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REVIEW ARTICLE

Two centuries of water-level records at Lake George, NSW

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ABSTRACT
The year 2020 marked the 200th anniversary of European settlers first encountering the 'noble expanse of water' of Lake George in New South Wales. Since 1820, unofficial observations and official measurements of the lake's water-level have been recorded almost continuously by various individuals, research teams, government departments and private companies. The lake's recent hydrographic history has been characterised by periods of flood and drought, which correspond with the prevailing climate conditions of SE Australia. This is the longest water-level record of its sort in the Southern Hemisphere and hence of great scientific and historic value. Here, we have compiled all available historic water-level data for Lake George, referenced them to common datums and presented a methodology for continuing the record using satellite imagery in lieu of on-site measurements.

KEY POINTS
1. The 200-year water-level record of Lake George, NSW has been compiled and referenced to a common datum.
2. This is the longest record of its type in the South Hemisphere, documenting the modern periods of flood and drought in southeastern Australia.
3. Water levels for the period 1986–2019 when no on-site measurements were recorded have been estimated using satellite imagery and the lake's bathymetry.

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endorheic lake; long record; hydrological changes; remote sensing; Landsat; Sentinel

Introduction

Lake George is a large endorheic lake located in Australia's southeast. The lake's unique physiography and hydrology mean that water levels respond rapidly to changes in decadal climate fluctuations—primarily rainfall and evaporation. These fluctuating water levels are of constant fascination to the nearby residents of the towns of Bungendore and Collector, as well as long-time residents of Canberra, which has led to numerous myths regarding the mechanisms (*e.g.* emptying through a subterranean river, connections with other lakes in New Zealand or South Australia; Barrow, 2012; Gale, 1927; Jones, 2001).

Numerous researchers from nearby research organisations have undertaken short- to medium-term studies that have recorded surface water levels as part of studies on hydrology (*e.g.* Abbay, 1876; Bowd, 2009; C.E.P.B., 1923; Gates & Diesendorf, 1977; Jacobson & Schuett, 1979; Jacobson *et al.*, 1991; Noakes, 1962; Russell, 1886), fluid dynamics (*e.g.* Babanin *et al.*, 2001; Torgersen, 1984; Tsagareli *et al.*, 2010; Young & Babanin, 2006; Zieger *et al.*, 2015), and paleo-environmental change (*e.g.* Coventry, 1976; Coventry & Walker, 1977; De Deckker, 1982; Fitzsimmons & Barrows, 2010; Lees & Cook, 1991; Macphail *et al.*, 2015, 2016; McEwan Mason, 1991; Singh & Geissler, 1985; Singh *et al.*, 1981).

The studies on paleo-environmental change have included reconstructions of Lake George's water-level fluctuations back to the last glacial maximum using ancient shoreline deposits and sediment cores taken from the lakebed. The findings of these studies indicate that fluctuating water levels are not just a characteristic of the modern lake. Lake George is also of great social/historical importance because of its rich modern history (*e.g.* early European exploration and investigation of the Australian continent, and identified as a possible site for the nation's capital; Anonymous, 1908; Barrow, 2012; Johnson, 2004; Mayer, 2000), as well as its much longer cultural

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This article has been corrected with minor changes. These changes do not impact the academic content of the article.

connection and significance to First Nations people (Barrow, 2012; Bell, 1999; Jackson-Nakano, 2001).

During a recent multidisciplinary study, which focussed on Lake George's geomorphology/paleo-environments (Macphail et al., 2015, 2016), hydrogeochemistry (Short, 2017), and archaeology (Way, 2017, 2018), the modern water-level record of Lake George (*i.e.* post-1820) was compiled and referenced to the Australian Height Datum (AHD). These data have never been made publicly available in a compiled form, despite the public interest. This water-level record is of significance because it is very likely to be the longest continuous record of any lake in the Southern Hemisphere, and its fluctuations are closely tied to the prevailing climatic conditions of SE Australia.

In addition to presenting a compilation of the record of reconstructed and on-site water-level measurements, we present remotely sensed water observation data based on Landsat and Sentinel satellite imagery. These new data present a method for maintaining the water-level record in the absence of maintaining on-site measurement infrastructure at the lake.

Site description

Lake George is located in the Southern Tablelands of New South Wales (NSW), approximately 40 km northeast of Canberra (Figure 1). The generally accepted aboriginal language name for the lake is Weereewa (also recorded as Weereewaa in Governor Lachlan Macquarie's diary written in 1820; Barrow, 2012) but is also referred to as Ngungara by other First Nations elders (Barrow, 2012; Bell, 1999). There are two main townships close to the lake: Bungendore to the south, and Collector to the north, both of which have a population of less than 5000. The Federal Highway, which is the main arterial road connecting Canberra and Sydney, runs through Gearys Gap and along the western shore of the lake.

