer (1965), which determines the monthly evapotranspiration flux using the principal that if potential evapotranspiration (PET) for a month is greater that the available soil water, then all available water of the soil layer is removed through evapotranspiration. If the PET is less than the available water, then just the PET value is transpired from the soil. However, this method has a tendency to underestimate evapotranspiration if applied over multiple time-steps during one month, as per equations 3 & 4. While monthly PET is greater than the available upper layer soil water ($RES_{SS}$), the water lost through evapotranspiration for each time-step becomes a percentage of $RES_{SS}$ rather than the PET demand of that time-step. This results in $RES_{SS}$ remaining saturated through the summer months and acting as a second slower subsurface flow, delaying the water going through the soil (Fig. 8). This is probably the cause of the lower amplitude seasonal cycle displayed by SRAB2010 for Castor Lake in the model validation experiment (Fig. 6). While this may be an issue for some lakes, it is not a concern for the NVP lakes, as there is little runoff and all catchment flux is through the slower subsurface drainage (Jones et al. 2001).

This underestimated evapotranspiration from the catchment also results in SRAB2010 achieving higher lake isotopic concentrations than CHIMBLE, as for each month that $RES_{SS}$ remains saturated it mixes with rainfall that increases in isotopic concentration through March to June (-15.2 $\delta^{18}O$ to -10.2 $\delta^{18}O$). This isotopically enriched water then flows to the inflow reservoir ($RES_{IN}$) increasing the isotopic concentration of $RES_{IN}$ and hence the lake. In contrast, $RES_{IN}$ in CHIMBLE gains most of its influx directly from snowmelt, with an average isotopic concentration of -15.3 $\delta^{18}O$.

A potential improvement to CHIMBLE that would allow it to model most scenarios would be the division of the current single flow path for deep soil drainage and run off, into separate flow paths with different rates of flow.

## Lake Gnotuk and Bullen Merri calibrations

Lake Gnotuk and Bullen Merri required a different calibration approach than Lake Castor and Scanlon investigated by Steinman et al. (2010). For those smaller lakes the catchment inflow variable ($C_{IN}$) was used to delay and extend the yearly peak inflow from the catchment (equation 9), so that lake levels increased over several months, rather than an immediate rise in levels following snowmelt.

$$F_{IN} = RES_{IN}.C_{\mathrm{IN}}.dt^{-1} \qquad (9)$$

In contrast, the lack of runoff, large catchment size and a soil water conductivity of $10^{-3}$ to $10^{2}$ m/day (Yihdego et al. 2014) mean that inflow from the catchments of Bullen Merri and Gnotuk produces a more consistent base-flow throughout the year, as water percolates down to the unconfined aquifer of the basalts and Moorabool Viaduct formation and then to the lakes. A $C_{IN}$ value of 0.01 was chosen to approximate the time taken for water to move the ~300 m from the edge of the catchment to the lake based on average hydraulic conductivity. Using lower values for $C_{IN}$ presented a problem with regard to calibration, as to achieve a sufficient flux into the lake from the catchment also required a very large inflow reservoir specified as an initial boundary condition ($RES_{IN}$) (equation 9). If this volume was significantly incorrect, then it could influence the entire model run. Several concepts were used to narrow down the range of likely initial $RES_{IN}$ volumes.

- There should be a consistent change in $RES_{IN}$ as it transitioned from the initial specified volume to the volume resulting from drawdown and recharge.
- The model run should follow historical observations accurately for beginning of run.
- The $RES_{IN}$ value for both lakes should have similar starting volumes due to similar catchment soil volumes.

With catchment inflow and outseepage rates fixed, and $RES_{IN}$ either estimated or jump-started, calibration of the lakes was performed using two variables – available soil water content ($AWC_{SS}$ & $AWC_{DS}$) and variation of the Penman wind function (PWF). Modifying the soil water content allowed for different amounts of water to be stored and then evapotranspired instead of percolating down to the $RES_{IN}$ aquifer. This had a similar effect to the percolation rate variable (KQ) used by Jones et al. (2001) acting as a control on the amount of water percolating through the soil.

The Penman wind function is a component of the Penman evaporation equation (Penman 1948) used to estimate the effect on evaporation due to the aerodynamic resistance of the surface the air passes over. The wind function suggested by Penman for evaporation of open water was ʃu = 1 + 0.536u (u = windspeed at 2m height). It was later decreased to ʃu = 0.5 + 0.536u (Penman 1956), followed by a further suggested reduction by Linacre (1993) to ʃu = 0.54u. All three of these functions have been used for estimating evaporation in hydrological applications. Valiantzas (2006) proposed that the Penman (1948) function is appropriate for small lakes, and the Linacre (1993) function is more suitable for large lakes. As it is likely that the studied lakes fall on the continuum between the wind function of Penman (1948) and Linacre (1993) this function was considered as a variable for calibration purposes.

As both lakes have similar geology and soil types it was assumed that both lakes would have similar AWC variables, while the wind function for each lake would be unique due to the differing surface areas. The ideal calibration would therefore result in similar AWC values for both lakes, with a unique wind function for each lake. An additional check on the wind function was that the amplitude of the seasonal cycle for each lake should be similar between modelled and historical lake levels, as observed in the calibrations. The similarities in AWC values for calibration runs used for Gnotuk and Bullen Merri (Table 4) suggest that this technique has validity, and may be used as a starting point for calibration of other lakes in the NVP with similar catchment geology.

## Comparison with previous studies

The calibrations of Lake Bullen Merri and Gnotuk shared strong similarities with the results of the hydrological modelling of Jones et al. (2001). In both cases no single calibration was able to model the change in lake depth from 1889 to current. Reconciling the modelled lake levels with historical levels required an increasing influx per unit area from the catchment as lake levels dropped, a result also observed by Jones et al. (2001). This demonstrates that flow from the catchment is not proportional to catchment area, a common assumption used when modelling lakes. Jones et al. (2001) suggested several hypotheses for this result: an increase in percolation rate through the soil over time, a bias in meteorological records, or a positive feedback from groundwater due to the fall in lake level (Jones et al. 1998, Jones et al. 2001).

Two additional explanations can also be put forward. The change of vegetation from native bush to pasture since European settlement may have resulted in an increase in percolation to deep drainage, as grasses can have lower evapotranspiration than woodlands due to less canopy interception of rainfall and shallower root systems (Abramopoulos et al. 1988, Samraj et al. 1988, Sharda et al. 1988, Allen et al. 1998). The second possibility is an extension to the groundwater feedback proposal by Jones et al. (2001). Rather than considering the groundwater influence to be predominantly due to the low yield Port Campbell Aquifer, the basalts and Moorabool Viaduct formation should also be considered as an unconfined aquifer. At high levels, the lake, and surrounding aquifer would be an outseepage system, with drainage away from the lakes to regions of lower topography to the north and west. Lower lake levels would draw down on the aquifer, buffering the falling water level. More recent studies (Dahlhaus et al. 2002, Barton et al. 2006, Yihdego et al. 2014, Raiber et al. 2015) also support both the treatment of the basalts and Moorabool Viaduct Formation as an unconfined aquifer, and increased recharge from land use changes. CHIMBLE can buffer the lake to some degree through use of a small $C_{IN}$ value and a large $RES_{IN}$ value. However, the use of such a technique over the comparatively short calibrations can skew model results, as discussed in the previous section. As many lakes in the NVP and worldwide (Gibson et al. 2002, Stets et al. 2010, Watras et al. 2014) have similar groundwater influence, a future development for CHIMBLE will be to improve this modelling of groundwater.

The limited isotopic data made it difficult to assess the reliability of the isotopic functions. Variability of observed values is interpreted as a result of shallow water diurnal thermal stratification (Imberger 2001). While the broad trends were similar the deviation between observed and modelled values increased over the model run, provoking some uncertainty about the climate data and code underlying the model (Fig. 15). Regardless of this limitation, the presence of opposing slopes of $\delta^{18}O$ and $\delta D$ in both modelled and observed isotopic data is significant. Isotopic fractionation due to evaporation results in a proportionate enrichment in a lake's $\delta^{18}O$ and $\delta D$ along a local evaporation line (LEL) (Gibson et al. 1993, Gibson et al. 2015). The opposing slopes of $\delta^{18}O$ and $\delta D$ in Gnotuk and Bullen Merri suggest that these lakes are moving to a new LEL, perhaps indicating a change in humidity or atmospheric isotopic composition (Fig. 16) (Gibson et al. 1993, Gibson et al. 2015), possibly due to the change to drier conditions that occurred around 1840 (Jones et al. 1998). Further research is required to investigate how the lakes achieved their current isotopic composition.

The need for differing calibrations dependent on lake levels at Bullen Merri and Gnotuk also highlights issues with modelling lakes in general. Many lakes are modelled based on a fairly narrow range of data, typically covering only a few years and, more importantly, only a narrow band of lake conditions, often just the seasonal cycle. This study shows that modelling over such short timeframes can result in apparently effective calibrations that do not withstand scrutiny outside the scope of the calibration. There are two solutions to this: either the complete hydrological system of the lake must be well understood, especially with regard to groundwater and subsurface fluxes, or the observations used to calibrate the model must cover a significant range of lake conditions. While oxygen and hydrogen isotopes are very useful for calibration checks, their transient nature as seen in the morphology experiments makes them unsuitable for calibration. Ideally, any lakes that are being used for palaeoclimate studies should have long-term water level records.

## Basin morphology

Lake hydrological change in terminal lakes occurs due to a change in the ratio of hydrological influx and evaporation and continues until the lake achieves a surface area whereby the evaporation rate equals water influx to the lake. Stable isotopes in lake water also exhibit isotopic excursions in response to hydrological perturbations, but have an additional feedback mechanism, whereby the changing lake isotopic concentration affects the evaporative fractionation of isotopes. At its most extreme, a very enriched lake undergoes no evaporative fractionation once the lake reaches the isotopic enrichment limit (Gibson et al. 1993, Steinman et al. 2010, Gibson et al. 2015). The isotopic evolution following an excursion is also well studied and the isotopic composition of a lake that is in hydrological equilibrium will tend towards the isotopic equilibrium (Gonfiantini 1986, Gibson et al. 2002). It follows that the peak isotopic excursion must occur before the lake achieves hydrological equilibrium. This is observed in the basin slope experiment, where lakes that could achieve hydrological equilibrium faster – those that have shallower slopes and require less mass balance change to achieve the equilibrium surface area – also had more rapid isotopic excursions (Fig. 17). The initial slope of the isotopic excursions, prior to the evaporative fractionation feedback effect becoming significant, is described by the mixing calculation (equation 2). As the rate of volume change is limited by the imbalance of incoming and outgoing fluxes, lakes with greater volumes will have a slower rate of initial isotopic excursion, as observed in the residence time experiment (Fig. 18). These observations provide important limits on the magnitude and timing of isotopic excursions resulting from climate change. The ramifications of these observations are observed in the transient climate change experiment, where seasonal and ENSO cycles decreased as lake volume increased. These results are important from a palaeoclimate perspective, as they constrain which lake sediments are likely to provide signals from long-term hydroclimatic change, and climatic cycles such as the ENSO cycle. Deep terminal lakes are more likely to provide evidence of past long-term P/E changes because seasonal and ENSO type isotope responses are subdued, while the long residence time of the lakes increases the duration of the isotopic response to P/E change. The obfuscation of the ENSO cycle amongst the seasonal cycle (Fig. 19) also suggests that climate proxies that capture a signal over several years, or during a specific time of the year, thereby averaging out or bypassing the seasonal cycle, may be required to detect such a signal.

## Future model developments

There is a need for an extensible and flexible model for palaeoclimate and hydrological studies of lakes. CHIMBLE, which extends the model of Steinman et al. (2010), is written as a structured R program and is designed to be upgradeable as modelling methods are improved. CHIMBLE performed well for this study, but there are many improvements that can be made. The incorporation of salinity is of particular importance, as the salinity of a lake has an effect on evaporation rates (Al-Shammiri 2002). The framework for salinity could also be extended to include conservative isotopes. Given CHIMBLE utilizes a lot of climate data, thermal evolution of a lake, including thermal stratification and heat storage should be modelled computationally, as seen in models such as the General Lake Model (GLM) (Hipsey et al. 2013), thereby extending the use of CHIMBLE to lakes that are lacking in those observations. Improved groundwater modelling is important, as it is the most likely cause of the buffering of lake levels seen at Gnotuk and Bullen Merri, and similar groundwater interactions are common worldwide (Gibson et al. 2002, Stets et al. 2010, Watras et al. 2014). Outseepage rates should be linked to permeability of lake sediments, bank slope and surface area as discussed in Steinman et al. (2012) and Genereux and Bandopadhyay (2001), rather than the current use of lake volume as a proxy.

## CONCLUSIONS

A coupled hydrologic-isotopic mass balance model (CHIMBLE) was developed to improve understanding of lake hydrological and isotopic behaviour. CHIMBLE was validated against the model of Steinman et al. (2010) and calibrated for Lake Gnotuk and Bullen Merri in western Victoria, which were accurately modelled over decades during which water levels remained relatively stable. No single calibration was able to accurately model the entire historical record for the lake. Calibrations beginning at earlier dates, and higher water levels, required disproportionally less inflow from the catchment than later calibrations at lower water levels. Therefore, influx from the catchment to the lake is not proportional to catchment area and is likely linked to the unconfined aquifer of the Newer Volcanic Basalts and Moorabool Viaduct Formation. The fact that accurate calibrations over decadal timescales may not be accurate outside the scope of the calibrations emphasizes the need for long-term lake monitoring, documenting a range of hydrological conditions. CHIMBLE was able to model the isotopic evolution of both lakes from a sparse data set. It was observed that in both modelled and observed isotope data the hydrogen and oxygen isotopes were not changing in proportion, instead trending towards a modelled local evaporation line for the lakes, indicative of past climate change.

Morphometry experiments demonstrated that basin slope and residence time influence the extent and timing of isotopic excursions – transient isotopic responses to changes in P/E ratio. Lakes with shallow slopes were able to achieve hydrological equilibration more rapidly and had smaller, more rapid isotopic excursions. Lakes with longer residence times had longer, subdued isotopic excursions. An experiment in transient, large scale climate change using the Gnotuk catchment demonstrated that specific basin morphologies, combined with sediment proxies that form over multiple years or during specific seasons, may help identify both short-term climatic cycles, such as ENSO events, and long-term changes in hydroclimate.

## ACKNOWLEDGMENTS

The author would like to thank Jonathan Tyler and Derrick Hasterok for their guidance, advice and comments throughout the project, and Rosalind King and Katie Howard for providing advice and support throughout the year. Special thanks go to Byron Steinman for sharing his Stella hydrologic-isotopic model, John Tibby for sharing his data on lake temperatures, Peter Dahlhaus and Matthew Currell for sharing their isotopic data, and Paul Leahy, for sharing the historical lake data. Thanks also go to Rebecca Hill and Christopher Trenouth for proof reading this thesis.

## REFERENCES

ABRAMOPOULOS F., ROSENZWEIG C. & CHOUDHURY B. 1988. Improved Ground Hydrology Calculations for Global Climate Models (GCMs): Soil Water Movement and Evapotranspiration. *Journal of Climate*. 1, 921-941.

AL-SHAMMIRI M. 2002. Evaporation rate as a function of water salinity. *Desalination*. 150, 189-203.

ALDUCHOV O. A. & ESKRIDGE R. E. 1996. Improved Magnus Form Approximation of Saturation Vapor Pressure. *Journal of Applied Meteorology*. 35, 601-609.

ALLEN R. G., PEREIRA L. S., RAES D. & SMITH M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome*. 300, p.D05109.

ALLEY W. M. 1984. On the Treatment of Evapotranspiration, Soil Moisture Accounting, and Aquifer Recharge in Monthly Water Balance Models. *Water Resources Research*. 20, 1137-1149.

AYDIN M. 2008. A model for Evaporation and Drainage investigations at Ground of Ordinary Rainfed-areas. *Ecological Modelling*. 217, 148-156.

BARR C., TIBBY J., GELL P., TYLER J., ZAWADZKI A. & JACOBSEN G. E. 2014. Climate variability in south-eastern Australia over the last 1500 years inferred from the high-resolution diatom records of two crater lakes. *Quaternary Science Reviews*. 95, 115-131.

BARTON A., COX J., DAHLHAUS P. & HERCZEG A. 2006. Groundwater flows and groundwater-surface water interactions in the Corangamite CMA region. *Regolith: Consolidation and dispersion of ideas*. 377-384.

BATTARBEE R. W. 2000. Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews*. 19, 107-124.

BAYLY I. & WILLIAMS W. 1964. Chemical and biological observations on some volcanic lakes in the south-east of South Australia. *Marine and Freshwater Research*. 15, 123-132.

BAYLY I. A. E. & WILLIAMS W. D. 1966. Further chemical observations on some volcanic lakes of south-east Australia of South Australia. *Marine and Freshwater Research*. 17, 229-238.

BECHT R. & HARPER D. 2002. Towards an understanding of human impact upon the hydrology of Lake Naivasha, Kenya. *The International Journal of Aquatic Sciences*. 488, 1-11.

BENSON L. & PAILLET F. 2002. HIBAL: a hydrologic-isotopic-balance model for application to paleolake systems. *Quaternary Science Reviews*. 1521-1539.

BLACK T. A., GARDNER W. R. & THURTELL G. W. 1969. The Prediction of Evaporation, Drainage, and Soil Water Storage for a Bare Soil1. *Soil Science Society of America Journal*. 33, p.655.

