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Modelling lake levels under climate change conditions: three closed lakes in Western Victoria

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Abstract: Lakes Keilambete, Gnotuk and Bullenmerri are lakes in Western Victoria that are highly regarded for their ecological, social and scientific values. These are maar lakes (lakes in shallow craters of volcanic tuff) and are recognized as being of National (Gnotuk) and International Significance (Keilambete, Bullenmerri). As closed lakes, they have no streams coming in or out, and are predominantly controlled by rainfall and evaporation at the water's surface. These crater lakes are very sensitive to climate change and have been used to diagnose past changes in climate. Previous research has shown that the lakes have been falling since the mid 1800s and that the likely cause was a decrease in rainfall and increase in evaporation of natural origin. Recent rainfall decreases have increased the rate of lake level decline. With the prospect of future climate change further altering regional rainfall and evaporation, this study assesses the potential impact of climate change due to enhanced greenhouse gas on future lake levels at these lakes.

Lake levels (~1880–2100) are constructed using the lake water balance model of Jones et al. (2001). This model is quite robust in modelling historical lake levels, and has been used for simulating climatic conditions reproducing lake levels for the past 16,000 years. Time series of monthly climate data were obtained from 14 global climate model simulations contained in the database used in the IPCC's Fourth Assessment Report (IPCC, 2007). For the future, these GCM simulations were forced by the A1B and A2 greenhouse gas and sulphate aerosol emission scenarios. The use of multiple GCMs and different future emission scenarios, result in scenarios that represent the range of likely outcomes of regional climate under enhanced greenhouse conditions to 2100.

The results suggest that all lake levels will continue to fall, with the declines for Bullenmerri expected to be larger than those for the other two lakes. The decline was initiated with the historical change in climate from around the mid 19th century. Recent reductions in the precipitation/evaporation ratio show that the rate of decline is accelerating. For Bullenmerri, the median model simulation projects a rainfall/evaporation (*P/E*) ratio of around 0.73, 0.69, and 0.67 in the 2030s, 2050s and 2070s, respectively. These are similar to the median values for Lake Keilambete and Lake Gnotuk (0.71, 0.68 and 0.64, respectively). The median estimates of the rate of change for Keilambete is -7.8, -5.8, and -4.2 cm/year in the 30 year periods centred on 2030, 2050 and 2070, respectively. For Gnotuk these are -14.5, -15 and -10.9 cm/year and for Bullenmerri they are -24.4, -26.1 and -30.4 cm/year respectively.

In addition to the drying trend, proposed land subdivision and urbanization within the Gnotuk catchment, for example, threatens the visual amenity of the lake and will add to the nutrient and sediment load to the lake. The deeper crater lakes, particularly Lake Bullenmerri, are becoming increasingly important as a resource for recreation and amenity for the regional community. This is placing added pressure on the scientific and environmental qualities of the lakes. Lakes Keilambete and Gnotuk will become increasingly hypersaline, and Lake Bullenmerri will also become more saline. This may reduce the invertebrate diversity in the lakes. In Bullenmerri, the rising salinity could cause a shift in the algal plankton and so influence the whole food web, recreational fish species included, putting its place as an important recreational fishery at risk. This suggests that a regional plan to manage the quality and amenity of lakes in Western Victoria under a drying climate and other threats is urgently needed.

Keywords: *Modelling lake level, Climate Change, Saline lakes, Western Victoria*

1. INTRODUCTION

In Western Victoria, Australia, there are many saline volcanic crater lakes – often known as maar lakes. A maar is a broad, roughly circular, flat-floored volcanic crater with steep inner walls and a low surrounding rim built of fragments of rock materials blown out of the crater during eruptions (tuff). These lakes are highly regarded for their recreational, economic, social, ecological, conservation and scientific values. Lakes Keilambete, Bullenmerri, and Gnotuk, in particular, are recognized as being of National (Gnotuk) and International Significance (Keilambete, Bullenmerri). The significance of these lakes is recognized in the Corangamite Planning Scheme by application of a Public Conservation and Resource Zone to the craters and a 100m wide Environmental Rural Zone buffer to land beyond the crater rims (www.ces.vic.gov.au).