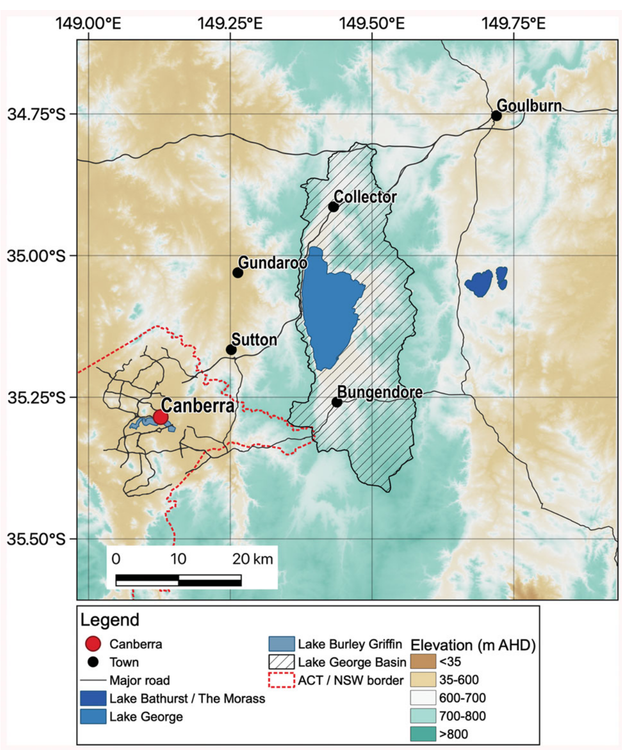

Figure 1. Site location map of Lake George.

Climate

All climate data presented in the following section are compiled from the daily patched-point data (combination of observations and interpolated data when no observations exist) for the period 1889 to 2019 at Bungendore Post Office (site 70011), downloaded from the SILO Australian climate data portal (Jeffrey *et al.*, 2001; Queensland Government, 2020).

The present-day climate around Lake George is temperate with warm summers (Figure 2a) with no distinct wet

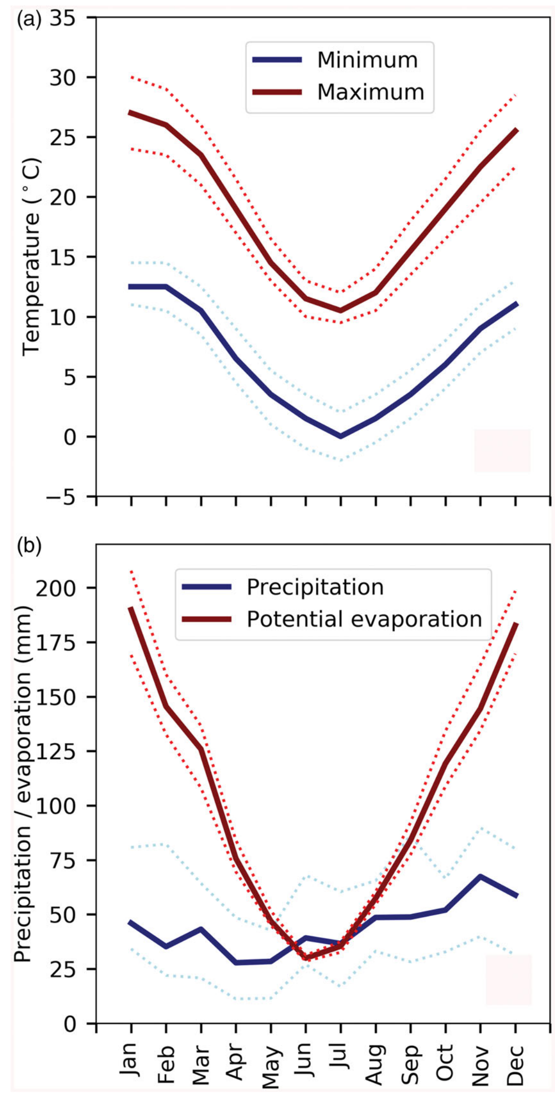

Figure 2. (a) Bungendore median daily maximum and minimum temperature, and (b) median monthly precipitation and evaporation. Upper and lower bounds of each curve represent the 75th and 25th percentiles, respectively.

season (Figure 2b)—denoted as Cfb by the Köppen climate classification (Peel *et al.*, 2007) and dry-subhumid according to the region's aridity index of 0.54 (*i.e.* the mean annual ratios of precipitation and potential evaporation; Middleton & Thomas, 1997). Median annual rainfall and potential evaporation for Lake George over the last 30-year period is 645 and 1257 mm, respectively.