BOUGHTON W. 2005. Catchment water balance modelling in Australia 1960–2004. *Agricultural Water Management*. 71, 91-116.

BOWEN G. J. & REVENAUGH J. 2003. Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research*. 39.

BOWEN G. J. 2015 The Online Isotopes in Precipitation Calculator, version 2.2. http://www.waterisotopes.org.

BOYCE J. 2013. The Newer Volcanics Province of southeastern Australia: a new classification scheme and distribution map for eruption centres. *Australian Journal of Earth Sciences*. 60, 449-462.

CLEVELAND W. S. 1981. LOWESS: A program for smoothing scatterplots by robust locally weighted regression. *American Statistician*. 54-54.

COHEN A. S. 2003 Paleolimnology: the history and evolution of lake systems*.* Oxford University Press, USA.

CURREY D. T. 1970. Lake systems, Western Victoria. *Australian Society for Limnology Bulletin*. 3, 1-13.

DAHLHAUS P., HEISLERS D. & DYSON P. 2002. Glenelg Hopkins Catchment Management Authority, Groundwater Flow Systems. *Consultancy report no. GHCMA*. 2.

DAHLHAUS P., COX J., MACEWAN R. & CODD P. 2003 Victorian Volcanic Plains Scoping Study. CSIRO Land and Water.

DINCER T. 1968. The Use of Oxygen 18 and Deuterium Concentrations in the Water Balance of Lakes. *Water Resources Research*. 4, 1289-1306.

DODSON J. R. 1974. Vegetation history and water fluctuations at Lake Leake, south-eastern South Australia. 1. 10,000 B.P. to present. *Australian Journal of Botany*. 22, 719-741.

--- 1977. Pollen deposition in a small closed drainage basin lake. *Review of Palaeobotany and Palynology*. 24, 179-193.

DONDERS T. H., HABERLE S. G., HOPE G., WAGNER F. & VISSCHER H. 2007. Pollen evidence for the transition of the Eastern Australian climate system from the post-glacial to the present-day ENSO mode. *Quaternary Science Reviews*. 26, 1621-1637.

FRITZ S. C., JUGGINS S., BATTARBEE R. W. & ENGSTROM D. R. 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. *Nature*. 352, p.706.

GALLANT J., DOWLING T., READ A., WILSON N., TICKLE P. & INSKEEP C. 2011. 1 second SRTM derived digital elevation models user guide. *Geoscience Australia, Canberra*. 106.

GAT J. R. 1981 Stable isotope hydrology : deuterium and oxygen-18 in the water cycle*.* International Atomic Energy Agency, Vienna.

GENEREUX D. & BANDOPADHYAY I. 2001. Numerical investigation of lake bed seepage patterns: effects of porous medium and lake properties. *Journal of Hydrology*. 241, 286-303.

GIBSON J., EDWARDS T., BURSEY G. & PROWSE T. 1993. Estimating evaporation using stable isotopes: quantitative results and sensitivity analysis for. *Nordic Hydrology*. 24, 79-94.

GIBSON J. J., PREPAS E. E. & MCEACHERN P. 2002. Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modelling and results from a regional survey of Boreal lakes. *Journal of Hydrology*. 262, 128-144.

GIBSON J. J., BIRKS S. J. & YI Y. 2015. Stable isotope mass balance of lakes: a contemporary perspective. *Quaternary Science Reviews*.

GONFIANTINI R. 1986. Environmental isotopes in lake studies. *Handbook of environmental isotope geochemistry*. 2, 113-168.

GOURAMANIS C., DE DECKKER P., SWITZER A. D. & WILKINS D. 2013. Cross-continent comparison of high-resolution Holocene climate records from southern Australia—Deciphering the impacts of far-field teleconnections. *Earth-Science Reviews*. 121, 55-72.

HIPSEY M., BRUCE L. & HAMILTON D. 2013. GLM General Lake Model. Model overview and user information. *The University of Western Australia Technical Manual, Perth, Australia*.

HOSTETLER S. W. & BENSON L. V. 1994. Stable isotopes of oxygen and hydrogen in the Truckee River–Pyramid Lake surface-water system. 2. A predictive model of δ18O and 182H in Pyramid Lake. *Limnology and Oceanography*. 39, 356-364.

IHAKA R. & GENTLEMAN R. 1996. R: a language for data analysis and graphics. *Journal of computational and graphical statistics*. 5, 299-314.

IMBERGER J. 2001. Characterizing the dynamical regimes of a lake. *Physical processes in natural waters. Univ. de Girona, Spain: Servei de Publicacions*. 77-92.

JEFFREY S. J., CARTER J. O., MOODIE K. B. & BESWICK A. R. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling and Software*. 16, 309-330.

JONES M. D., LENG M. J., ROBERTS C. N., TÜRKEŞ M. & MOYEED R. 2005. A Coupled Calibration and Modelling Approach to the Understanding of Dry-Land Lake Oxygen Isotope Records. *Journal of Paleolimnology*. 34, 391-411.

JONES R., BOWLER J. & MCMAHON T. 1998. A high resolution Holocene record of P/E ratio from closed lakes in Western Victoria. *Palaeoclimates*. 3, 51-82.

JONES R. N., MCMAHON T. A. & BOWLER J. M. 2001. Modelling historical lake levels and recent climate change at three closed lakes, Western Victoria, Australia (c.1840–1990). *Journal of Hydrology*. 246, 159-180.

KIRONO D. G., JONES R. N. & KENT D. M. 2009 Modelling future lake levels and salinity at three lakes, Western Victoria. National Research Flagships, Climate Adaptation CSIRO—A report prepared for the Environment Protection Authority (EPA) Victoria.

LEAHY P., ROBINSON D., PATTEN R. & KRAMER A. 2010 Lakes in the Western District of Victoria and climate change*.* EPA Victoria.

LEANEY F. W. J., ALLISON G. B., DIGHTON J. C. & TRUMBORE S. 1995. The age and hydrological history of Blue Lake, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 118, 111-130.

LINACRE E. T. 1993. Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agricultural and Forest Meteorology*. 64, 237-256.

MAGNUS G. 1844. Versuche über die Spannkräfte des Wasserdampfs. *Annalen der Physik*. 137, 225-247.

MCVICAR T. R., VAN NIEL T. G., LI L. T., RODERICK M. L., RAYNER D. P., RICCIARDULLI L. & DONOHUE R. J. C. L. 2008. Wind speed climatology and trends for Australia, 1975,Äì2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. 35.

MORTON F. I. 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. *Journal of Hydrology*. 66, 1-76.

NEILSON R. P. 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications*. 5, 362-385.

NEUKOM R. & GERGIS J. 2012. Southern Hemisphere high-resolution palaeoclimate records of the last 2000 years. *The Holocene*. 22, 501-524.

PALMER W. C. 1965 Meteorological drought. US Department of Commerce, Weather Bureau Washington, DC, USA.

PANIGRAHI B. & PANDA S. N. 2003. Field test of a soil water balance simulation model. *Agricultural Water Management*. 58, 223-240.

PENMAN H. L. 1948. Natural Evaporation from Open Water, Bare Soil and Grass. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*. 193, 120-145.

PENMAN H. L. 1956. Estimating evaporation. *Eos, Transactions American Geophysical Union*. 37, 43-50.

RAIBER M., WEBB J. A., CENDÓN D. I., WHITE P. A. & JACOBSEN G. E. 2015. Environmental isotopes meet 3D geological modelling: Conceptualising recharge and structurally-controlled aquifer connectivity in the basalt plains of south-western Victoria, Australia. *Journal of Hydrology*. 527, 262-280.

RICKETTS R. D. & JOHNSON T. C. 1996. Climate change in the Turkana basin as deduced from a 4000 year long δO 18 record. *Earth and Planetary Science Letters*. 142, 7-17.

SAMRAJ P., SHARDA V. N., CHINNAMANI S., LAKSHMANAN V. & HALDORAI B. 1988. Hydrological behaviour of the Nilgiri sub-watersheds as affected by bluegum plantations, part I. The annual water balance. *Journal of Hydrology*. 103, 335-345.

SCHOTTERER U., OLDFIELD F. & FRÖHLICH K. 1996. GNIP. Global Network for Isotopes in Precipitation.

SHAPLEY M. D., ITO E. & DONOVAN J. J. 2008. Isotopic evolution and climate paleorecords: modeling boundary effects in groundwater-dominated lakes. *Journal of Paleolimnology*. 39, 17-33.

SHARDA V. N., SAMRAJ P., CHINNAMANI S. & LAKSHMANAN V. 1988. Hydrological behaviour of the Nilgiri sub-watersheds as affected by bluegum plantations, part II. Monthly water balances at different rainfall and runoff probabilities. *Journal of Hydrology*. 103, 347-355.

STEINMAN B. A., ROSENMEIER M. F., ABBOTT M. B. & BAIN D. J. 2010. The isotopic and hydrologic response of small, closed-basin lakes to climate forcing from predictive models: Application to paleoclimate studies in the upper Columbia River basin. *Limnology and Oceanography*. 55, 2231–2245.

STEINMAN B. A., ABBOTT M. B., MANN M. E., STANSELL N. D. & FINNEY B. P. 2012. 1,500 year quantitative reconstruction of winter precipitation in the Pacific Northwest. *Proceedings of the National Academy of Sciences*. 109, 11619-11623.

STETS E. G., WINTER T. C., ROSENBERRY D. O. & STRIEGL R. G. 2010. Quantification of surface water and groundwater flows to open- and closed-basin lakes in a headwaters watershed using a descriptive oxygen stable isotope model. *Water Resources Research*. 46.

TELFER A. L. 2000. Identification of processes regulating the colour and colour change in an oligotrophic, hardwater, groundwater-fed lake, Blue Lake, Mount Gambier, South Australia. *Lakes & Reservoirs: Research & Management*. 5, 161-176.

TIBBY J. & TILLER D. 2007. Climate–water quality relationships in three Western Victorian (Australia) lakes 1984–2000. *Hydrobiologia*. 591, 219-234.

TIERNEY J. E., SMERDON J. E., ANCHUKAITIS K. J. & SEAGER R. 2013. Multidecadal variability in East African hydroclimate controlled by the Indian Ocean. *Nature*. 493, p.389.

TIMMS B. 1974. Morphology and benthos of three volcanic lakes in the Mt. Gambier district, South Australia. *Marine and Freshwater Research*. 25, 287-297.

TIMMS B. V. 1976. A Comparative study of the limnology of three maar lakes in western Victoria. I. Physiography and physicochemical features. *Marine and Freshwater Research*. 27, 35-60.

TWEED S., LEBLANC M. & CARTWRIGHT I. 2009. Groundwater–surface water interaction and the impact of a multi-year drought on lakes conditions in South-East Australia. *Journal of Hydrology*. 379, 41-53.

TYLER J. J., MILLS K., BARR C., SNIDERMAN J. M. K., GELL P. A. & KAROLY D. J. 2015. Identifying coherent patterns of environmental change between multiple, multivariate records: an application to four 1000-year diatom records from Victoria, Australia. *Quaternary Science Reviews*. 119, 94-105.

VALIANTZAS J. D. 2006. Simplified versions for the Penman evaporation equation using routine weather data. *Journal of Hydrology*. 331, 690-702.

VAN BOXEL J. H., GONZÁLEZ-CARRANZA Z., HOOGHIEMSTRA H., BIERKENS M. & VÉLEZ M. I. 2013. Reconstructing past precipitation from lake levels and inverse modelling for Andean Lake La Cocha. *Journal of Paleolimnology*. 51, 63-77.

WATRAS C. J., READ J. S., HOLMAN K. D., LIU Z., SONG Y. Y., WATRAS A. J., MORGAN S. & STANLEY E. H. 2014. Decadal oscillation of lakes and aquifers in the upper Great Lakes region of North America: Hydroclimatic implications. *Geophysical Research Letters*. 41, 456-462.

WIGDAHL C. R., SAROS J. E., FRITZ S. C., STONE J. R. & ENGSTROM D. R. 2014. The influence of basin morphometry on the regional coherence of patterns of diatom-inferred salinity in lakes of the northern Great Plains (USA). *The Holocene*. 24, 603-613.

WILKINS D., GOURAMANIS C., DE DECKKER P., FIFIELD L. K. & OLLEY J. 2013. Holocene lake-level fluctuations in Lakes Keilambete and Gnotuk, southwestern Victoria, Australia. *The Holocene*. 23, 784-795.

YIHDEGO Y. & WEBB J. 2012. Modelling of seasonal and long-term trends in lake salinity in southwestern Victoria, Australia. *Journal of Environmental Management*. 112, 149-159.

YIHDEGO Y., WEBB J. A. & LEAHY P. 2014. Modelling of lake level under climate change conditions: Lake Purrumbete in southeastern Australia. *Environmental Earth Sciences*. 73, 3855-3872.

YIHDEGO Y. & WEBB J. 2015. Use of a conceptual hydrogeological model and a time variant water budget analysis to determine controls on salinity in Lake Burrumbeet in southeast Australia. *Environmental Earth Sciences*. 73, 1587-1600.