The catchments of these three lakes are totally contained within their craters and there is no stream flow in or out. Having high lake/catchment area ratios and relatively low groundwater input these lakes are predominantly controlled by rainfall and evaporation at the water's surface. Compared to other ecosystems, salt lakes are very sensitive to climate change. Even small changes in the hydrological budget are reflected rapidly and directly by physico-chemical and biological events (Williams, 2002; Timms, 2005). They therefore offer unique opportunity to quantify the effects and mechanisms of climate change (Jones et al, 2001; Williamson et al., 2009).

Previous research has shown that the lakes have been falling since the mid 1800s, following a period of relative stability lasting most of the previous millennium (Bowler, 1981; De Deckker, 1982). The fall coincides with the first European occupation of the region in around 1840 (Kiddle, 1961) and precedes the widespread change to the landscape that followed occupation. Bowler (1970) and Sutcliffe (1968) concluded that the fall in water level at these three lakes was due to climate change of natural origin. Jones et al (2001) provided further support for this conclusion. The fall in water level was initiated by a decrease in rainfall and evaporation ratio from a pre-1840 value of P/E ratio of 0.94-0.96 to an historical value of 0.79 (Jones et al., 2001). Given the prospect of future climate change, further modification of regional rainfall and evaporation, warming and associated changes in rainfall may adversely affect most of the salt lakes in the region (Williams, 2002). This paper uses a predictive approach to estimate the impact of climate change on the lake levels. Future climate change scenarios of some climate variables are generated and then fed into the lake water balance model of Jones et al. (2001). This model has been shown to be quite robust for modelling historical lake levels, and has been used to simulate climatic conditions contributing to the past 16,000 years' lake level (Jones et al., 1998).

2. OVERVIEW OF THE LAKES

The lakes lie about 150 km southwest of Melbourne at altitudes less than 200 m above sea level (Figure 1). Geomorphologically, they are in the area of the Western Volcanic Plains of Victoria – a broad plain of Newer Volcanic Province of southeastern Australia (Williams, 1981; Joyce, 2003). Lake Keilambete is situated 3 km northwest of the town of Terang, while lakes Gnotuk and Bullenmerri are 20 km east of Terang and several kilometres west of Camperdown. Lake Keilambete is a circular lake with an average diameter of about 1.8 km covering an area of 250 ha in a catchment of 417 ha (Jones et al., 2001). It is surrounded by a basaltic tuff ring which gives a maximum enclosed crater depth of 40 m. Lake Bullenmerri is a cloverleaf-shaped lake with an average diameter of 3.2 km and covers an area of 490 ha (in 1990) within a catchment of 882 ha (Jones et al., 2001). The crater has a steep cone-shaped floor with present maximum water depth of 67m and a mean depth of 40 m. Adjacent to the north of Lake Bullenmerri, Lake Gnotuk is a smaller lake, 220 ha in area within a catchment of 722 ha. Bullenmerri and Gnotuk are linked by an overflow channel in the common wall at an altitude of 175 m. Lake Bullenmerri was recorded as overflowing into Lake Gnotuk in 1841 (Sutcliffe in Jones et al.,

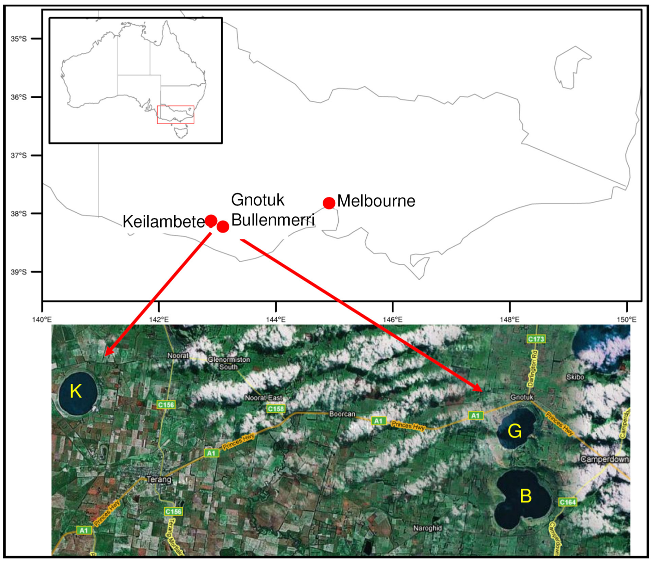

Figure 1. Locations and aerial view of Lakes Keilambete (K), Gnotuk (G) and Bullenmerri (B). Satellite image: http://maps.google.com.