Although precipitation is relatively uniformly distributed throughout the year (median of 28–67 mm month^{-1} with a large variance; Figure 2b), a large contrast in seasonal evaporation (Figure 2b) means that the present-day lake is mostly ephemeral, with surface water accumulating during the winter and early-spring months when evaporation rates are lower and runoff is higher, and then evaporating to dryness in the late-spring and summer months when evaporation rates are higher (Bowd, 2009; Jacobson & Schuett, 1979; Jacobson et al., 1991). Surface water in the lake is only sustained when above average rainfall has fallen in several consecutive months.

Paleodrainage

The formation of the Lake George Basin is estimated to have begun approximately 4 million years ago when the north–south-orientated Lake George fault activated as a reverse fault in response to the onset of the current compressive crustal stress regime in SE Australia (Clark *et al.*, 2017). This tectonic movement resulted in the formation of the Lake George Range, which currently rises approximately 120–220 m above the lakebed. Progressive uplift along the Lake George fault, and subsequent isolation of the drainage system from catchments to the west, is recorded by up to 165 m of Cenozoic lakebed sediments consisting of three formations (Abell, 1985), from oldest to youngest:

1. Deeply weathered fluvial sand and gravel in the basal formation (Gearys Gap Formation).
2. Fluvio-lacustrine sand, silt and clay layers in the central formation (Ondyong Point Formation).
3. Lacustrine silt and clay of the surficial formation (Bungendore Formation).

Prior to the uplift along the Lake George fault, it is postulated by Abell (1985), Ollier (1978) and Taylor (1907) that the four southernmost creek catchments (Allianoyonyiga, Taylors, Butmaroo and Turallo) joined into one main channel that flowed through the low saddle, Gearys Gap, on the western boundary into the Yass River catchment (Figure 3). The two main tributaries of the Collector Creek catchment, Currawang Creek and Willow Tree Creek, are postulated to have drained to the north-west into the Lachlan River catchment (Abell, 1985). This can be seen in their modern form by their abrupt southward bends as they join the main Collector Creek channel and flow towards the lake.

Paleo-environmental investigations of ancient shorelines and dating of sediment cores indicate that Lake George was likely to be a mega-lake with a depth of approximately 37 m between 30.3 and 25.4 thousand calibrated radiocarbon years BP (Coventry, 1976) (new ages calibrated following Reimer *et al.*, 2013, and Stuiver et al., 2020). This precedes the last glacial maximum when Galloway (1965) postulated that the lake would have received less precipitation with estimated temperatures up to 9°C cooler than present in the warmest month, and subsequently much lower evaporation rates (*e.g.* Figure 2). However, it was recently noted by De Deckker (2020) that dating of Lake George's paleo-environmental record needs to be better resolved before it can be linked with specific climatic periods during the Quaternary.

Regardless of timing, at a depth of 37 m, the towns of Bungendore and Collector would be inundated (Figure 4), and water would come close to spilling through Gearys Gap into the headwaters of the Yass River *via* what is now Brooks Creek (formerly Shingle House Creek; Figure 4). The water-level of Lake George has not come close to returning to these mega-lake levels in the last 200 years.