## APPENDIX A: CHIMBLE.R CODE

```
#This program is a lake modelling program based on Steinman et al (2010)
#Version 1.0917
#Things to do
#Rework groundwater to flow into the lake based on the percentage of Fdos and Fsos
that flows out for a timestep. This will avoid the complicated issue of which reservoir to
run the flux in and out of.
#Mixing for soil layers (See Gaziz & Feng 2004)
#Update outseepage routine based on surface area and permeability.
#First thing we need to do is set a working directory, based on where the program was
loaded from. - done. No need. Just drag and drop from the lake folder.

#We're going to start with a file to store all sorts of stuff like albedo and things that we
don't want coded into the R code. This will allow us to tweak anything, hopefully in an
easy fashion. The file will consist of a three column, tab separated list with the first
column being the variable name, and the second being the value and the third column
being comments.

require(compiler)
enableJIT(3)
#************************* Read
Preferences************************************
Prefs <- read.table("Preferences.txt",header=TRUE, sep="\t", row.names = 1,
stringsAsFactors = FALSE)
Historicaldata <- Prefs["Historicallevels","Value"]
Lakedatafile <- Prefs["Lakedatafile","Value"]
ISOdatafile <- Prefs["Isotopefile","Value"]
Modelparamfile <- Prefs["Modelparamfile","Value"]
Metfile <- Prefs["Metfile", "Value"]
Lakeoutfile <- Prefs["Lakeoutput","Value"]
Fluxoutfile <- Prefs["Fluxoutput","Value"]
Cleanoutputfile <- Prefs["Cleanoutput","Value"]
Metoutfile <- Prefs["Metoutfile", "Value"]
O18output <- Prefs["18Ooutput","Value"]
Doutfile <- Prefs["Doutput","Value"]
```

```
Datarate <- Prefs["Datarate", "Value"]
Timestep <- as.numeric(Prefs["Timestep", "Value"])
ALBlake <- as.numeric(Prefs["ALBlake","Value"])
Interpolationtype <- Prefs["Interpolationtype", "Value"]
ALBearth <- as.numeric(Prefs["ALBearth","Value"])
PWF <- as.numeric(Prefs["PWF","Value"])
KcSS <- as.numeric(Prefs["KcSS","Value"])
KcDS <- as.numeric(Prefs["KcDS","Value"])
KcLwin <- as.numeric(Prefs["KcLwin","Value"])
KcLsum <- as.numeric(Prefs["KcLsum","Value"])
Latitude <- as.numeric(Prefs["Latitude","Value"])
Fitspan <- as.numeric (Prefs["Fitspan","Value"])
Sampledepth <- as.numeric(Prefs["Sampledepth","Value"])
Soilmixing <- as.numeric(Prefs["Soilmixing","Value"])
RunoffRatio <- as.numeric(Prefs["RunoffRatio","Value"])/100
Deeproot <- as.numeric(Prefs["Deeprootpercent","Value"])/100
PMod <- as.numeric(Prefs["PMod","Value"])
TaMod <- as.numeric(Prefs["TaMod","Value"])
TwMod <- as.numeric(Prefs["TwMod","Value"])
WSMod <- as.numeric(Prefs["WSMod","Value"])
RHMod <- as.numeric(Prefs["RHMod","Value"])
RsMod <- as.numeric(Prefs["RsMod","Value"])
GWMod <- as.numeric(Prefs["GWMod","Value"])

#************************** Read Hyspographic Data
**************************************

#This first section is used to convert a table of lake data (Height, Volumes, Area) to a
function.
#The file chosen should be tab separated text, with headers, and columns of
Depth(height), Volume and Area.
if (Lakedatafile == ""){
message("*****************\nThis program is designed to convert lake data
(Height/Depth, Volumes and Areas to a Loess function.\nIt requires a tab separated text
file with three columns for height, volume and area. \nPS: Make sure your lake data
extends well above the height of the current lake level (preferably to include the entire
catchment or to overflow level. The highest lake level/maximum volume should be at
the top of the file.)\n")
readline(prompt = "To select your lake data file, please hit <Enter>")
Lakedatafile <- tryCatch(file.choose(), error = function(e) "")
} else { # end if
message ("Reading lake volume file specified in Preferences")
}#end else
Lakevolumes <- read.table(Lakedatafile,header=TRUE)
message("\nThe file ",basename(Lakedatafile) ," has been loaded. This program will
now fit a loess function to the hypsographic data.")

options(digits=7) # Just to keep things legible.
```

```
options(scipen=999) #This bit of code pushes R to display things in decimal rather than
scientific format.

#********************************* Interpolation
**************************************

func.Lakearea <- function (volume){
if (Interpolationtype == "Loess"){
Area <- predict(LakeVA, volume)
return (Area)
} else if (Interpolationtype == "Segments"){
Mindex <-
which(Lakevolumes$Volume==min(Lakevolumes$Volume[(Lakevolumes$Volume>vo
lume)]))
Slope <- (Lakevolumes$Area[Mindex] -
Lakevolumes$Area[Mindex+1])/(Lakevolumes$Volume[Mindex] -
Lakevolumes$Volume[Mindex+1])
Intercept <- Lakevolumes$Area[Mindex] - Lakevolumes$Volume[Mindex]*Slope
Area <- volume*Slope + Intercept
return (Area)
} else {
message ("Interpolation type unrecognised (Lakearea Function)")
}
} #end func

func.Lakedepth <- function (volume){
if (Interpolationtype == "Loess"){
Depth <- predict(LakeVH, volume)
return (Depth)
} else if (Interpolationtype == "Segments"){
Mindex <-
which(Lakevolumes$Volume==min(Lakevolumes$Volume[(Lakevolumes$Volume>vo
lume)]))
Slope <- (Lakevolumes$Depth[Mindex] -
Lakevolumes$Depth[Mindex+1])/(Lakevolumes$Volume[Mindex] -
Lakevolumes$Volume[Mindex+1])
Intercept <- Lakevolumes$Depth[Mindex] - Lakevolumes$Volume[Mindex]*Slope
Depth <- volume*Slope + Intercept
return (Depth)
} else {
message ("Interpolation type unrecognised (Lakedepth Function)")
}
} #end func

func.Lakevolume <- function (depth){
if (Interpolationtype == "Loess"){
Volume <- predict(LakeHV, depth)
return (Volume)
```

```
} else if (Interpolationtype == "Segments"){
Mindex <-
which(Lakevolumes$Depth==min(Lakevolumes$Depth[(Lakevolumes$Depth>depth)])
)
Slope <- (Lakevolumes$Volume[Mindex] -
Lakevolumes$Volume[Mindex+1])/(Lakevolumes$Depth[Mindex] -
Lakevolumes$Depth[Mindex+1])
Intercept <- Lakevolumes$Volume[Mindex] - Lakevolumes$Depth[Mindex]*Slope
Volume <- depth*Slope + Intercept
return (Volume)
} else {
message ("Interpolation type unrecognised (Lakevolume Function)")
}
} #end func

#********************************* Loess Interpolation
**********************************
#These three lines are just to enable these objects as global variables
LakeVA <- 0
LakeVH <- 0
LakeHV <- 0
if (Interpolationtype == "Loess"){
LakeVA <- loess (Lakevolumes[,3] ~ Lakevolumes[,2], span = Fitspan, surface =
"direct")
message ("\nVolume to area best fit completed with a loess function. Standard error =
",summary(LakeVA)[5])

LakeVH <- loess (Lakevolumes[,1] ~ Lakevolumes[,2], span = Fitspan, surface =
"direct")
message ("Volume to lake depth best fit completed with a loess function. Standard error
= ",summary(LakeVH)[5])

#This function is required for the SVC calculation.
LakeHV <- loess (Lakevolumes[,2] ~ Lakevolumes[,1], span = Fitspan, surface =
"direct")
}
#********************************* Interpolation Plots
**********************************


if (Interpolationtype == "Loess"){
par(mfrow=c(2,2))
} else {
par(mfrow=c(2,1))
}

plot (Lakevolumes[,2], Lakevolumes[,1], main="Volumes & Lake Depth", sub="",
xlab="Volume", ylab="Depth")
```

```
if (Interpolationtype == "Loess"){
lines (Lakevolumes[,2], (predict(LakeVH)), col="red")
plot (Lakevolumes[,2], resid(LakeVH), main="Volumes & Lake Depth Residuals",
sub="", xlab="Volume", ylab="Depth")
} else {
lines (Lakevolumes[,2], Lakevolumes[,1], col="red")
}

plot(Lakevolumes[,2], Lakevolumes[,3], main="Volumes & Surface Area", sub="",
xlab="Volume", ylab="Surface Area")
if (Interpolationtype == "Loess"){
lines (Lakevolumes[,2], (predict(LakeVA)), col="red")
plot (Lakevolumes[,2], resid(LakeVA), main="Volumes & Surface Area Residuals",
sub="", xlab="Volume", ylab="Surface Area")
} else {
lines (Lakevolumes[,2], Lakevolumes[,3], col="red")
}

#The above section should be redone. Rather than trying to define an entire lake using a
single polynomial function, I will instead use this: When a volume is called, find the
nearest volume, and 1 or 2 above and below that volume. Then create a function just
through those datapoints. This will be a lot more accurate than the polynomial. - This is
now fixed - a Loess function has been used, which seems to do the job nicely.



#********************************* Main Code
*************************************

#Main code
#Lets start by defining a few variables. These are the variables defined in Steinman's
model.
#
#Generally defined by external input (eg: meteorological data)
#RESsl Surface lake reservoir (m3)
#RESdl Deep lake reservoir (m3)
#RESss Surface soil reservoir (m3)
#RESds Deep soil reservoir (m3)
#RESin Inflow reservoir (m3)
#RESsp Snowpack reservoir (m3)
#Ta, Tw Temp of air and water
#CA catchment area
#AWCss Available water capacity of surface soil
#AWCds Available water capacity of deep soil
#Cin Catchment inflow delay constant (estimated from model calibration)
#SVC Surface lake volume control
#Csr Seepage rate (estimated from model calibration)
#ALB Albedo of lake surface
```

```
#Rs Solar radioation (MJ m-2 d-1)
#Ra Extraterrestrial solar radiation (MJ m-2 d-1)
#RH Relative humidity (%)
#PWF Penman wind function
#WS Wind speed
#Fr Rainfall on catchment
#
#Generally defined by model calculation
#Fp Precipitation on lake surface (m3 month-1)
#Fin Catchment inflow into lake
#Fe Evaporation from lake surface
#Fsos Shallow lake outseepage
#Fdos Deep lake outseepage
#Fslm Shallow lake mixing
#Fdlm Deep lake mixing
#Fsm Catchment snowmelt
#Fssi Surface soil infiltration
#Fsse Surface soil evapotranspiration
#Fssd Surface soil drainage to deep soil
#Fdse Deep soil evapotranspiration
#Fro Catchment runoff
#Fdsd Deep soil drainage
#Fsf Snowfall
#dE Isotopic composition of evaporation (0/00)
#dL Isotopic composition of lake surface
#dA Isotopic composition of atmospheric moisture
#ALPHA Equilibrium isoptopic composition
#RALPHA Reciprocal of equilibrium isotopic composition
#hn Normalised relative humidity
#Etot Total isotopic separation
#Eeq Equilibrium isotopic separation
#Ek Kinetic isotopic separation
#Esa Saturation vapour pressure of air
#Esw Saturation vapour pressure of water
#C Kinetic isotopic value
#PET Potential evapotranspiration

#A few additional ones not defined in the table
#Time Typically months in steinman's model. For some applications and datasets we may want to run days, and (unlikely) years.
#d18Op Isotopic ratio of 18Oxygen in rainfall
#dDp Isotopic ratio of deuterium in rainfall
#Toff Temperature offset between lake water and Ta
#Depth
#Area
#Timestep Timestep for integration. Can't use dt as it's used for T distribution in R
#Datarate Daily, Monthly or other datasets.
```

```
#Procedure
#Two files to be read. 1, being the initial lake morphology and reservoirs
#2 being meteorological data
#The second file is also used to determine how many cycles the program should run either using a "if no data, then stop" routine, or just using the number of rows as a counter.
#We also need a dataframe to keep track of fluxes.

#*************** Read Parameter, Meteorological and Isotope Data ************************



if (Modelparamfile == ""){
	message("\n*****************\nNow that the hypsographic data has been calculated, we require two files.\nThe first file required is the hydrological model parameters and initial values.")
	message("This file requires a header line, followed by a tab separated row with the following values: \nCatchment Area (m^2)\nAvailable water capacity in shallow soil (m)\nAvailable water capacity in deep soil (m)\nCatchment inflow delay constant (estimated from model calibration. Use 0 until after calibration)\nCatchment outseepage rate (estimated from model calibration. Use 0 until after calibration)\nSurface lake reservoir (m^3)\nDeep lake reservoir (m^3)\nShallow soil reservoir (m^3)\nDeep soil reservoir (m^3)\nInflow reservoir (m^3)\nSnowpack reservoir (m^3)\n")
	readline(prompt = "To select the model parameters file, hit <Enter>")
	Modelparamfile <- tryCatch(file.choose(), error = function(e) "")
} else {
	message ("*****************\nReading lake parameter file specified in Preferences")
}#end else
Modelparam <- read.table(Modelparamfile, header=TRUE)
message("The file ",basename(Modelparamfile) ," has been loaded")

if (is.na(Historicaldata)) {
message ("*****************\nYou have not specified a historical levels file in preferences.")
Historicallevels <-0
} else {
message ("*****************\nLoading historical level data.")
Historicallevels <- read.table(Historicaldata,header=TRUE)
message (nrow(Historicallevels), " records identified in the historical levels data")

} #end if


if (Metfile == ""){
	message("\n*****************\nThe second file required is meteorological values for the time period of interest")
	message("This file requires a header line, followed by a tab separated rows with the following values: \nMonth\nPrecipitation (mm)\nTemperature (ºC)\nRelative
```

```
Humidity (%)\nSolar radiation (MJ m-2d-1)\nWind speed (m/s)\nd18O in precipitation
(0/00)\ndDeuterium in precipitation (0/00)\nStratification depth (m)\n Lake air
temperature offset (ºC)\n")
        readline(prompt = "To select the meteorological file, hit <Enter>")
        Metfile <- tryCatch(file.choose(), error = function(e) "")
        message("The file ",basename(Metfile) ," has been loaded")

        #Now to assign some variables from these files.
        #One point to remember is that growing a dataframe in R is very slow. It would
be better to precalculate the size of the data frame, and leaving it empty. We can do this
simply by looking at the length of the Metfile dataframe.
        #Just an aside, I'll be using data frames rather than lists to allow for the use of
other data types such as strings used for notes, etc in the future.
} else {#end if
        message ("*****************\nReading meteorological data file specified in
Preferences")
}#end else
Met <- read.table(Metfile,header=TRUE)
if (Datarate == "Monthly"){
message (nrow(Met), " months identified in the Meteorological
data\n*****************\n")
} else {
message (nrow(Met), " days identified in the Meteorological
data\n*****************\n")
}

#************************* Smooth Stratification Level
********************************

#This little section smooths out the stratification layer, otherwise we see large
excursions in isotopes whenever the SL changes. We could also tie the SL change to the
timestep, but that tends to result in a half distance paradox. By building this little section
in here, we can use whatever smoothing we like for the SL. We can also apply this to
other things that change over time, but are represented as steps for each month (eg: solar
radiation).

func.SLsmooth <- function(){
SLsmooth <- data.frame(Timestep = numeric (nrow(Met) / Timestep) , SL=numeric
(nrow(Met) / Timestep))
for (Time in 1:(nrow(Met))){ #Possibly parallelizable
        for (step in 0:((1/Timestep)-1)) {
        Index <- ((Time-1)/Timestep)+step+1
        if (Time < nrow(Met)){
        SLsmooth$SL[Index] <- Met$SL[Time] + step*(Met$SL[Time+1] -
Met$SL[Time])*Timestep
        } else {
        SLsmooth$SL[Index] <- Met$SL[Time]