2001). Despite their proximity, the water depth of Gnotuk is lower than that of Bullenmerri, with a maximum depth of less than 20 m.

As mentioned previously, all the study lakes are saline. In 2008, Keilambete was hypersaline (about 100 ppt), Bullenmerri was brackish (around 10 ppt), while Gnotuk was hypersaline (around 70 ppt) (EPA, in prep). The origin of the salt in Australian lakes has been the subject of much discussion and is beyond the purpose of this paper to discuss it at length. One of the speculations is that the salt can be the results of natural accumulations within the closed catchments of each lake in accordance with the balance or ratio between rainfall on to a lake's catchment and evaporation from its surface (e.g. EPA, 1980).

The characteristics of the biota of Victorian salt lakes have been reviewed by Williams (1981). He showed that: (1) fewer species occur at high salinities than at lower ones; (2) at low salinities, temperature is relatively unimportant, but at high salinities it is important and increase in temperature at any given salinity increases mortality; (3) for some animals the upper limit of salinity tolerance may be the lower limit of dissolved oxygen tolerance. In regard to composition, the fauna of all south-east Australian salt lakes is highly endemic, distinctive, and in some cases unique to individual lakes. Williams also showed that the fauna of salt lakes are predominantly evolved from a freshwater fauna.

Before the European invasions, the Western Volcanic Plains were occupied, at least in part, by 6 or 7 separate Koorie (Aboriginal) tribes in which each tribal area was further divided between a number of clans (Gott, 1999). Occupation of the plains extended back for possibily 60,000 years. In her review, Gott showed that the plains provided many important plants. Out of 550 species listed by Willis (1964), approximately 25% of the plants are used by the Koories (out of which about 20% are used for food). After the European occupation of Western Victoria in 1841, most of the indigenous vegetation surrounding the lakes was almost entirely cleared (by 1900), but the lakes themselves were not altered as their water was too saline for domestic use (Jones, 1995). Although most of the plains were then essentially treeless, settlement had considerable impact upon vegetation, i.e., most of the original grassland is replaced by alien pasture grasses, clovers, crop plants and weeds (Williams, 1981). Jones et al. (2001) showed that this land-use change did not contribute to declining water levels. The region is now an area of dryland farming. Lake Bullenmerri has also become a popular recreational area for fishing, boating, water skiing and swimming. The lake is regularly stocked with rainbow trout and Chinook salmon.

3. HISTORICAL AND FUTURE CLIMATE CHANGE

3.1. Historical climate

The regional climate of the study area is temperate. Annual mean temperature is around 13^{o}C (ranges around 8^{o}C in winter to 17^{o}C in summer) and annual rainfall is around 800 mm (ranges around 115 mm in summer to 240 mm in winter). During summer, solar radiation is relatively high leading to a high atmospheric moisture deficit, hence evaporation exceeds precipitation.

For the historical period (~1860s to 1990), high quality or quality controlled observed rainfall datasets were constructed by Jones et al. (2001); one for Lake Keilambete and one for Lakes Gnotuk and Bullenmerri. The former was based on records from Terang while the latter was based on Camperdown. Records were also prepared for temperature, sunshine ratio and or downward short-wave radiation, and dewpoint temperature, as required by the lake water balance model. In this study, these data sets were extended up until 2008 based on data from Terang (for Keilambete) and Camperdown (for Gnotuk and Bullenmerri) as obtained from the SILO Patched Point Dataset (Jeffrey et al., 2001). Although the SILO data are available for the 1889–2008 period, Jones' data were used as they have undergone rigorous quality

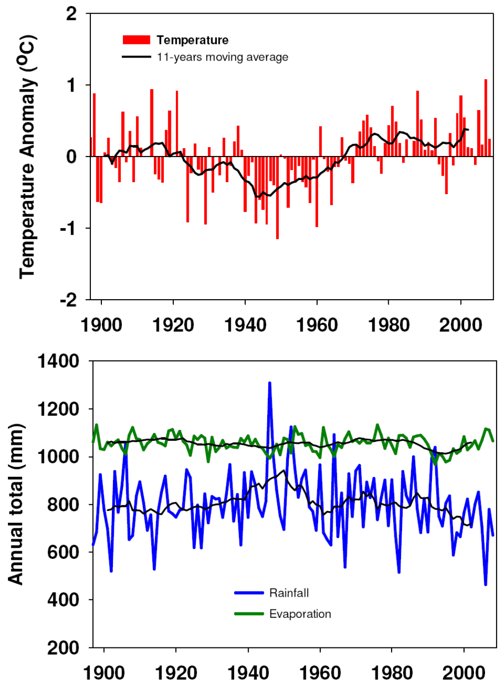

Figure 2. Terang annual temperature anomalies relative to the long-term average (upper panel) and annual rainfall and fresh-water evaporation (bottom panel).