        }
```

```
		}
		}
		return (SLsmooth)
}


#************************** Apply meteorological modifiers
*****************************

#Apply modifiers to Met data
Met$P <- Met$P * PMod
Met$Ta <- Met$Ta * TaMod
Met$Toff <- Met$Toff * TwMod
Met$WS <- Met$WS * WSMod
Met$RH <- Met$RH * RHMod
Met$Rs <- Met$Rs * RsMod
Met$Groundwater <- Met$Groundwater + GWMod

#Apply the 4 degree check to the Met data. If air temp + lake temp offset would set the
lake to less than 4º, then lake goes to 4º (Required for cold weather lakes, eg: Steinman
2010)
func.Toff <- function(temp){
if (temp < 4) {
temp <- 4 - Met$Ta[i]
} else {
temp <- Met$Toff[i]
}
return (temp)
}

for (i in 1:nrow(Met)){ #Parallelizable
Met$Toff[i] <- func.Toff(Met$Toff[i]+Met$Ta[i])
}

if (Timestep < 1){
SLsmooth <- func.SLsmooth()$SL #Replace the stepped SL with the smoothed one.
} else {
SLsmooth <- Met$SL
}#SLsmooth takes a while to run. This prevents it running if not required (Timestep =
1).

Met <- Met[rep(1:nrow(Met),each=(1/Timestep)),] #This duplicates the metrows by the
timestep factor, so that we don't require multiple indexes. For more information, check
out the main program for loop at the end of the functions.
Metrows <- nrow(Met)
Met$SL <- SLsmooth
```

```
#************************** Create Dataframes
*********************************


#Now for the parameters file. We want to create a data table with the same number of
rows as the Metfile +1. The plus one is for the initial conditions.
Lake <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = numeric(Metrows + 1), CA =
numeric(Metrows + 1),AWCss = numeric(Metrows + 1),AWCds = numeric(Metrows +
1),Cin  = numeric(Metrows + 1),Csr = numeric(Metrows + 1),RESsl =
numeric(Metrows + 1),RESdl = numeric(Metrows + 1),RESss = numeric(Metrows +
1),RESds = numeric(Metrows + 1),RESin = numeric(Metrows + 1),RESsp =
numeric(Metrows + 1),Volume = numeric(Metrows + 1),Area = numeric(Metrows + 1),
Depth = numeric(Metrows + 1),stringsAsFactors = FALSE)


if (Datarate == "Monthly") {
Clean <- data.frame(Time = numeric(nrow(read.table(Metfile,header=TRUE))+1), Year
= numeric(nrow(read.table(Metfile,header=TRUE))+1), Month =
character(nrow(read.table(Metfile,header=TRUE))+1),Day =
numeric(nrow(read.table(Metfile,header=TRUE))+1), Volume =
numeric(nrow(read.table(Metfile,header=TRUE))+1),Area =
numeric(nrow(read.table(Metfile,header=TRUE))+1), Depth =
numeric(nrow(read.table(Metfile,header=TRUE))+1), StratificationDepth =
numeric(nrow(read.table(Metfile,header=TRUE))+1), dD_sampledepth =
numeric(nrow(read.table(Metfile,header=TRUE))+1), d18O_sampledepth =
numeric(nrow(read.table(Metfile,header=TRUE))+1),stringsAsFactors = FALSE)
}else {
Clean <- data.frame(Time =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1), Year =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1), Month =
character(length(unique(Met$Month))*length(unique(Met$Year))+1),Day =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1), Volume =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1),Area =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1), Depth =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1),
StratificationDepth =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1), dD_sampledepth
= numeric(length(unique(Met$Month))*length(unique(Met$Year))+1),
d18O_sampledepth =
numeric(length(unique(Met$Month))*length(unique(Met$Year))+1),stringsAsFactors =
FALSE)
}

#Now for the flux data frame. We'll make this the same structure as the Lake file, just in
case we have to do any integration to fluxes over months.
```

```
Flux <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = numeric(Metrows + 1), Fr =
numeric(Metrows + 1), Fp = numeric(Metrows + 1), Fsm = numeric(Metrows + 1),Fe =
numeric(Metrows + 1),Fsos = numeric(Metrows + 1),Fdos = numeric(Metrows +
1),Fdlm = numeric(Metrows + 1),Fssi = numeric(Metrows + 1),Fsse =
numeric(Metrows + 1),Fssd = numeric(Metrows + 1),Fdse = numeric(Metrows +
1),Fdsd = numeric(Metrows + 1), Fro = numeric(Metrows + 1),Fin = numeric(Metrows
+ 1), Fsf = numeric(Metrows + 1),Fgw = numeric(Metrows + 1),Fof =
numeric(Metrows + 1),E = numeric(Metrows + 1), PET = numeric(Metrows +
1),stringsAsFactors = FALSE)

Flux18O <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = numeric(Metrows + 1), Fr =
numeric(Metrows + 1), Fp = numeric(Metrows + 1), Fsm = numeric(Metrows + 1),Fe =
numeric(Metrows + 1),Fsos = numeric(Metrows + 1),Fdos = numeric(Metrows +
1),Fdlm = numeric(Metrows + 1),Fssi = numeric(Metrows + 1),Fsse =
numeric(Metrows + 1),Fssd = numeric(Metrows + 1),Fdse = numeric(Metrows +
1),Fdsd = numeric(Metrows + 1), Fro = numeric(Metrows + 1),Fin = numeric(Metrows
+ 1), Fsf = numeric(Metrows + 1),Fgw = numeric(Metrows + 1),Fof =
numeric(Metrows + 1),E = numeric(Metrows + 1), PET = numeric(Metrows +
1),stringsAsFactors = FALSE)

FluxD <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = numeric(Metrows + 1), Fr =
numeric(Metrows + 1), Fp = numeric(Metrows + 1), Fsm = numeric(Metrows + 1),Fe =
numeric(Metrows + 1),Fsos = numeric(Metrows + 1),Fdos = numeric(Metrows +
1),Fdlm = numeric(Metrows + 1),Fssi = numeric(Metrows + 1),Fsse =
numeric(Metrows + 1),Fssd = numeric(Metrows + 1),Fdse = numeric(Metrows +
1),Fdsd = numeric(Metrows + 1), Fro = numeric(Metrows + 1),Fin = numeric(Metrows
+ 1), Fsf = numeric(Metrows + 1),Fgw = numeric(Metrows + 1),Fof =
numeric(Metrows + 1),E = numeric(Metrows + 1), PET = numeric(Metrows +
1),stringsAsFactors = FALSE)

#We also need a dataframe to hold isotopic values for the reservoirs.
ISOD <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = numeric(Metrows + 1),ISOp =
numeric(Metrows + 1),ISORESsl = numeric(Metrows + 1),ISORESdl =
numeric(Metrows + 1),ISORESss = numeric(Metrows + 1),ISORESds =
numeric(Metrows + 1),ISORESin = numeric(Metrows + 1),ISORESsp =
numeric(Metrows + 1), dE = numeric(Metrows + 1),dPET = numeric(Metrows +
1),stringsAsFactors = FALSE)

ISO18O <- data.frame(Timestep = numeric(Metrows + 1), Year = numeric(Metrows +
1),Month = character(Metrows + 1),Day = character(Metrows + 1),ISOp =
numeric(Metrows + 1),ISORESsl = numeric(Metrows + 1),ISORESdl =
numeric(Metrows + 1),ISORESss = numeric(Metrows + 1),ISORESds =
numeric(Metrows + 1),ISORESin = numeric(Metrows + 1),ISORESsp =
```

```
numeric(Metrows + 1), dE = numeric(Metrows + 1),dPET = numeric(Metrows +
1),stringsAsFactors = FALSE)
#Plan is define each equation as a function, and just call that function as required. Some
attention must be paid to calling functions in the right order, so all dependent functions
are updated from current data.

#Time is initially 1. This refers to the first line of the Met data frame.
#We can iterate through the Met data frame as long as Time < or <= Metrows
Time <- 1

#************************** Main hydrologic functions
*********************************


#We need a function to calculate the actual catchment area as the initial value in the
Lake data frame is the total catchment which consists of lake surface + earth catchment.
This will vary depending on lake level. This function should be used instead of
Lake$CA[Time] for most equations.


func.CAe <- function(Time){
        CAe <- Lake$CA[Time] - Lake$Area[Time]#end if
        return (CAe) #end else
}#end function

#Equation 10. :FIRST!!! To call this function Fsm <- func.Fsm(time) and you'll get the
value for Fsm for the current month.
#Monthly data requirement
func.Fsm <- function(Time){
        if (Datarate == "Monthly") {
        snowmelt <- 0.021 #mm per month
        } else {
        snowmelt <- 0.00069 #mm per day
        }
        #This section has been replaced. Now, if Ta > -2 and RESsp > 0, then snowmelt
is calculated. The issue may be that Stella may not be able to do negative fluxes and that
therefore having a negative flux isn't an issue. In R it's a problem.
        if (Lake$RESsp[Time] > (snowmelt * (Met$Ta[Time] + 2) * func.CAe(Time) *
Timestep) && Met$Ta[Time] > -2) {
                Fsm <- snowmelt * (Met$Ta[Time] + 2) * func.CAe(Time) * Timestep
                Fsm18O <- Fsm * ISO18O$ISORESsp[Time]
                FsmD <- Fsm * ISOD$ISORESsp[Time]
        } else if (Lake$RESsp[Time] < (snowmelt * (Met$Ta[Time] + 2) *
func.CAe(Time) * Timestep) && Met$Ta[Time] > -2){
                Fsm <- Lake$RESsp[Time]
                Fsm18O <- Fsm * ISO18O$ISORESsp[Time]
                FsmD <- Fsm * ISOD$ISORESsp[Time]
        } else {
```

```
                Fsm <- 0
                Fsm18O <- 0
                FsmD <- 0
}
Fsm <- list(Fsm = Fsm,Fsm18O = Fsm18O, FsmD = FsmD)
return (Fsm)
}#end func


func.Fgw <- function(Time){
        Fgw <- Met$Groundwater[Time] * Timestep
        Fgw18O <- Fgw*Met$d18Ogw[Time]
        FgwD <- Fgw*Met$dDgw[Time]
        Fgw <- list(Fgw = Fgw,Fgw18O = Fgw18O, FgwD = FgwD)
return (Fgw)
}#end function

func.Soil <- function (Time){
SSmax <- (func.CAe(Time) * Lake$AWCss[Time])#Max volume of soil
DSmax <- (func.CAe(Time) * Lake$AWCds[Time])
Influx <- func.Fr(Time)$Fr + func.Fsm(Time)$Fsm #this has to balance
SSflux <- Lake$RESss[Time] + Influx - func.Evap(Time)$Fsse #RESss + fluxes
SSexcess <- SSflux - SSmax #excess from RESss
DSflux <- Lake$RESds[Time] - func.Evap(Time)$Fdse


Influx18O <- func.Fr(Time)$Fr18O + func.Fsm(Time)$Fsm18O #this has to balance
InfluxD <- func.Fr(Time)$FrD + func.Fsm(Time)$FsmD #this has to balance
if (Influx == 0) {
        Fssi <- 0
        Fssi18O <- 0
        FssiD <- 0
        Fssd <- 0
        Fssd18O <- 0
        FssdD <- 0
        Fdsd <- 0
        Fdsd18O <- 0
        FdsdD <- 0
        Fro <- 0
        Fro18O <- 0
        FroD <- 0
} else if (SSmax >= SSflux){#RESss can hold all flux in and out
        Fssi <- Influx
        Fssi18O <- Influx18O
        FssiD <- InfluxD
        Fssd <- 0
        Fssd18O <- 0
        FssdD <- 0
```

```
        Fdsd <- 0
        Fdsd18O <- 0
        FdsdD <- 0
        Fro <- 0
        Fro18O <- 0
        FroD <- 0
        } else if (SSmax < SSflux && DSmax >= DSflux + SSexcess*RunoffRatio) {
        #RESss cannot hold all flux, so some is diverted to RESds, some to Fro (decided
by runoff ration). RESds is able to hold all additional flux.
        Fssi <- SSmax - Lake$RESss[Time] + func.Evap(Time)$Fsse
        Fssd <- SSexcess*RunoffRatio
        Fdsd <- 0
        Fro <- SSexcess*(1-RunoffRatio)
        Fssi18O <- Influx18O * Fssi/(Fssi+Fssd+Fdsd+Fro)
        Fssd18O <- Influx18O * Fssd/(Fssi+Fssd+Fdsd+Fro)
        Fdsd18O <- Influx18O * Fdsd/(Fssi+Fssd+Fdsd+Fro)
        Fro18O <- Influx18O * Fro/(Fssi+Fssd+Fdsd+Fro)
        FssiD <- InfluxD * Fssi/(Fssi+Fssd+Fdsd+Fro)
        FssdD <- InfluxD * Fssd/(Fssi+Fssd+Fdsd+Fro)
        FdsdD <- InfluxD * Fdsd/(Fssi+Fssd+Fdsd+Fro)
        FroD <- InfluxD * Fro/(Fssi+Fssd+Fdsd+Fro)
        } else if ((SSmax < SSflux && DSmax < DSflux + SSexcess*RunoffRatio)){
        #RESss cannot hold all flux, so some is diverted to RESds, some to Fro. RESds
is also unable to hold all additional flux.
        Fssi <- SSmax - Lake$RESss[Time] + func.Evap(Time)$Fsse
        Fssd <- DSmax - Lake$RESds[Time] + func.Evap(Time)$Fdse
        Fdsd <- SSexcess*RunoffRatio - Fssd
        Fro <- SSexcess*(1-RunoffRatio)
        Fssi18O <- Influx18O * Fssi/(Fssi+Fssd+Fdsd+Fro)
        Fssd18O <- Influx18O * Fssd/(Fssi+Fssd+Fdsd+Fro)
        Fdsd18O <- Influx18O * Fdsd/(Fssi+Fssd+Fdsd+Fro)
        Fro18O <- Influx18O * Fro/(Fssi+Fssd+Fdsd+Fro)
        FssiD <- InfluxD * Fssi/(Fssi+Fssd+Fdsd+Fro)
        FssdD <- InfluxD * Fssd/(Fssi+Fssd+Fdsd+Fro)
        FdsdD <- InfluxD * Fdsd/(Fssi+Fssd+Fdsd+Fro)
        FroD <- InfluxD * Fro/(Fssi+Fssd+Fdsd+Fro)
        } else {
        message ("You missed an option in the func.Soil routine")
        }
        Soil <- list(Fssi = Fssi,Fssd = Fssd, Fdsd = Fdsd, Fro= Fro, Fssi18O = Fssi18O,
FssiD = FssiD, Fssd18O = Fssd18O, FssdD = FssdD, Fdsd18O = Fdsd18O, FdsdD =
FdsdD, Fro18O = Fro18O, FroD = FroD)
        return (Soil)
}

func.Evap <- function(Time){
#We need to estimate the actual evapotranspiration ET.  We'll do this based on Van
Boxel's model, rather than Palmer. 1965 which is approximately what Steinman does.
```

```
#First we will use two coefficients to create a linear relationship between ET and Soil water content.
#Additional future work would be to include saturation, as well as field capacity for soil, so that the RESss can go above field capacity and be withdrawn at the full rate.

SSETC <- Lake$RESss[Time]/(func.CAe(Time) * Lake$AWCss[Time])
DSETC <- Lake$RESds[Time]/(func.CAe(Time) * (Lake$AWCds[Time]))

SSETa <- (func.CAe(Time) * func.PET(Time) * KcSS * SSETC)
DSETa <- (func.CAe(Time) * func.PET(Time) * KcDS * DSETC * Deeproot)
#These two coefficients will result in a two step evaporation rate with most evaporation coming from upper soil and a lower rate from the deeper soil. Of interest is that this method also removes the dependency of evaporation in stages (first layer 1, then layer 2), as the lower layer now simply represents the evapotranspiration from deep rooted plants, thereby simplifying the code.

if (Lake$RESss[Time] > (SSETa * Timestep)) {
        Fsse <- SSETa * Timestep
        } else {
        Fsse <- Lake$RESss[Time]
        }#endif
Fsse18O <- Fsse * ISO18O$ISORESss[Time]
FsseD <- Fsse * ISOD$ISORESss[Time]

if (Lake$RESds[Time] > (DSETa * Timestep)) {
        Fdse <- DSETa * Timestep
        } else {
        Fdse <- Lake$RESds[Time]
        }#endif
Fdse18O <- Fdse*ISO18O$ISORESds[Time]
FdseD <- Fdse*ISOD$ISORESds[Time]
#as evapotranspiration is not supposed to result in fractionation (steinman 2010), we simply set the isotopic flux to be the same as the soil reservoir.

                Evap <- list(Fsse = Fsse, Fdse = Fdse, Fsse18O = Fsse18O,
                FsseD=FsseD,Fdse18O=Fdse18O,FdseD=FdseD)
                return (Evap)
}


#Function for Fr over the catchment (catchment area - lake surface area)
func.Fr <- function(Time){
        if (Met$Ta[Time] > 0){
                Fr <- ((Met$P[Time]*0.001) * func.CAe(Time) * Timestep)
                Fr18O <- Fr * Met$d18Op[Time]
                FrD <- Fr * Met$dDp[Time]
        } else {
                Fr <- 0
```

```
                Fr18O <- 0
                FrD <- 0
        }
        Fr <- list (Fr=Fr, Fr18O = Fr18O, FrD=FrD)
        return (Fr)
}#end function


func.Fsf <- function(Time){
        if (Met$Ta[Time] <= 0){
                Fsf <- ((Met$P[Time]*0.001) * func.CAe(Time) * Timestep)
                Fsf18O <- Fsf * Met$d18Op[Time]
                FsfD <- Fsf * Met$dDp[Time]
        } else {
                Fsf <- 0
                Fsf18O <- 0
                FsfD <- 0
        } #end else
        Fsf <- list (Fsf = Fsf, Fsf18O = Fsf18O, FsfD = FsfD)
        return (Fsf)
}#end func


#Monthly data requirement
#Cin has been adapted to be 12/365 times the rate if daily data is used.
func.Fin <- function(Time){
        if (Lake$RESin[Time] > (func.CAe(Time) * 0.001)) { #This just gives us a
value that assumes that RESin will drain until AWC in the runoff and deeper drainage
drops to 0.001mm over the catchment.
                Fin <- Lake$RESin[Time] * Lake$Cin[Time] * Timestep
                Fin18O <- Fin * ISO18O$ISORESin[Time]
                FinD <- Fin * ISOD$ISORESin[Time]
        } else {
                Fin <- 0
                Fin18O <- 0
                FinD <-         0
        }
        Fin <- list (Fin = Fin, Fin18O = Fin18O, FinD = FinD)
        return (Fin)
}#end function


###Ok, this one is a problem. The functions in Steinman's equations are hardcoded to be
active on certain months (Oct, Nov, Dec) We're going to have to revise this section as
the month requirement is lake, or at the very least, hemisphere dependant. As the
stratification profiles have quite a few months of 0 depth, I see no issue with simply
relying on the stratification profiles. When they're 0, mixing will occur in the entire
lake.
```

```
###In his equations Deep_lake_depth is derived from the stratification profiles. From
that a volume is calculated (Deep_lake_volume_m3). This volume is then subtracted
from the total lake volume to give SVC.
###In our version, SVC is volume determined by Total volume - Volume(Lake Height -
Stratification depth). When the depth is 0, SVC = 0.
###If SVC > 0, then SVC - RESsl is used. If SVC > RESsl, then Fdlm is positive, water
flows into the upper layer. If SVC < RESsl, then Fdlm is negative, and water moves into
the lower layer. It should be possible to have the Fslm and Fdlm fluxes as a single
positive/negative flux.
###We cannot rely on the predicted LakeHV function when the lake level gets very
low, as the slope with the loess smoothing can go negative. Therefore, we will assume
that if the lake gets to within 0.5m of the minimum level, that the entire lake is mixed
into RESsl.

func.SVC <- function(Time){
    Basemix <- ifelse (Interpolationtype == "Loess", 0.6, 0)
    if (Met$SL[Time] == 0){
        SVC <- 0
    } else if (func.Lakedepth(Lake$Volume[Time]) - min(Lakevolumes[,1]) -
Met$SL[Time] <= Basemix) {
        SVC <- Lake$Volume[Time]
    } else {
        SVC <- (Lake$Volume[Time] - func.Lakevolume(Lake$Depth[Time] -
Met$SL[Time]))
    }
    return (SVC)
}#end function

#func.Fslm <- function(Time) This flux should no longer be needed. It's function will
be taken up by the Fdlm as a positive/negative function.
Fslm <- 0

func.Fdlm <- function(Time){
    ##SVCfunc=0 This step is moved into the main program loops, as it's required
to determine whether the fluxes go into RESsl or RESsl
    Fdlm <- (func.SVC(Time) - Lake$RESsl[Time])
        if (Fdlm < 0){
        Fdlm18O <- Fdlm*ISO18O$ISORESsl[Time]
        FdlmD <- Fdlm*ISOD$ISORESsl[Time]
        } else {
        Fdlm18O <- Fdlm*ISO18O$ISORESdl[Time]
        FdlmD <- Fdlm*ISOD$ISORESdl[Time]
        }
        Fdlm <- list (Fdlm = Fdlm, Fdlm18O = Fdlm18O, FdlmD = FdlmD)
        return(Fdlm)
    #so if SVC is larger than RESsl, Fdlm is positive showing water moving from
deep to shallow, else, negative
}#end function
```

```
func.Fsos <- function (time){
        Fsos <- Lake$Csr[Time] * Lake$RESsl[Time] * Timestep
        Fsos18O <- Fsos * ISO18O$ISORESsl[Time]
        FsosD <- Fsos * ISOD$ISORESsl[Time]
        Fsos <- list(Fsos = Fsos, Fsos18O = Fsos18O, FsosD = FsosD)
        return (Fsos)}

func.Fdos <- function (time){
        Fdos <- Lake$Csr[Time] * Lake$RESdl[Time] * Timestep
        Fdos18O <- Fdos * ISO18O$ISORESdl[Time]
        FdosD <- Fdos * ISOD$ISORESdl[Time]
        Fdos <- list(Fdos = Fdos, Fdos18O = Fdos18O, FdosD = FdosD)
        return (Fdos)
}

#Evaporation section. Note that evaporation is calculated on a daily basis, and then
multiplied by 30 in Steinman's model. In our case, we'll probably multiply it by the
number of days in the month, as that's relatively easy to code for (feb = 28 days).
#Ra is probably defined from the simplified expressions on P696 in Valiantzas' paper.
#This means that Ra can be derived entirely from the site latitude.

#Latitude <- 48.3230 #Latitude in ddd.mmsssss format (degress, minutes, decimal
seconds). Negative for southern hemisphere. Moved to preferences file.

func.DMS <- function(Latitude){ #It's a bit of overkill to put this in as a function, but it
means that we can ask the user for the latitude, or call it from a file.
        Ldegrees <- trunc(Latitude) #Loses the decimals
        Lminutes <- trunc((Latitude - Ldegrees)*100) #extracts minutes
        Lseconds <- 10000 * (Latitude - (Lminutes/100 + Ldegrees)) #extracts seconds
        Latitude <- Ldegrees + (Lminutes / 60) + (Lseconds / 3600) #This section
converts dms to decimal degrees.
        Latitude <- Latitude * pi/180 #and convert to radians
        return(Latitude)
}#end function

func.Month <- function (Time){
        Month <- sapply((substr (Met$Month[Time],1,3)),function(x)
grep(paste("(?i)",x,sep=""),month.abb))
        if (Datarate == "Monthly") {
        Month <- Month + (Timestep)%%1
        } else {
        Month <- Month + (as.numeric(Met$Day[Time])/30) #assumes 30 days per
month. Should be close enough.
        }
        return(Month)
```

```
    #The grep component removes the case sensitivity from the match. This
function assigns months by their name with a number. Jan = 1. This is used for Ra
calculation and possibly elsewhere.
}# end function

func.Ra <- function(Latitude){ #Ra from Valiantzas' paper. Checked against example
on P697.
    N <- 4 * (func.DMS(Latitude)) * sin(0.53 * (func.Month(Time)) - 1.65) + 12
#Number of hours of sunlight. Required by Ra calc following.
    if (Mod(Latitude) > 23.5*pi/180){ #Tropic check
        Ra <- 3 * N * sin((0.131 * N) - (0.95 * Mod(func.DMS(Latitude))))
    } else if (Mod(Latitude) <= 23.5 * pi/180){ #end if
        Ra <- 118*(N^0.2)*sin(0.131*N - (0.2 * Mod(func.DMS(Latitude))))
    }#end else
    return (Ra)
}#end function

#Equation 22
#Monthly data requirement
#ALBlake <- 0.08 #albedo for lake (from Steinman 2010) These three variables have
been moved into the preferences file.
#ALBearth <- 0.25 #albedo for surface (from Steinman 2010)
#PWF <- 1 # Penman Wind Constant. 1 for original Penman wind function. 0.5 for
reduced Penman wind function. 0 for Linacre wind function.
func.E <- function(Time){
    if (Met$Ta[Time] <=0) {
    E <- 0
    } else {
    E <- 0.051 * (1-ALBlake) * Met$Rs[Time] * ((Met$Ta[Time] + 9.5)^0.5) - (2.4
* ((Met$Rs[Time]/func.Ra(Latitude))^2)) + 0.052 * (Met$Ta[Time] + 20) * (1 -
Met$RH[Time]/100) * (PWF - 0.38 + 0.54 * Met$WS[Time])
    }
    E <- E *0.001 #convert to metres for Daily evap rate.
    if (Datarate == "Monthly") {
        if (func.Month(Time) == 1|2|4|7|9|11){ #This section (and same in
func.PET) changes the daily rate to a per month rate, based on the number of days in
each month. This is different from Steinman who uses 30 days per month.
            E <- (E*31)
        }#end if
        else if (func.Month(Time) == 3|5|6|10){
            E <- E*30
        } else {#end else if
            E <- E*28.25
        }#end else
    } else {
        E <- E
    }#end daily/monthly modifier.
    return (E)
```

```
}#end function

#Equation 23
func.PET <- function(Time){
        if (Met$Ta[Time] <=0) {
        E <- 0
        } else {
        E <- 0.051 * (1-ALBearth) * Met$Rs[Time] * ((Met$Ta[Time] + 9.5)^0.5) - (2.4
* ((Met$Rs[Time]/func.Ra(Latitude))^2)) + 0.048 * (Met$Ta[Time] + 20) * (1 -
Met$RH[Time]/100) * (PWF/2 + 0.536 * Met$WS[Time]) #Daily evap rate.
        }
        E <- E *0.001 #convert to metres
        if (Datarate == "Monthly") {
                if (func.Month(Time) == 1|2|4|7|9|11){
                        E <- (E*31)
                }#end if
                else if (func.Month(Time) == 3|5|6|10){
                        E <- E*30
                } else {#end else if
                        E <- E*28.25
                }#end else
        } else {
                E <- E
        }#end daily/monthly modifier.
        return (E)
}#end function

func.Fp <- function(Time){#Precipitation
        Fp <- Met$P[Time] * 0.001 * Lake$Area[Time] * Timestep
        Fp18O <- Fp * Met$d18Op[Time]
        FpD <- Fp * Met$dDp[Time]
        Fp <- list(Fp = Fp, Fp18O = Fp18O, FpD = FpD)
        return (Fp)
}#end function

func.KcLake <- function (Time){ #This routines sets a seasonal variable Kc, based on
month, with a slight offset to account for the lag in average lake and air temperatures.
        Kcamplitude <- (KcLwin-KcLsum)/2
        Kcseasonoffset <- 0.8
        Kcshift <- (KcLwin+KcLsum)/2
        KcLake <- Kcshift +
(sin(((func.Month(Time)/12)+Kcseasonoffset)*pi*2)*Kcamplitude)
return (KcLake)
}

func.Fe <- function(Time) {
        Fe <- func.E(Time) * Lake$Area[Time] * Timestep * func.KcLake(Time)
        Fe18O <- Fe * ISO18O$dE[Time]
```

```
	FeD <- Fe *  ISOD$dE[Time]
	Fe <- list(Fe = Fe, Fe18O = Fe18O, FeD = FeD)
	return (Fe)
}#end function
#This is the end of the hydrology functions.

#************************* Main isotopic functions
********************************

#This is the isotopic functions.
#equation 24.
func.dE <- function(Time, Isotype){
Tlake <- Met$Ta[Time]+Met$Toff[Time]
if (Isotype == "18O"){
	C <- 14.2
	ALPHA <- exp ((0.35041 * (10^6)/(273.15 + Tlake)^3) -
(1.6664*(10^3)/(273.15 + Tlake)^2) + (6.7123 * 1/(273.15 + Tlake)) - 0.007685)
	#Checked against graphs from Horita et al 2008
} #end if
else if (Isotype == "D"){
	C <- 12.5
	ALPHA <- exp ((1.1588 * ((273.15 + Tlake)^3)/10^9) - (1.6201 * ((273.15 +
Tlake)^2)/10^6) + (0.79484 * (273.15 + Tlake)/1000) + (2.9992 * (10^6)/(273.15 +
Tlake)^3) - 0.16104)
	#Checked against graphs from Horita et al 2008
} #end else if
Esa <- 6.108 * exp((17.27*Met$Ta[Time])/(Met$Ta[Time] + 237.7))
Esw <- 6.108 * exp((17.27*Tlake)/(Tlake + 237.7))
RALPHA <- 1/ALPHA
hn = Met$RH[Time] * (Esa/Esw) *.01
Ek <- C * (1 - hn)
Eeq <- 1000 * (1 - RALPHA)
Etot <- Ek + Eeq
func.df <- function(column){eval((if(Isotype == "D"){ISOD} else
{ISO18O})[Time,column])}
#func.df allows us to grab data from a particular dataframe. eg: ISOD[Time,column]
#need to set this to take from RESdl if SL = 0
#This has been updated with isotopic enrichment version from Gibson, 2002 also used
by Steinman.
limit <- (hn*(func.df("ISOp") - Eeq) + Etot)/(hn - 0.001*Etot)
if (func.SVC(Time) == 0 & func.df("ISORESdl") >= (hn*(func.df("ISOp") - Eeq) +
Etot)/(hn - 0.001*Etot)){
	dE <- func.df("ISORESdl")
	} else if (func.SVC(Time) == 0 & func.df("ISORESdl") < (hn*(func.df("ISOp")
- Eeq) + Etot)/(hn - 0.001*Etot)){
	dE <- ((RALPHA * func.df("ISORESdl") - (hn * (func.df("ISOp") - Eeq)) -
Etot)/(1 - hn + 0.001*Ek))
```

```
	} else if (func.SVC(Time) != 0 & func.df("ISORESsl") >= (hn*(func.df("ISOp")
- Eeq) + Etot)/(hn - 0.001*Etot)) {
	dE <- func.df("ISORESsl")
	} else if (func.SVC(Time) != 0 & func.df("ISORESsl") < (hn*(func.df("ISOp") -
Eeq) + Etot)/(hn - 0.001*Etot)){
	dE <- ((RALPHA * func.df("ISORESsl") - (hn * (func.df("ISOp") - Eeq)) -
Etot)/(1 - hn + 0.001*Ek))
}

return (dE)
} #end function. The values for O18 appear comparable with those of Horita 2008 (-
30pmil)


#************************** Populate Dataframes
***********************************

Lake$Year[1:nrow(Met)] <- Met$Year
Lake$Month[1:nrow(Met)] <- as.character(Met$Month)
if (Datarate == "Monthly"){
Lake$Day[1:nrow(Met)] <- floor(as.numeric(row.names(Met))%%1 * 10 * Timestep *
30)+1
}else {
Lake$Day[1:nrow(Met)] <- Met$Day
}
#This assigns an approximate day for the start of each timestep.
#as.character(Met$Day)
Lake$CA[1] <- Modelparam$CA #These line adds the initial conditions to the Lake
data frame.
Lake$AWCss[1] <- Modelparam$AWCss
Lake$AWCds[1] <- Modelparam$AWCds
Lake$Cin[1] <- Modelparam$Cin
Lake$Csr[1] <- Modelparam$Csr
Lake$RESsl[1] <- Modelparam$RESsl
Lake$RESdl[1] <- Modelparam$RESdl
Lake$RESss[1] <- Modelparam$RESss
Lake$RESds[1] <- Modelparam$RESds
Lake$RESin[1] <- Modelparam$RESin
Lake$RESsp[1] <- Modelparam$RESsp

Lake$Volume[1] <- (Lake$RESsl[1] + Lake$RESdl[1]) #fills in the last three columns
with initial volume, area and depth
Lake$Area[1] <- func.Lakearea(Lake$Volume[1])
Lake$Depth[1] <- func.Lakedepth(Lake$Volume[1])


#lets start by populating the ISOD and ISO18O dataframes with some data. If there is
no datafile then we'll use initial precipitation values from the Met file. It will be wrong,
```

```
but probably closer than starting at 0. This is probably fine for most, but dE should be
overwritten from the dE function.
if (ISOdatafile == ""){
ISOD[1,1:ncol(ISOD)] <- Met$dDp[1]
ISO18O[1,1:ncol(ISO18O)] <- Met$d18Op[1]
} else {
ISOdata <- read.table(ISOdatafile,header=TRUE)
ISOD$Year[1:nrow(Met)] <- Met$Year
ISOD$Month[1:nrow(Met)] <- as.character(Met$Month)
ISOD$Day[1:nrow(Met)] <- Met$Day
ISOD$ISOp[1] <- Met$dDp[1]
ISOD$ISORESsl[1] <- ISOdata$RESsl[1]
ISOD$ISORESdl[1] <- ISOdata$RESdl[1]
ISOD$ISORESss[1] <- ISOdata$RESss[1]
ISOD$ISORESds[1] <- ISOdata$RESds[1]
ISOD$ISORESin[1] <- ISOdata$RESin[1]
ISOD$ISORESsp[1] <- ISOdata$RESsp[1]
ISOD$dE[1] <- func.dE(Time,"D")
ISOD$dPET[1] <- func.dE(Time,"D")

ISO18O$Year[1:nrow(Met)] <- Met$Year
ISO18O$Month[1:nrow(Met)] <- as.character(Met$Month)
ISO18O$Day[1:nrow(Met)] <- Met$Day
ISO18O$ISOp[1] <- Met$d18Op[1]
ISO18O$ISORESsl[1] <- ISOdata$RESsl[2]
ISO18O$ISORESdl[1] <- ISOdata$RESdl[2]
ISO18O$ISORESss[1] <- ISOdata$RESss[2]
ISO18O$ISORESds[1] <- ISOdata$RESds[2]
ISO18O$ISORESin[1] <- ISOdata$RESin[2]
ISO18O$ISORESsp[1] <- ISOdata$RESsp[2]
ISO18O$dE[1] <- func.dE(Time,"18O")
ISO18O$dPET[1] <- func.dE(Time,"18O")
}

Flux$Year[1:nrow(Met)] <- Met$Year
Flux$Month[1:nrow(Met)] <- as.character(Met$Month)
Flux$Day[1:nrow(Met)] <- Met$Day


#************************* Main program loop
***********************************

#And this is the end of the isotopic functions. Now to make it all work. We'll use the
Metfile as a base. It's extremely simply and quick to duplicate rows in the dataframe, so
rather than trying to have two separate timestepping functions, we'll instead duplicate
the Metfile rows by the Timestep function.
```

```
if (nrow(Met)/38 < 60){
message ("There are ",nrow(Met), " integrations. This will take around ", round
(nrow(Met)/38, digits = 0), " seconds to run.")
}else {
message ("There are ",nrow(Met), " integrations. This will take around ", round
(nrow(Met)/2280, digits = 0), " minutes to run.")}
readline(prompt = "To run the lake model please hit enter.")
pb <- txtProgressBar(min = 0, max = nrow(Met), style = 3)
Excess.Fsos <- 0
Excess.Fr <- 0

        #These steps - Timestep to Csr can be changed to a single process, if the
program is running slowly. They don't have to be calculated at each time step. They are
there in case we decide to have variable catchment areas or stuff in the future. This has
now been done to try and speed up the app a bit.
        Lake$CA <- Lake$CA[1]
        Lake$AWCss <- Lake$AWCss[1]
        Lake$AWCds <- Lake$AWCds[1]
        if (Datarate == "Monthly"){
        Lake$Cin <- Lake$Cin[1]
        Lake$Csr <- Lake$Csr[1]
        } else { #This step drops the rate to take into account daily data.
        Lake$Cin <- Lake$Cin[1] * 12/365
        Lake$Csr <- Lake$Csr[1] * 12/365
        }

for (Time in 1:nrow(Met)){ #Steps through the met file.