control. A detailed comparison showed that the 1889–1990 data for Terang and Camperdown obtained from SILO are highly similar to those of Jones et al, with a correlation coefficient of more than 0.97 for each of the climate variables. The extended data sets were then subjected to a quality control process. The quality control for climate time series is necessary to account for any discontinuity in the record due to, for example, equipment changes, location changes, and changes in observers.

The data were then used to estimate the lake evaporation based on Morton's Complementary Relationship Lake Evaporation (CRLE) method (Morton, 1983, 1986, Morton et al, 1985) which had been incorporated in the Jones et al. (2001) lake balance model. Results from the CRLE method have been compared to those obtained from lake water budgets across the world, and found to be within 7%, a figure well within the experimental error (Morton, 1986).

Recent climate variability from Keilambete is shown in Figure 2. Air temperature generally showed no significant movements over first century, but shows a significant upward trend from about 1960 (Jones, 2005). Similarly, there is no large trend in rainfall, although there were wetter (1950s) and drier (1998–2008) periods. Freshwater evaporation (E) shows no significant trend. The long-term (1897–2008) average of E (1,056 mm) and rainfall (P = of 801 mm) yield a P/E ratio of 0.76. For the period 1998–2008, the P/E ratio was 0.68.

3.2. Future climate

In this study, time series of monthly rainfall, air temperature, solar radiation, and specific humidity (converted into dewpoint temperature) were obtained from global climate model simulations available in the Coupled Model Intercomparison Project 3 (CMIP3) database – produced for the IPCC's Fourth Assessment Report (IPCC, 2007). Of the 23 GCM simulations available in this database, 14 GCMs provide data for all climate variables required by the lake model. For 1900–2000, the simulations were forced by observed atmospheric emissions of greenhouse gases and sulphate aerosols. For 2001–2100, the available simulations were forced by the A1B (11 GCMs) and by the A2 (3 GCMs) emission scenario. The SRES-A1B depicts a very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies, with a balance across all energy sources. The SRES-A2 scenario depicts a very heterogeneous world, with self reliance and preservation of local identities as the underlying theme for energy use (IPCC, 2000). The use of multiple GCMs and future emission scenarios result in scenarios that represent the range of likely outcomes of climate under enhanced greenhouse conditions as described by CSIRO and BoM (2007).

The performance of the GCMs over Australia has been assessed by comparing the simulated seasonal-mean temperature, rainfall and mean sea level pressure for the period 1961–1990 (Suppiah et al., 2007) and 1958–2001 (Watterson, 2008) with observations. Suppiah et al. (2007) used a subjective demerit point system and considered a given GCM to have satisfactory performance over the Australian region if the GCM had less than eight demerit points across all seasons. Watterson (2008) concluded that most GCMs have considerable skill over Australia, using a scoring system in which zero indicates no capacity and a score of 1000 indicates perfect performances. Most of the GCMs used in this study have Watterson skill scores of more than 500 and Suppiah et al. demerit points of less than 8. For this study, each GCM is also evaluated, in part, by its ability to simulate the present climatology (Whetton et al., 2005). Comparison between the observed monthly climatology and modelled climatology in the location of the lakes (not shown here, but available from the authors) indicates that most GCMs have reasonable capability in simulating the present climate. We conclude that all 14 GCMs are suitable for the purpose of modelling future lake levels.

The lake-hydrological processes occur on a finer spatial scale than simulated within GCMs. Given limited resources, this study used the empirical scaling method to translate the GCM information for local use. Firstly, for each GCM and each climate variable, the GCM raw time series was converted into an anomaly time series, relative to GCM baseline period (1881–2008 for Bullenmerri and Gnotuk, and 1987–2008 for Keilambete). Secondly, the GCM anomaly time series were used to scale the observed (historical) baseline data to create modelled climate time series.

4. ESTIMATING LAKE LEVEL UNDER CLIMATE CHANGE

Both the observed climate data and climate scenarios were applied to the lake water balance model of Jones et al. (2001) to estimate the historical and future lake levels. Jones (1995) and Jones et al. (2001) have demonstrated that this lake balance model reproduces the annual amplitude and historical rates of decline in lake level of each of the study lake very well.

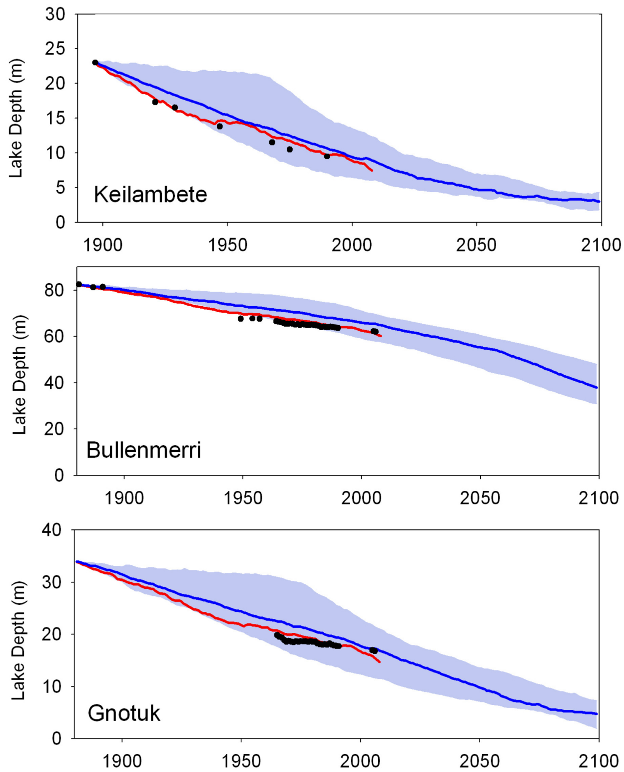

Figure 2. Observed (black dots) and modelled annual lake level**.** Red line is the observation-based estimate, blue line is the multi model median, while the blue envelope shows the 10th and 90th percentile range.

This model was specifically constructed and or calibrated for each of the above three closed lakes. In a closed lake, the water balance is predominantly determined by rainfall and evaporation at the lake surface. The volume of groundwater flowing into the lake is derived from springflow (baseflow) originating from a surrounding low-yield aquifer and infiltration into the water table within the topographic catchment. Therefore, the change in lake level can be modelled based on the knowledge of rainfall, lake evaporation, baseflow, and the lake and catchment area.

Lake evaporation, which is calculated in the model (see s3.1) is modified to account for the suppression of lake evaporation due to the presence of dissolved salts. A simple baseflow model represents the deep percolation of soil moisture to the watertable and its discharge to the lake as baseflow. This baseflow model assumes the ratio of actual evapotranspiration to potential evapotranspiration declines linearly when soil moisture is between field capacity and wilting point (Boughton, 1966). The rate of percolation is assumed to be proportional to soil moisture storage, and implicitly, of soil transmissivity.

Simulations from the lake model of Jones et al. (2001) driven by climate scenarios scaled relative to the long-term baseline resulted in a range of estimated lake levels from the late 1880s to 2100. These are shown in Figure 3 with the estimated lake levels based on observed data also overlaid. Although the range of GCM-based estimates within the historical period can be relatively large, those for the future are all relatively narrow, suggesting a strong agreement among the GCMs. All models suggest lake levels will continue to fall, with the declines for Bullenmerri expected to be larger than those for the other two lakes. This is due to the lower salt content leading to higher lake evaporation rates. Lake Keilambete is likely to reach its equilibrium level in late 2090s. The median estimates of the rate of change for Keilambete is -7.8, -5.8, and -4.2 cm/year in the 30 year periods centred on 2030, 2050 and 2070, respectively (Table 2). For Gnotuk these are -14.5, -15 and -10.9 cm/year and for Bullenmerri they are -24.4, -26.1 and -30.4 cm/year respectively.

We also estimated the projected rate of lake level change based on climate change scenarios relative to the climate of the last ten years (1998–2008), which has been anomalously dry (Cai and Cowan, 2008). The potential evolution of lake levels through to 2100 (not shown here), relative to the 1998–2008 baseline is similar to Figure 3. All lakes levels are projected to decline, with a much smaller window of uncertainty in projected rates of change than produced by down-scaling changes from the entire historical climate. In addition, the declines are likely to be much faster compared to those based on the long-term baseline. There is a risk that Keilambete and Gnotuk will reach a depth of less than 3 metres around the mid 2040s and the mid 2050s, respectively.