        ISO18O$ISOp[Time] <- Met$d18Op[Time]
        ISOD$ISOp[Time] <- Met$dDp[Time]
        Lake$Timestep[Time] <- (row.names(Met)[Time])
        Flux$Timestep[Time] <- (row.names(Met)[Time])
        ISO18O$Timestep[Time] <- (row.names(Met)[Time])
        ISOD$Timestep[Time] <- (row.names(Met)[Time])



        #Rather than calling each function over and over, we'll call them once, and store
results in a variable. This should speed up the model a lot.
        VardE18O <- func.dE(Time,"18O")
        VardED <- func.dE(Time,"D")
        ISO18O$dE[Time] <- VardE18O
        ISO18O$dPET[Time] <- VardE18O
        ISOD$dE[Time] <- VardED
        ISOD$dPET[Time] <- VardED
```

```
        #These need to be called first, as later functions (func.evap, func.E) call the dE
values from the ISO dataframes. We can work around this by replacing the specific calls
with function calls, but that will slow the program down a bit.
        VarFp <- func.Fp(Time)
        VarFr <- func.Fr(Time)
        VarFin <- func.Fin(Time)
        VarFdos <- func.Fdos(Time)
        VarFsos <- func.Fsos(Time)
        VarFe <- func.Fe(Time)
        VarEvap <- func.Evap(Time)
        VarSoil <- func.Soil(Time)
        VarFgw <- func.Fgw(Time)
        VarFsf <- func.Fsf(Time)
        VarFsm <- func.Fsm(Time)
        VarE <- func.E(Time)
        VarPET <- func.PET(Time)

        if (Met$SL[Time] == 0) { #Fluxes have to go to-from RESdl. This should
possibly be changed to assess the Met file, rather than SVC condition - removed
SVCfunc.
                #Fdlm has to be applied separately, as it's a condition that has to be met,
rather than a flux incrementing over a month.
                Lake$RESdl[Time + 1] <- Lake$RESdl[Time] + VarFgw$Fgw +
VarFp$Fp + VarFin$Fin - VarFdos$Fdos - VarFe$Fe - VarFsos$Fsos
                if (Lake$RESdl[Time+1] == 0){
                        ISO18O$ISORESdl[Time+1] <- 0
                        ISOD$ISORESdl[Time+1] <- 0
                        }else {
                        ISO18O$ISORESdl[Time+1] <-
(ISO18O$ISORESdl[Time]*Lake$RESdl[Time] + VarFgw$Fgw18O + VarFp$Fp18O
+ VarFin$Fin18O - VarFdos$Fdos18O - VarFsos$Fsos18O -
VarFe$Fe18O)/Lake$RESdl[Time+1]
                        ISOD$ISORESdl[Time+1] <-
(ISOD$ISORESdl[Time]*Lake$RESdl[Time] + VarFgw$FgwD + VarFp$FpD +
VarFin$FinD - VarFdos$FdosD - VarFsos$FsosD -  VarFe$FeD)/Lake$RESdl[Time+1]
                        }
                Lake$RESsl[Time + 1] <- Lake$RESsl[Time]
                ISO18O$ISORESsl[Time+1] <- ISO18O$ISORESsl[Time]
                ISOD$ISORESsl[Time+1] <- ISOD$ISORESsl[Time]
        } else if (Lake$RESsl[Time] < VarFsos$Fsos + VarFe$Fe - VarFp$Fp -
VarFin$Fin){
                #This condition is for when the RESsl is too small to hold all the fluxes,
but does exist (shallow SL layer). In this case, excess fluxes are run in/out of the RESdl.
                #First thing to do is create a couple of excess values. These will be a
percentage of the excess, based on the relative sizes of Fe and Fsos.
                Excess.Fe <- (VarFsos$Fsos + (VarFe$Fe) - Lake$RESsl[Time] -
VarFp$Fp - VarFin$Fin) * (VarFe$Fe/(VarFe$Fe + VarFsos$Fsos))
```

```
        Excess.Fsos <- (VarFsos$Fsos + (VarFe$Fe) - Lake$RESsl[Time] -
VarFp$Fp - VarFin$Fin) * (VarFsos$Fsos/(VarFe$Fe + VarFsos$Fsos))
        #And here is the calculations so the excess flux that would make RESsl
negative, instead gets removed from RESdl
        Lake$RESsl[Time + 1] <- Lake$RESsl[Time] + VarFp$Fp + VarFin$Fin
- (VarFsos$Fsos - Excess.Fsos) - (VarFe$Fe - Excess.Fe)
        ISO18O$ISORESsl[Time + 1] <- 0 # check here first for ISO imbalance.
        ISOD$ISORESsl[Time + 1] <- 0
        Lake$RESdl[Time + 1] <- Lake$RESdl[Time] + VarFgw$Fgw -
VarFdos$Fdos - Excess.Fe - Excess.Fsos
        ISO18O$ISORESdl[Time + 1] <-
(Lake$RESdl[Time]*ISO18O$ISORESdl[Time] + VarFgw$Fgw18O -
VarFdos$Fdos18O - Excess.Fe*ISO18O$dE[Time] -
Excess.Fsos*ISO18O$ISORESdl[Time])/Lake$RESdl[Time + 1]
        ISOD$ISORESdl[Time + 1] <-
(Lake$RESdl[Time]*ISOD$ISORESdl[Time] + VarFgw$FgwD - VarFdos$FdosD -
Excess.Fe*ISOD$dE[Time] -
Excess.Fsos*ISOD$ISORESdl[Time])/Lake$RESdl[Time + 1]

    } else {#end if else
        #and now we need one more, assuming that there is stratification and
RESsl is big enough to take the fluxes. (These are the equations from Steinman 2010).
        Excess.Fe <- 0
        Excess.Fsos <- 0
        #And here is the calculations so the excess flux that would make RESsl
negative, instead gets removed from RESdl
        Lake$RESsl[Time + 1] <- Lake$RESsl[Time] + VarFp$Fp + VarFin$Fin
- VarFsos$Fsos - VarFe$Fe

        if (Lake$RESsl[Time + 1] == 0){
        ISO18O$ISORESsl[Time + 1] <- 0
        ISOD$ISORESsl[Time + 1] <- 0
        } else {
        ISO18O$ISORESsl[Time + 1] <-
(Lake$RESsl[Time]*ISO18O$ISORESsl[Time] + VarFp$Fp18O + VarFin$Fin18O -
VarFsos$Fsos18O - VarFe$Fe18O)/Lake$RESsl[Time + 1]
        ISOD$ISORESsl[Time + 1] <-
(Lake$RESsl[Time]*ISOD$ISORESsl[Time] + VarFp$FpD + VarFin$FinD -
VarFsos$FsosD - VarFe$FeD)/Lake$RESsl[Time + 1]}

        Lake$RESdl[Time + 1] <- Lake$RESdl[Time] + VarFgw$Fgw -
VarFdos$Fdos
        if (Lake$RESdl[Time + 1] == 0){
        ISO18O$ISORESdl[Time + 1] <- 0
        ISOD$ISORESdl[Time + 1] <- 0
        } else {
```

```
                ISO18O$ISORESdl[Time + 1] <- (Lake$RESdl[Time] *
ISO18O$ISORESdl[Time] + VarFgw$Fgw18O -
VarFdos$Fdos18O)/Lake$RESdl[Time + 1]
                ISOD$ISORESdl[Time + 1] <- (Lake$RESdl[Time] *
ISOD$ISORESdl[Time] + VarFgw$FgwD - VarFdos$FdosD)/Lake$RESdl[Time + 1]
                }
        } #end else

        Lake$RESss[Time + 1] <- Lake$RESss[Time] + VarSoil$Fssi - VarEvap$Fsse

        if (Lake$RESss[Time + 1] == 0){
        ISO18O$ISORESss[Time+1] <- 0
        ISOD$ISORESss[Time+1]  <- 0
        }else{
        ISO18O$ISORESss[Time+1] <-
(Lake$RESss[Time]*ISO18O$ISORESss[Time] + VarSoil$Fssi18O -
VarEvap$Fsse18O)/Lake$RESss[Time + 1]
        ISOD$ISORESss[Time+1] <- (Lake$RESss[Time]*ISOD$ISORESss[Time] +
VarSoil$FssiD - VarEvap$FsseD)/Lake$RESss[Time + 1]}

        Lake$RESds[Time + 1] <- Lake$RESds[Time] + VarSoil$Fssd - VarEvap$Fdse
        if (Lake$RESds[Time + 1] == 0){
        ISO18O$ISORESds[Time+1] <- 0
        ISOD$ISORESds[Time+1]  <- 0
        }else{
        ISO18O$ISORESds[Time+1] <-
(Lake$RESds[Time]*ISO18O$ISORESds[Time] + VarSoil$Fssd18O -
VarEvap$Fdse18O)/Lake$RESds[Time + 1]
        ISOD$ISORESds[Time+1] <- (Lake$RESds[Time]*ISOD$ISORESds[Time] +
VarSoil$FssdD - VarEvap$FdseD)/Lake$RESds[Time + 1]}

        Lake$RESin[Time + 1] <- Lake$RESin[Time] + VarSoil$Fro + VarSoil$Fdsd -
VarFin$Fin
        if (Lake$RESin[Time + 1] == 0){
        ISO18O$ISORESin[Time+1] <- 0
        ISOD$ISORESin[Time+1]  <- 0
        }else{
        ISO18O$ISORESin[Time+1] <-
(Lake$RESin[Time]*ISO18O$ISORESin[Time] + VarSoil$Fro18O +
VarSoil$Fdsd18O - VarFin$Fin18O)/Lake$RESin[Time + 1]
        ISOD$ISORESin[Time+1] <- (Lake$RESin[Time]*ISOD$ISORESin[Time] +
VarSoil$FroD + VarSoil$FdsdD - VarFin$FinD)/Lake$RESin[Time + 1]
        }

        Lake$RESsp[Time + 1] <- Lake$RESsp[Time] + VarFsf$Fsf - VarFsm$Fsm
        if (Lake$RESsp[Time + 1] == 0){
        ISO18O$ISORESsp[Time+1] <- 0
        ISOD$ISORESsp[Time+1]  <- 0
```

```
	}else{
	ISO18O$ISORESsp[Time+1] <-
(Lake$RESsp[Time]*ISO18O$ISORESsp[Time] + VarFsf$Fsf18O -
VarFsm$Fsm18O)/Lake$RESsp[Time + 1]
	ISOD$ISORESsp[Time+1] <- (Lake$RESsp[Time]*ISOD$ISORESsp[Time] +
VarFsf$FsfD - VarFsm$FsmD)/Lake$RESsp[Time + 1]}

	#Overflow code can go here.
	#Need 3 scenarios SL==0, RESsl < Overflow amount. RESsl > overflow.
	if ((Lake$RESsl[Time + 1] + Lake$RESdl[Time + 1]) >
Lakevolumes$Volume[1]){
		if (Time < nrow(Met)) {
			SLcheck <- Met$SL[Time+1]
			} else {
			SLcheck <- Met$SL[1]
			}#end if
			Foverflow <- (Lake$RESsl[Time + 1] + Lake$RESdl[Time + 1])
- Lakevolumes$Volume[1] + 0.01 #The 0.01 is added to avoid the odd rounding error.
		if (SLcheck == 0){
			#overflow to be removed from deep lake
			Lake$RESdl[Time+1] <- Lake$RESdl[Time+1] - Foverflow
			Flux$Fof[Time+1] <- Foverflow
			Flux18O$Fof[Time+1] <- Foverflow *
ISO18O$ISORESdl[Time+1]
			FluxD$Fof[Time+1] <- Foverflow * ISOD$ISORESdl[Time+1]
		} else if (Lake$RESsl[Time+1] < Foverflow){
			# All of RESsl and some of RESdl needed for overlow
			Lake$RESdl[Time+1] <- Lake$RESdl[Time+1] - (Foverflow -
Lake$RESsl[Time+1])
			Flux$Fof[Time+1] <- Foverflow
			Flux18O$Fof[Time+1] <- (Foverflow - Lake$RESsl[Time+1]) *
ISO18O$ISORESdl[Time+1] + Lake$RESsl[Time+1]*ISO18O$ISORESsl[Time+1]
			FluxD$Fof[Time+1] <- (Foverflow - Lake$RESsl[Time+1]) *
ISOD$ISORESdl[Time+1] + Lake$RESsl[Time+1]*ISOD$ISORESsl[Time+1]
			Lake$RESsl[Time+1] <- 0
			ISO18O$ISORESsl[Time+1] <- 0
			ISOD$ISORESsl[Time+1] <- 0
		} else {
			#RESsl can handle all of the overflow
			Lake$RESsl[Time+1] <- Lake$RESsl[Time+1] - Foverflow
			Flux$Fof[Time+1] <- Foverflow
			Flux18O$Fof[Time+1] <- Foverflow *
ISO18O$ISORESsl[Time+1]
			FluxD$Fof[Time+1] <- Foverflow * ISOD$ISORESsl[Time+1]
		} #end if
	#set overflow flux in flux files
	} #end overflow code
```

```
    Lake$Volume[Time + 1] <- (Lake$RESsl[Time + 1] + Lake$RESdl[Time + 1])
    if (Lake$Volume[Time + 1] > 0) {
    #Now to find the depth and area.
    Lake$Area[Time + 1] <- func.Lakearea(Lake$Volume[Time + 1])
    Lake$Depth[Time + 1] <- func.Lakedepth(Lake$Volume[Time + 1])
    } else {
    Lake$Volume[Time + 1] <- 0
    Lake$Area[Time+1] <- 0
    Lake$Depth[Time+1] <- min(Lakevolumes[,1])
    }
    #and finally we have to calculate the stratification.
    #Make sure these are calculated in this order as Lake$RESsl (before calcing
stratification) is used in the Fdlm calc.

    if (Time < nrow(Met)) {
        VarFdlm <- func.Fdlm(Time + 1)
    #ISO has to be calculated first for these two, otherwise it will use the RESdl and
RESsl after the Fdlm has been applied
        Flux$Fdlm[Time + 1] <- VarFdlm$Fdlm
        Flux18O$Fdlm[Time + 1] <- VarFdlm$Fdlm18O
        FluxD$Fdlm[Time + 1] <- VarFdlm$FdlmD

        if (Lake$Volume[Time+1] == 0) {
            ISO18O$ISORESdl[Time+1] <- 0
            ISOD$ISORESdl[Time+1]  <- 0
            ISO18O$ISORESsl[Time+1] <- 0
            ISOD$ISORESsl[Time+1]  <- 0
        } else if (Lake$RESsl[Time + 1] + VarFdlm$Fdlm == 0){
            ISO18O$ISORESdl[Time+1] <- (Lake$RESdl[Time +
1]*ISO18O$ISORESdl[Time+1] - VarFdlm$Fdlm18O)/(Lake$RESdl[Time + 1] -
VarFdlm$Fdlm)
            ISOD$ISORESdl[Time+1] <- (Lake$RESdl[Time +
1]*ISOD$ISORESdl[Time+1] - VarFdlm$FdlmD)/(Lake$RESdl[Time + 1] -
VarFdlm$Fdlm)
            ISO18O$ISORESsl[Time+1] <- 0
            ISOD$ISORESsl[Time+1]  <- 0
        } else if (Lake$RESdl[Time + 1] - VarFdlm$Fdlm <= 0.01) {#Using
0.01 here as I've seen occasional "0" volumes that aren't 0 (rounding error).
            ISO18O$ISORESsl[Time+1] <- (Lake$RESsl[Time +
1]*ISO18O$ISORESsl[Time+1] + VarFdlm$Fdlm18O)/(Lake$RESsl[Time + 1] +
VarFdlm$Fdlm)
            ISOD$ISORESsl[Time+1] <- (Lake$RESsl[Time +
1]*ISOD$ISORESsl[Time+1] + VarFdlm$FdlmD)/(Lake$RESsl[Time + 1] +
VarFdlm$Fdlm)
            ISO18O$ISORESdl[Time+1] <- 0
            ISOD$ISORESdl[Time+1] <- 0
        }else {
```

```
            ISO18O$ISORESdl[Time+1] <- (Lake$RESdl[Time +
1]*ISO18O$ISORESdl[Time+1] - VarFdlm$Fdlm18O)/(Lake$RESdl[Time + 1] -
VarFdlm$Fdlm)
            ISOD$ISORESdl[Time+1] <- (Lake$RESdl[Time +
1]*ISOD$ISORESdl[Time+1] - VarFdlm$FdlmD)/(Lake$RESdl[Time + 1] -
VarFdlm$Fdlm)
            ISO18O$ISORESsl[Time+1] <- (Lake$RESsl[Time +
1]*ISO18O$ISORESsl[Time+1] + VarFdlm$Fdlm18O)/(Lake$RESsl[Time + 1] +
VarFdlm$Fdlm)
            ISOD$ISORESsl[Time+1] <- (Lake$RESsl[Time +
1]*ISOD$ISORESsl[Time+1] + VarFdlm$FdlmD)/(Lake$RESsl[Time + 1] +
VarFdlm$Fdlm)
        }
        #Now that dISO has been calculated we can update the Lake file with the
correct volumes.
        if (Lake$RESdl[Time + 1] - VarFdlm$Fdlm <=0.01){
        Lake$RESdl[Time+1] <- 0
        }else{
        Lake$RESdl[Time + 1] <- Lake$RESdl[Time + 1] - VarFdlm$Fdlm
    }
        Lake$RESsl[Time + 1] <- Lake$RESsl[Time + 1] + VarFdlm$Fdlm

    } else { #Probably don't need this, but just in case.
        Flux$Fdlm[Time + 1] <- func.Fdlm(Time)$Fdlm
        Lake$RESdl[Time + 1] <- Lake$RESdl[Time + 1] -
func.Fdlm(Time)$Fdlm
        Lake$RESsl[Time + 1] <- Lake$RESsl[Time + 1] +
func.Fdlm(Time)$Fdlm
    }
    # I think that's it for Lake calcs. Fluxes are next
    Flux$Fr[Time] <- VarFr$Fr
    Flux18O$Fr[Time] <- VarFr$Fr18O
    FluxD$Fr[Time] <- VarFr$FrD
    Flux$Fp[Time] <- VarFp$Fp
    Flux18O$Fp[Time] <- VarFp$Fp18O
    FluxD$Fp[Time] <- VarFp$FpD
    Flux$Fin[Time] <- VarFin$Fin
    Flux18O$Fin[Time] <- VarFin$Fin18O
    FluxD$Fin[Time] <- VarFin$FinD
    Flux$Fe[Time] <- VarFe$Fe
    Flux18O$Fe[Time] <- VarFe$Fe18O
    FluxD$Fe[Time] <- VarFe$FeD
    Flux$Fsos[Time] <- VarFsos$Fsos
    Flux18O$Fsos[Time] <- VarFsos$Fsos18O
    FluxD$Fsos[Time] <- VarFsos$FsosD
    Flux$Fdos[Time] <- VarFdos$Fdos
    Flux18O$Fdos[Time] <- VarFdos$Fdos18O
    FluxD$Fdos[Time] <- VarFdos$FdosD
```

```
        #Flux$Fslm[Time] <- 0
        Flux$Fsm[Time] <- VarFsm$Fsm
        Flux18O$Fsm[Time] <- VarFsm$Fsm18O
        FluxD$Fsm[Time] <- VarFsm$FsmD
        Flux$Fssi[Time] <- VarSoil$Fssi
        Flux18O$Fssi[Time] <- VarSoil$Fssi18O
        FluxD$Fssi[Time] <- VarSoil$FssiD
        Flux$Fsse[Time] <- VarEvap$Fsse
        FluxD$Fsse[Time] <- VarEvap$FsseD
        Flux18O$Fsse[Time] <- VarEvap$Fsse18O
        Flux$Fssd[Time] <- VarSoil$Fssd
        Flux18O$Fssd[Time] <- VarSoil$Fssd18O
        FluxD$Fssd[Time] <- VarSoil$FssdD
        Flux$Fdse[Time] <- VarEvap$Fdse
        Flux18O$Fdse[Time] <- VarEvap$Fdse18O
        FluxD$Fdse[Time] <- VarEvap$FdseD
        Flux$Fro[Time] <- VarSoil$Fro
        Flux18O$Fro[Time] <- VarSoil$Fro18O
        FluxD$Fro[Time] <- VarSoil$FroD
        Flux$Fdsd[Time] <- VarSoil$Fdsd
        Flux18O$Fdsd[Time] <- VarSoil$Fdsd18O
        FluxD$Fdsd[Time] <- VarSoil$FdsdD
        Flux$Fsf[Time] <- VarFsf$Fsf
        Flux18O$Fsf[Time] <- VarFsf$Fsf18O
        FluxD$Fsf[Time] <- VarFsf$FsfD
        Flux$E[Time] <- VarE
        Flux18O$E[Time] <- VardE18O
        FluxD$E[Time] <- VardED
        Flux$PET[Time] <- VarPET
        Flux18O$PET[Time] <- VardE18O
        FluxD$PET[Time] <- VardED
        Flux$Fgw[Time] <- VarFgw$Fgw
        Flux18O$Fgw[Time] <- VarFgw$Fgw18O
        FluxD$Fgw[Time] <- VarFgw$FgwD
        Met$Ra[Time] <- round(func.Ra(Latitude),digits = 3)
        setTxtProgressBar(pb, Time)
} #end timestep loop
close(pb)

#************************** Checks and Reports
*********************************


message ("Model run complete\n****************\nSystem Balance Check.")
message ("Sum of evaporation and outseepage - sum of rainfall, snowfall and
groundwater = ", round(sum (Flux$Fsse) + sum (Flux$Fdse)+sum (Flux$Fe) + sum
(Flux$Fof) + sum (Flux$Fdos) + sum (Flux$Fsos) - (sum(Flux$Fr) + sum(Flux$Fsf) +
sum(Flux$Fp) + sum(Flux$Fgw)),digits = 1))
```

```
message ("Initial system volume - final system volume = ", round((Lake$RESsl[1] +
Lake$RESdl[1] + Lake$RESss[1] + Lake$RESds[1] + Lake$RESin[1] +