Table 2. Median estimate and ranges (10th–90th percentile) of projected rate of changes in lake level (cm/year).

30 yr period centred on	Keilambete	Bullenmerri	Gnotuk
2030	-7.8 (-3.0 to -15.0)	-24.4 (-17.5 to -28.4)	-14.5 (-9.2 to -21.3)
2050	-5.8 (-2.7 to -13.5)	-26.1 (-20.6 to -32.9)	-15.0 (-6.1 to -22.6)
2070	-4.2 (-1.3 to -10.5)	-30.4 (-21.8 to -37.8)	-10.9 (-6.1 to -21.3)

5. DISCUSSION AND CONCLUSION

Salt lakes are typical features of the Australian landscape. They are of interest not only because of the significant economic value (for the mineral deposits they yield) but also for their biological components, some of which can be significant sources of food and various chemicals such as food dyes (De Deckker, 1983). Lakes Keilambete, Gnotuk and Bullenmerri are of particular scientific value, especially for its sedimentary record useful in the study of past climates (Jones, 2001).

Previous studies have demonstrated that the study lakes are very sensitive to climate and climate change. The pre-European levels of the study lakes were maintained for up to a millennium and were at climate-lake equilibrium before their depth started to decline in mid 1800s due to decreased rainfall and increased evaporation of natural climatic origin (Bowler, 1981; De Deckker, 1982; Jones et al., 1998). Jones et al. (2001) predicted that these trends will continue in each of the lakes until all components of the lake water balance are in equilibrium with climate or until the climate changes again. To maintain the pre-European lake levels, for example, rainfall would have to be about 95% of lake evaporation (Jones et al., 2001). We show that averaged over the last hundred years or so, the rainfall/evaporation ratio at Keilambete, Bullenmerri and Gnotuk was about 0.76, 0.79 and 0.77, respectively. For the last ten years, these ratios become 0.68, 0.67 and 0.66, respectively, causing accelerated falls in the lake levels.

The potential evolution of lake levels modelled through to 2100 based on climate scenarios from 14 GCMs suggest that all levels will continue to fall, with the declines for Bullenmerri expected to be larger than those for the other two lakes. The continuation of the decline is associated with the historical change in climate from around the mid 19th century. Recent reductions in the precipitation/evaporation ratio show that the rate of decline is accelerating. The median model simulation suggests that for Bullenmerri the future rainfall/evaporation ratio is likely around 0.73, 0.69, and 0.67 in the 2030s, 2050s and 2070s, respectively. These are relatively similar compared to the likely values for either Lake Keilambete (i.e. 0.71, 0.68 and 0.64, respectively) or Lake Gnotuk (i.e. 0.71, 0.68 and 0.64, respectively).

The present climate (last 100 years or so) has a rainfall/evaporation ratio comparable to that of the early Holocene. If climate continues to be as dry or drier than the historical period the lake levels will fall to those of 9-10.5 ka years before present (Jones, 1995). Therefore, the next hundred years may be the driest sustained period since the early Holocene.

Other issues concerning salt lakes in Australia have been reviewed by Timms (2005). In addition to climate change, proposed land subdivision and urbanization within the Gnotuk catchment threatens the visual amenity of the lake and will add to the nutrient and sediment load to the lake. The deeper crater lakes, particularly Lake Bullenmerri are becoming increasingly important as a resource for recreation and amenity for the regional community. This is placing added pressure on the scientific and environmental qualities of the lakes, which are rated as being of national and international importance. Lakes Keilambete and Gnotuk will become increasingly hypersaline, and Lake Bullenmerri will also become more saline (not shown here but are available from the authors). An empirical model shows a negative exponential relationship between salinity and invertebrate diversity in the lakes (EPA, in prep), which is consistent with the existing literature. In Bullenmerri, the rising salinity could cause a shift in the algal plankton and so influence the whole food web, recreational fish species included hence putting its place as an important recreational fishery at risk. This suggests that a regional plan to manage the quality and amenity of lakes in Western Victoria under a drying climate and other threats is urgently needed. This can be reached, for example, by an open forum if there is sufficient and relevant scientific background as it is demonstrated by a consultation to the conservation lobby by the local council in response to a proposed urbanization of Lake Gnotuk (Timms, 2005).

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