Lake$RESsp[1]) - (Lake$RESsl[nrow(Lake)] + Lake$RESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)] + Lake$RESds[nrow(Lake)] + Lake$RESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)]), digits = 1))

message ("Difference = ",round((sum(Flux$Fsse) + sum (Flux$Fdse) + sum
(Flux$Fof)+sum (Flux$Fe) + sum (Flux$Fdos) + sum (Flux$Fsos)- (sum(Flux$Fr) +
sum(Flux$Fsf) + sum(Flux$Fp) + sum(Flux$Fgw)))  - ((Lake$RESsl[1] +
Lake$RESdl[1] + Lake$RESss[1] + Lake$RESds[1] + Lake$RESin[1] +
Lake$RESsp[1]) - (Lake$RESsl[nrow(Lake)] + Lake$RESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)] + Lake$RESds[nrow(Lake)] + Lake$RESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)])), digits = 1))

message ("Sum of d18O flux out - sum of d18O flux in = ", round(sum (Flux18O$Fsse)
+ sum (Flux18O$Fdse) + sum (Flux18O$Fof) +sum (Flux18O$Fe) + sum
(Flux18O$Fdos) + sum (Flux18O$Fsos)- (sum(Flux18O$Fr) + sum(Flux18O$Fsf) +
sum(Flux18O$Fp) + sum(Flux18O$Fgw)),digits = 1))

message ("Initial d18O volume - final d18O volume = ",
round((Lake$RESsl[1]*ISO18O$ISORESsl[1] + Lake$RESdl[1]*
ISO18O$ISORESdl[1] + Lake$RESss[1]*ISO18O$ISORESss[1] +
Lake$RESds[1]*ISO18O$ISORESds[1] + Lake$RESin[1]*ISO18O$ISORESin[1] +
Lake$RESsp[1]*ISO18O$ISORESsp[1]) -
(Lake$RESsl[nrow(Lake)]*ISO18O$ISORESsl[nrow(Lake)] +
Lake$RESdl[nrow(Lake)]* ISO18O$ISORESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)]*ISO18O$ISORESss[nrow(Lake)] +
Lake$RESds[nrow(Lake)]*ISO18O$ISORESds[nrow(Lake)] +
Lake$RESin[nrow(Lake)]*ISO18O$ISORESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)]*ISO18O$ISORESsp[nrow(Lake)]), digits = 1))

message ("Difference = ",round((sum(Flux18O$Fsse) + sum (Flux18O$Fdse) + sum
(Flux18O$Fof) +sum (Flux18O$Fe) + sum (Flux18O$Fdos) + sum (Flux18O$Fsos)-
(sum(Flux18O$Fr) + sum(Flux18O$Fsf) + sum(Flux18O$Fp) + sum(Flux18O$Fgw)))
- ((Lake$RESsl[1]*ISO18O$ISORESsl[1] + Lake$RESdl[1]* ISO18O$ISORESdl[1] +
Lake$RESss[1]*ISO18O$ISORESss[1] + Lake$RESds[1]*ISO18O$ISORESds[1] +
Lake$RESin[1]*ISO18O$ISORESin[1] + Lake$RESsp[1]*ISO18O$ISORESsp[1]) -
(Lake$RESsl[nrow(Lake)]*ISO18O$ISORESsl[nrow(Lake)] +
Lake$RESdl[nrow(Lake)]* ISO18O$ISORESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)]*ISO18O$ISORESss[nrow(Lake)] +
Lake$RESds[nrow(Lake)]*ISO18O$ISORESds[nrow(Lake)] +
Lake$RESin[nrow(Lake)]*ISO18O$ISORESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)]*ISO18O$ISORESsp[nrow(Lake)])), digits = 1))

message ("Sum of dD flux out - sum of dD flux in = ", round(sum (FluxD$Fsse) + sum
(FluxD$Fof) + sum (FluxD$Fdse)+sum (FluxD$Fe) + sum (FluxD$Fdos) + sum
```

```
(FluxD$Fsos)- (sum(FluxD$Fr) + sum(FluxD$Fsf) + sum(FluxD$Fp) +
sum(FluxD$Fgw)),digits = 1))

message ("Initial dD volume - final dD volume = ",
round((Lake$RESsl[1]*ISOD$ISORESsl[1] +
Lake$RESdl[1]* ISOD$ISORESdl[1] + Lake$RESss[1]*ISOD$ISORESss[1] +
Lake$RESds[1]*ISOD$ISORESds[1] + Lake$RESin[1]*ISOD$ISORESin[1] +
Lake$RESsp[1]*ISOD$ISORESsp[1]) -
(Lake$RESsl[nrow(Lake)]*ISOD$ISORESsl[nrow(Lake)] +
Lake$RESdl[nrow(Lake)]* ISOD$ISORESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)]*ISOD$ISORESss[nrow(Lake)] +
Lake$RESds[nrow(Lake)]*ISOD$ISORESds[nrow(Lake)] +
Lake$RESin[nrow(Lake)]*ISOD$ISORESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)]*ISOD$ISORESsp[nrow(Lake)]), digits = 1))

message ("Difference = ",round((sum(FluxD$Fsse) + sum (FluxD$Fof) + sum
(FluxD$Fdse)+sum (FluxD$Fe) + sum (FluxD$Fdos) + sum (FluxD$Fsos)-
(sum(FluxD$Fr) + sum(FluxD$Fsf) + sum(FluxD$Fp) + sum(FluxD$Fgw)))  -
((Lake$RESsl[1]*ISOD$ISORESsl[1] + Lake$RESdl[1]* ISOD$ISORESdl[1] +
Lake$RESss[1]*ISOD$ISORESss[1] + Lake$RESds[1]*ISOD$ISORESds[1] +
Lake$RESin[1]*ISOD$ISORESin[1] + Lake$RESsp[1]*ISOD$ISORESsp[1]) -
(Lake$RESsl[nrow(Lake)]*ISOD$ISORESsl[nrow(Lake)] +
Lake$RESdl[nrow(Lake)]* ISOD$ISORESdl[nrow(Lake)] +
Lake$RESss[nrow(Lake)]*ISOD$ISORESss[nrow(Lake)] +
Lake$RESds[nrow(Lake)]*ISOD$ISORESds[nrow(Lake)] +
Lake$RESin[nrow(Lake)]*ISOD$ISORESin[nrow(Lake)] +
Lake$RESsp[nrow(Lake)]*ISOD$ISORESsp[nrow(Lake)])), digits = 1))


#This little section just grabs some useful information from the various dataframes and
compiles it into a nice simple dataframe for ease of reading.
func.Sample <- function(MetTime, Time){
if (Sampledepth >= Met$SL[MetTime]){
        Sample18O <- ISO18O$ISORESdl[Time]
        SampleD <- ISOD$ISORESdl[Time]
} else {
        Sample18O <- ISO18O$ISORESsl[Time]
        SampleD <- ISOD$ISORESsl[Time]
}
Sample <- list(Sample18O, SampleD)
return(Sample)
}

Lake$Timestep[nrow(Lake)] <- floor(as.numeric(Lake$Timestep[nrow(Lake)-1]))+1
Flux$Timestep[nrow(Flux)] <- floor(as.numeric(Lake$Timestep[nrow(Flux)]))+1
ISO18O$Timestep[nrow(ISO18O)] <-
floor(as.numeric(Lake$Timestep[nrow(ISO18O)-1]))+1
ISOD$Timestep[nrow(ISOD)] <- floor(as.numeric(Lake$Timestep[nrow(ISOD)-1]))+1
```

```
if (Datarate == "Monthly") {
for (Time in 1:nrow(Lake)){ #Parallelizable
        if (Time > nrow(Met)){
        MetTime <- 1
        }else {
        MetTime <- Time
        }
        if (as.numeric(Lake$Timestep[Time])%%1 == 0){
        temptime <- as.numeric(Lake$Timestep[Time])
        Clean$Time[temptime] <- Lake$Timestep[Time]
        Clean$Year[temptime] <- Met$Year[MetTime]
        Clean$Month[temptime] <- as.character(Met$Month[MetTime])
        Clean$Day[temptime] <- Met$Day[MetTime]
        Clean$RESsl[temptime] <- Lake$RESsl[Time]
        Clean$RESdl[temptime] <- Lake$RESdl[Time]
        Clean$RESss[temptime] <- Lake$RESss[Time]
        Clean$RESds[temptime] <- Lake$RESds[Time]
        Clean$RESin[temptime] <- Lake$RESin[Time]
        Clean$Volume[temptime] <- Lake$Volume[Time]
        Clean$Area[temptime] <- Lake$Area[Time]
        Clean$Depth[temptime] <- Lake$Depth[Time]
        Clean$StratificationDepth[temptime] <- Met$SL[MetTime]
        Clean$dD_sampledepth[temptime] <- as.numeric(func.Sample(MetTime,
Time)[2])
        Clean$d18O_sampledepth[temptime] <- as.numeric(func.Sample(MetTime,
Time)[1])
        }
        }
}else {
Cleanindex <- 1
for (Time in 1:nrow(Lake)){ #Parallelizable
        if (Time > nrow(Met)){
        MetTime <- 1
        }else {
        MetTime <- Time
        }
        if (as.numeric(Lake$Day[Time]) == 1 || as.numeric(Lake$Day[Time]) == 0){
        Clean$Time[Cleanindex] <- Lake$Timestep[Time]
        Clean$Year[Cleanindex] <- Met$Year[MetTime]
        Clean$Month[Cleanindex] <- as.character(Met$Month[MetTime])
        Clean$Day[Cleanindex] <- Met$Day[MetTime]
        Clean$RESsl[Cleanindex] <- Lake$RESsl[Time]
        Clean$RESdl[Cleanindex] <- Lake$RESdl[Time]
        Clean$RESss[Cleanindex] <- Lake$RESss[Time]
        Clean$RESds[Cleanindex] <- Lake$RESds[Time]
        Clean$RESin[Cleanindex] <- Lake$RESin[Time]
        Clean$Volume[Cleanindex] <- Lake$Volume[Time]
```

```
        Clean$Area[Cleanindex] <- Lake$Area[Time]
        Clean$Depth[Cleanindex] <- Lake$Depth[Time]
        Clean$StratificationDepth[Cleanindex] <- Met$SL[MetTime]
        Clean$dD_sampledepth[Cleanindex] <- as.numeric(func.Sample(MetTime,
Time)[2])
        Clean$d18O_sampledepth[Cleanindex] <- as.numeric(func.Sample(MetTime,
Time)[1])
        Cleanindex <- Cleanindex +1
        }
        }
}

message ("Final lake depth = ",round((Clean$Depth[nrow(Clean)]),digits=2))

loadgraphs <- function(){
quartz()
par(mfrow=c(2,2))
plot (1:nrow(Lake),Lake$Depth,main="Lake depth over time",xlab="Time",
ylab="Depth", col = "blue", xaxt = 'n')
Dates <- Lake[Lake$Month %in% c("January") & Lake$Day %in% c(1),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
abline (h=seq(min(Lake$Depth),max(Lake$Depth), 1) , col="grey83")
text(8000, 104, paste("KcSS = ", KcSS, "\nKcDS = ", KcDS, "\nCsr =",
Modelparam$Csr[1], "\nCin =", Modelparam$Cin[1], "\nGWinflow =", GWMod,
"\nPWF =", PWF, sep = "), pos = 4)
plot (1:nrow(ISO18O),ISO18O$ISORESsl,main="RESsl & RESdl O18
delta",xlab="Time", ylab="dO18", col = "blue", xaxt = 'n')
Dates <- Lake[Lake$Month %in% c("January") & Lake$Day %in% c(1),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines (1:nrow(ISO18O),ISO18O$ISORESdl)

plot (1:nrow(Clean),Clean$Depth,main="Lake depth over time",xlab="Time",
ylab="Depth", col = "blue", xaxt = 'n')
Dates <- Clean[Clean$Month %in% c("January"),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
abline (h=seq(min(Lake$Depth),max(Lake$Depth), 1) , col="grey83")
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines(1:nrow(Clean),Clean$Depth)
text(300, 104, paste("KcSS = ", KcSS, "\nKcDS = ", KcDS, "\nCsr =",
Modelparam$Csr[1], "\nCin =", Modelparam$Cin[1], "\nGWinflow =", GWMod,
"\nPWF =", PWF, sep = "), pos = 4)
plot (1:nrow(ISO18O),ISOD$ISORESsl,main="RESsl & RESdl D delta",xlab="Time",
ylab="dD", col = "blue", xaxt = 'n')
```

```
Dates <- Lake[Lake$Month %in% c("January") & Lake$Day %in% c(1),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines (1:nrow(ISO18O),ISOD$ISORESdl)

quartz()
par(mfrow=c(2,1))
plot (1:nrow(Clean),Clean$d18O,main="RESsl & RESdl O18 delta", sub =
paste("Sample Depth: ", Sampledepth),xlab="Time", ylab="dO18", col = "blue",xaxt =
'n')
Dates <- Clean[Clean$Month %in% c("January"),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines(1:nrow(Clean),Clean$d18O)
plot (1:nrow(Clean),Clean$dD,main="RESsl & RESdl D delta", sub = paste("Sample
Depth: ", Sampledepth),xlab="Time", ylab="dD", col = "blue",xaxt='n')
Dates <- Clean[Clean$Month %in% c("January"),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
#abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines(1:nrow(Clean),Clean$dD)

quartz()
par(mfrow=c(2,1))
LELfull <- lm(Clean$dD ~ Clean$d18O) # Create a LEL from the D and 18O
plot (Clean$d18O, Clean$dD,main="Complete LEL", sub = paste("Sample Depth: ",
Sampledepth),xlab="d18O", ylab="dD", col = "blue")
abline(LELfull, col="red")

LEL <- lm(Clean$dD[36:nrow(Clean)] ~ Clean$d18O[36:nrow(Clean)]) # Create a
LEL from the D and 18O
plot (Clean$d18O[36:nrow(Clean)], Clean$dD[36:nrow(Clean)], main=paste("LEL
36:", nrow(Clean), "months."), sub = paste("Sample Depth: ",
Sampledepth),xlab="d18O", ylab="dD", col = "blue")
abline(LEL, col="red")
}
loadgraphs()

#************************* Check against historical data
*****************************

#There are two separate routines for monthly or daily data. These can probably be
condensed, with just a single "if" on the subset selection, but for the moment I'll keep
the separate in case they require different graphs, etc.
calcheck <- function () {
if (is.na(Historicaldata)) {
```

```
message ("*****************\nYou have not specified a historical levels file in
preferences.")
} else if (Datarate == "Monthly") {
Historicallevels$Modelledlevel <- 0
for (i in 1:nrow(Historicallevels)){
Record <- Lake$Depth[(Lake$Year %in% Historicallevels$Year[i]) & (Lake$Month
%in% Historicallevels$Month[i])& (Lake$Day %in% 1)] #so just looks at year and
month
Historicallevels$Modelledlevel[i] <- Record
} # end for
quartz()
par(mfrow=c(2,1))
plot (Historicallevels$Height, Historicallevels$Modelledlevel,xlab="Historical Level",
ylab="Modelled Level")
Historicallevels$Residuals <- Historicallevels$Height - Historicallevels$Modelledlevel
message ("Average of residuals = ", round(mean(Historicallevels$Residuals), digits =
3), ". Standard deviation = ", round(sd(Historicallevels$Residuals), digits = 3))
message ("Ave=", round(mean(Historicallevels$Residuals), digits = 3), ". SD=",
round(sd(Historicallevels$Residuals), digits = 3))
#plot (1:nrow(Historicallevels), Historicallevels$Residuals)
plot (Historicallevels$Height, Historicallevels$Residuals, main="Modelled Lake Level
Residuals", sub="", xlab="Depth", ylab="Difference (m)")
} else { #daily datarate
Historicallevels$Modelledlevel <- 0
for (i in 1:nrow(Historicallevels)){
Record <- Lake$Depth[(Lake$Year %in% Historicallevels$Year[i]) & (Lake$Month
%in% Historicallevels$Month[i]) & (Lake$Day %in% Historicallevels$Day[i])]
Historicallevels$Modelledlevel[i] <- Record
} # end for
quartz()
par(mfrow=c(2,1))
plot (Historicallevels$Height, Historicallevels$Modelledlevel,xlab="Historical Level",
ylab="Modelled Level")
Historicallevels$Residuals <- Historicallevels$Modelledlevel - Historicallevels$Height
message ("Average of residuals = ", round(mean(Historicallevels$Residuals), digits =
3), ". Standard deviation = ", round(sd(Historicallevels$Residuals), digits = 3))
message ("Ave=", round(mean(Historicallevels$Residuals), digits = 3), ". SD=",
round(sd(Historicallevels$Residuals), digits = 3))
#plot (1:nrow(Historicallevels), Historicallevels$Residuals)
plot (Historicallevels$Height, Historicallevels$Residuals, main="Modelled Lake Level
Residuals", sub="", xlab="Depth", ylab="Difference (m)")
} #end if
} #end function
calcheck()

histplot <- function () {
if (is.na(Historicaldata)) {
```

```
message ("*****************\nYou have not specified a historical levels file in preferences.")
} else if (Datarate == "Monthly") {
Lake$Historicallevel <- NA
for (i in 1:nrow(Historicallevels)){
Histdate <- as.numeric(row.names(Lake[(Lake$Year %in% Historicallevels$Year[i]) & (Lake$Month %in% Historicallevels$Month[i]) & (Lake$Day %in% 1), ])) #so just looks at year and month
Histlevel <- Historicallevels$Height[i]
Lake$Historicallevel[Histdate] <- Histlevel
} # end for
temp <- na.omit(cbind(1:nrow(Lake),Lake$Historicallevel))
plot (1:nrow(Lake),Lake$Depth,, type = "l", main="Lake depth over time",xlab="Time", ylab="Depth", col = "blue", xaxt = 'n')
Dates <- Lake[Lake$Month %in% c("January") & Lake$Day %in% c(1),]
axis (side = 1, at = row.names(Dates), labels = Dates$Year )
abline (v=row.names(Dates), col="grey", lwd = 0.5)
abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines(temp)
} else {
Lake$Historicallevel <- NA
for (i in 1:nrow(Historicallevels)){
Histdate <- as.numeric(Lake$Timestep[(Lake$Year %in% Historicallevels$Year[i]) & (Lake$Month %in% Historicallevels$Month[i]) & (Lake$Day %in% Historicallevels$Day[i])])
Histlevel <- Historicallevels$Height[i]
Lake$Historicallevel[Histdate] <- Histlevel
} # end for
temp <- na.omit(cbind(1:nrow(Lake),Lake$Historicallevel))
#This sections adds dates. It's a little fragile at the moment, broken by using incorrect month labels.
plot (1:nrow(Lake),Lake$Depth,, type = "l", main="Modelled and Historical Lake Levels",xlab="Time", ylab="Depth", col = "blue", xaxt = 'n')
Dates <- Lake[Lake$Month %in% c("January") & Lake$Day %in% c(1),]
axis (side = 1, at = Dates$Timestep, labels = Dates$Year )
abline (v=Dates$Timestep, col="grey", lwd = 0.5)
abline (h=seq(ceiling(min(Lake$Depth)),floor(max(Lake$Depth)), 1) , col="grey83")
lines(temp)
} #end if
#return (Lake)
} #end function
histplot()

#************************ Final Output ******************************


#Output data to excel files.
```

```
Output <- function(){
write.table(Met, Metoutfile, sep="\t", row.names=FALSE)
write.table(Lake, Lakeoutfile, sep="\t", row.names=FALSE)
write.table(Clean, Cleanoutputfile, sep="\t", row.names=FALSE)
write.table(ISO18O, O18output, sep="\t", row.names=FALSE)
write.table(Flux, Fluxoutfile, sep="\t", row.names=FALSE)
write.table(ISOD, Doutfile, sep="\t", row.names=FALSE)
}
Output()
```

## APPENDIX B: CHIMBLE VERSION NOTES, PARAMETER, PREFERENCE AND EXAMPLE DATA FILES.

Version Notes:
Version 1.0425

- Major revision to Fdlm structure.
- If SVC is zero, then the fluxes are now run in and out of RESdl (as RESdl now represents the entire lake, fully mixed)
- IF RESss < the sum of the fluxes for that time period (in particular where evaporation is greater than precipitation), then the remaining fluxes are split proportionally and removed from the RESds.
- SVC and the Fdlm fluxes are calculated at the end of the main loop, after all other fluxes have been applied. This is because unlike the fluxes - representing a monthly input or outflow, the SVC represents a state of the system. Therefore it is calculated for the time period, using data for that time period. Example: July's (Time + 1) lake volume is calculated by the sum of fluxes over June (Time), and the June lake level (Time) . However, it's SVC is calculated from the July stratification data (Time + 1).
- Bug fixed in Fsse calculation. PET and E functions updated to return metres, rather than mm.
- Fslm removed from Flux table. It's not used for anything with Fdlm doing double duty as a positive and negative flux.

1.0501

- Major update to remove the ability for soil layers to go above maximum capacity. With snowmelt it was possible to dump a massive amount of water into the upper soil layers through Fssi, as the condition was checked based on RESss volume, without considering flux input. Now the excess flux is partitioned off into Fro, Fssd, and if necessary Fdsd as per Steinman's paper. This means the Fsse and Fssd fluxes are no longer subtracted in the RESss and RESds equations as the fluxes are partitioned correctly in the Soil function.

1.0503

- Isotope modelling for O18 is begun, but not yet complete. Fdlm is not sorted yet, and I need to check that RESdl Isotopes are working.

1.0505

- Added a section to smooth the lake stratification. Stratification occurs in a stepwise fashion in the Meteorological data. This has been smoothed with a linear transition from the SL at Month to the SL at Month+1. This allows for a steady increase in mixing over a month, rather than a sudden change and massive volume movement between RESsl and RESdl at the changeover of each month.

1.0507
- Epic rewrite of the isotope functions. Isotopes are now coupled at a function level. One single routine does hydrology and isotopes at the same time.
Isotopes balance, but there are a couple of boundary issues to be sorted. There are occasional massive excursions of isotopes (in the orders of magnitude range). I think this is due to a reservoir approaching zero.

1.0508
- Balance is done. Problem of stratification layer moving through the bottom of the lake is solved. If the stratification layer is within 0.5m of the lake floor, then the entire lake is considered as RESsl. This resolves the problem of negative volumes in the lowest reaches of a lake due to loess smoothing of the bethymetry.

1.0521
- Groundwater inflow is included. Reads groundwater and isotope values from the meteorological file. If there is no groundwater, then 0 can be used in the file. Groundwater values are m^3 per month. Groundwater is currently run into the inflow reservoir.
- Overflow routine added but not yet tested. Uses the maximum volume as specified in the first line of the Volumes file. This little snippet of code does't do anything with regard to isotopes, unless if drains the RESsl, in which case the RESsl isotopes are set to 0. As overflow is simply removing water without fractionation, then the isotopic composition shouldn't change.

1.0603
- Now runs 5 times faster. :D Can do 20 years at 40 integrations a month (9600) in under 4 minutes.
- Overflow module added. Now the lake will overflow when it reaches the top of the hypsographic curve.

1.0604
- Groundwater inflow has been switched from flux into the RESin reservoir, to flux directly into the RESDL reservoir. This is to avoid an interesting harmonic issue. If 1000m3 per timestep flows into the RESin, then RESin will increase in volume until the flux to the lake catches up. For a Cin constant of 0.2, this may take 12-24 months.
- Fixed the overflow function I broke in 1.0603. :P

1.0605
- Modifiers added to preferences allowing step changes to be applied to meteorological data without editing the meteorological file.

1.0607
- Lake can now dry out without crashing.

1.0622

- Evaporation is now calculated based to a degree on Van Boxel's model. A linear relationship is used to determine actual evapotranspiration from soil moisture content. The coefficient is current upper soil moisture content / field capacity (RESss/(AWCss * Area)) for the upper soil, and current lower soil moisture content / total field capacity for both layers. This approximates the more rapid evaporation & evapotranspiration of the upper soil, with a slower evapotranspiration through deep rooted plants of the lower soil as well as the decrease in evapotranspiration as soil water content decreases.
- Fractionation through evapotranspiration is set at 0, with both Fsse and Fdse having isotopic composition of their respective soil layers. This is based on the comment in Steinman (and a few other papers) that evapotranspiration is a non-fractionating effect.

1.0623

- Taking advantage of the split soil layers, Both layers now draw down as a linear function as per Van Boxel's model (as RESxs/AWCxs * Area). However, the lower soil layer has an additional coefficient, representing the area of the catchment with trees and other deep rooted plants that would draw from the lower soil layer. This can be found in the preferences file.
- GWMod has been added - allowing the stepwise change of groundwater flux.

1.0702

- Preliminary support for daily data is included. If using daily climate data, change Datarate to Daily, and Integrations to 1 (unless you really like looking at progress bars) in the preferences file.

1.0714

- Daily data improved massively. Now creates a clean file with the first of each month.
- Fixed epic bug in the temperature fudge routine (Lake temp will drop to a minimum of 4º)
- Fixed rogue zero line at end of clean file.

1.0716

- Model updated to use crop coefficients for catchment area.

1.0720

- CHIMBLE updated to incorporate to some degree the effect of deep lake heat storage on evaporation. It's an ad hoc fix, based on FAO56. Kc values for winter and summer lake evaporation, and a sin curve (with a slight offset to match air and water maximum and minimum temperatures) are used to estimate the Kc value for any time of the year.
- func.Month now includes timestep or day number to allow for calculation of Ra or other functions as a smooth curve, rather than a step change at each month.

1.0726

- Fixed bug in lake temperature offsets routine. Was setting the lake surface temperature in the Toff field, rather than the updated Toff.

1.0728

- Updated to include Gat's isotopic enrichment limitation, as described in Gat, 1991 - The heavy isotope enrichment of water in coupled evaporative systems.

1.0729

- Fixed bug in Ra calculations. ModØ required here RA ~ 3N sin(0:131N - 0:95Ø). (From Valiantzas 2006).

1.0730

- RunoffRatio added to preferences - to cater for soils such as in the volcanic plains of Victoria, where runoff is rarely observed and water seeps directly into the soil, with excess water draining to the watertable.

1.0806

- Preliminary support (Daily timesteps) added for comparisons with historical data. R2 plots and linear regression between modelled and historical data now available. Commands are histplot() and calcheck(). Histplot shows modelled vs historical data. Calcheck reports on model fit.

Monthly timesteps should work too, but haven't been tested yet.

1.0817

- Fixed bug in calcheck routine. Prevented RH and RHn values over 100%.
- Modifiers now use fractions (eg: 1.1 = 10% increase in rainfall. This is to avoid the threshold problem with rainfall and other climate factors. Groundwater is still additive (in m3 per day/month).
- Chimble can now use segmented lines instead of loess smoothing, allowing the modelling of lakes where loess smoothing may result in negative volumes at very low lake levels. This allows the user to move the smoothing back to the formation of the DTM.
- Incorrect use of linear regression. Linear regression removed from calcheck and replaced with average and standard deviation of residuals.

1.0901

- Added date labelling for axes and automated grid lines.
- Fixed bugs in Calcheck and Histplot using monthly data.

1.0911

- Fixed startup bug (func.SVC and func.dE called before they loaded)

1.0917

- Fixed bug with daily data - Days in Lake file were all set to 1.

Climate Example File

```
"Year" "Month"       "Day"  "P"     "Ta"    "RH"    "Rs"    "WS"    "d18Op"
       "dDp"  "SL"   "Toff" "Groundwater"           "d18Ogw"        "dDgw"
```

```
1       "January"       "1-31" 33.14   17.62   69.2770967741936        22.88
        2.27741935483871        -4.2    -23     15.0064516129032        2.99354838709677
        0       -4.77   -27
1       "February"      "1-29" 28.94   17.96   62.0765517241379        20.68
        2.28931034482759        -4.9    -29     15.951724137931 2.07689655172414
        0       -4.77   -27
1       "March" "1-31" 39.36   16.26   68.6170967741936        16.48
        2.13903225806452        -4.5    -30     17.7967741935484        2.4     0       -4.77
        -27
1       "April""1-30" 57.79   13.59   78.1056666666667        11.56   1.719   -5.3    -30
        20.8733333333333        2.12066666666667        0       -4.77   -27
1       "May" "1-31" 73.39   11.18   76.3712903225806        8.04    1.3058064516129
        -5.9    -35     29.541935483871 1.84935483870968        0       -4.77   -27
1       "June" "1-30" 74.02   8.84    80.0796666666667        6.50    1.47333333333333
        -6.2    -37     30.3266666666667        1.48866666666667        0       -4.77   -27
1       "July" "1-31" 84.53   8.27    83.2293548387097        7.27    1.68258064516129
        -6.1    -36     4.03870967741936        1.83193548387097        0       -4.77   -27
1       "August"        "1-31" 88.99   9.05    80.3245161290323        10.09
        2.31193548387097        -5.2    -28     0       1.42193548387097        0       -4.77
        -27
1       "September"     "1-30" 81.45   10.45   80.9743333333333        14.10
        1.85033333333333        -4.6    -24     3.10666666666667        2.08233333333333
        0       -4.77   -27
1       "October"       "1-31" 70.91   12.12   74.2693548387097        17.93
        1.99741935483871        -3.9    -20     19.8225806451613        1.61806451612903
        0       -4.77   -27
1       "November"      "1-30" 56.67   13.86   69.467 21.28   1.908   -3.2    -15
        17.4566666666667        1.71266666666667        0       -4.77   -27
1       "December"      "1-31" 47.90   15.93   73.0583870967742        22.59
        2.2858064516129 -3.3    -17     13.2612903225806        2.26838709677419
        0       -4.77   -27
```

Preference file structure

```
Name  Value  Comment
# ***INPUT FILES***
Historicallevels        NA      The name of the file with the historical lake levels. Year,
Month, Day, Level format.
Lakedatafile    Basin Small Hypsographics.txt   The name of the lake volume file.
If blank, then you can select from the program.
Isotopefile     Isotope Data.txt        The name of the file with starting values for
isotopes.
Modelparamfile          Parameter File Basin Small.txt          The name of the lake
parameters file. If blank, then you can select from the program.
MetfileMassbalance1200year 5%.txt The name of the meteorological file. If blank, then
you can select from the program.
# ***Output FILES***
Metoutfile      Output_Basin_Small_Met.txt The name of the meteorological out file. If
blank, then you can select from the program.
```

```
Lakeoutput      Output_Basin_Small_Lake.txt         The name of the lake Gnotuk file.
If blank, then you can select from the program.
Cleanoutput     Output_Basin_Small_Clean.txt        The name of the cleaned Gnotuk
file. If blank, then you can select from the program.
Fluxoutput      Output_Basin_Small_Fluxes.txt       The name of the flux Gnotuk file. If
blank, then you can select from the program.
18Ooutput       Output_Basin_Small_18O.txtThe name of the 18O Gnotuk file. If blank,
then you can select from the program.
Doutput         Output_Basin_Small_D.txt    The name of the Deuterium Gnotuk file. If
blank, then you can select from the program.
# ***MODEL AND CATCHMENT PARAMETERS***
Datarate        Monthly         Specify "Daily", or "Monthly" data.
Interpolationtype       Segments        Type of interpolation for hyposgraphic curves
("Loess", or "Segments")
Fitspan0.01     Span function for the Loess smoothing used to calculate hypsographic
curves. (default for 0.2m contours = 0.1)
Timestep        0.25    The number of integrations for each period of times specified in
the datarate. (eg 0.25 = 4 integrations).
Deeprootpercent         100     The amount of catchment with deep rooted plants that can
draw from the lower soil reservoir.
RunoffRatio     100     Percentage of soil that infiltrates soil once surface soil is
saturated.
ALBlake         0.08    Albedo of the lake. (Open Water - Allen et al. 1998)
ALBearth        0.25    Albedo of the land surface. (Grass - Allen et al. 1998)
KcSS   0.7      Kc value of shallow rooted plants (see FAO56)
KcDS  0.8       Kc value of deep rooted plants (see FAO56)
KcLsum          0.65    Kc value of summer open water (see FAO56)
KcLwin          1.25    Kc value of winter open water (see FAO56)
PWF    0        Penman wind function. 1 for original Penman wind function. 0.5 for
reduced Penman wind function. 0 for Linacre wind function. (0 used for large lakes -
Valiantzas 2006)
Latitude        -38.1405        Lake latitude (used for calculation of extraterrestrial
radiation. In DDD.MMSS).
Sampledepth   0         Depth at which to sample isotope values.
# ***MODIFIERS FOR SENSITIVITY TESTING***
Soilmixing      1       This value determines the isotopic composition of soil going to
the deep soil layer. 1 = same as for Fssi. 0.7 = 70% from fssi, 30% from RESss.
PMod  1         Modifier for precipitation (This modifier is multiplied by the monthly
precipitation.)
TaMod1          Modifier for air temperature (This modifier is  multiplied by the
temperature.)
TwMod           1       Modifier for water temperature (This modifier is  multiplied by
the water temp offset.)
WSMod           1       Modifier for wind speed (This modifier is  multiplied by the WS.)
RHMod           1       Modifier for relative humidity (This modifier is  multiplied by the
RH.)
RsMod1          Modifier for solar radiation (This modifier is  multiplied by the Rs.)
```

GWMod 0 Modifier for groundwater (This modifier is added to the monthly groundwater influx.)

Parameter file structure

| Timestep | CA | AWCss | AWCds | Cin | Csr | RESsl | RESdl | RESss | RESds | RESin | RESsp |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 300000 | 0.04 | 0.04 | .04 | 0 | 858962 | 0 | 0 | 0 | 42421 | 0 #0 fill from zero |

Isotope file structure

| Isotope | RESsl | RESdl | RESss | RESds | RESin | RESsp |
|---|---|---|---|---|---|---|
| D | 7 | 7 | -23 | -23 | -23 | -23 |
| 18O | 3.8 | 3.8 | -4.2 | -4.2 | -4.2 | -4.2 |

Hypsographic data file structure

| Depth | Volume | Area |
|---|---|---|
| 60.000 | 6477180.892 | 196297.212 |
| 55.000 | 5530837.519 | 182308.618 |
| 50.000 | 4654694.118 | 168225.526 |
| 45.000 | 3849238.183 | 154043.732 |
| 40.000 | 3115037.671 | 139735.110 |
| 35.000 | 2452740.469 | 125297.547 |
| 30.000 | 1863137.653 | 110677.222 |
| 25.000 | 1347188.824 | 95862.415 |
| 20.000 | 906140.854 | 80755.056 |
| 15.000 | 541666.246 | 65291.142 |
| 10.000 | 256154.261 | 49271.172 |
| 5.000 | 53770.703 | 32262.422 |
| 0.000 | 0.000 | 0.000 |