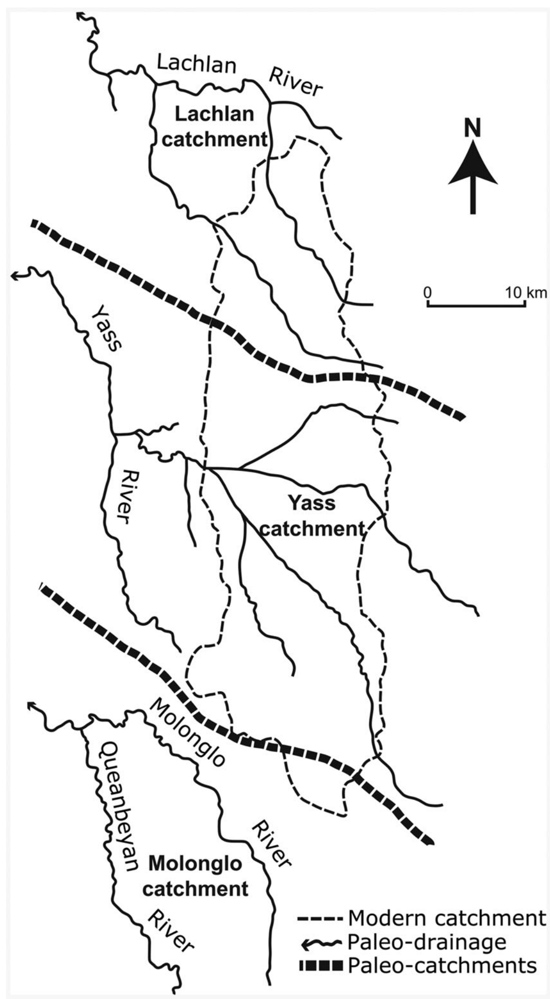

Figure 3. Paleodrainage system of the Lake George Basin's sub-catchments. Adapted from Abell (1985), Ollier (1978) and Taylor (1907).

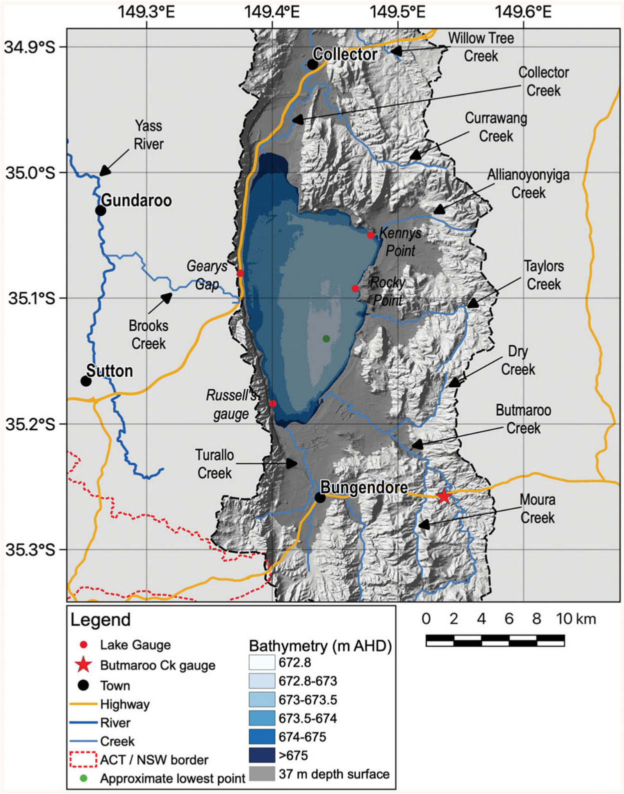

Figure 4. Lake George Basin hydrology and lake bathymetry.

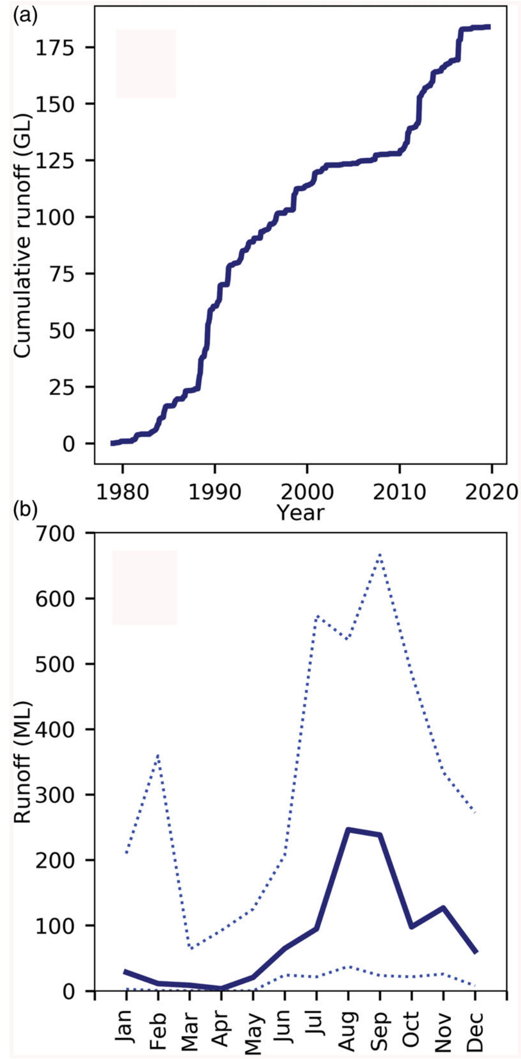

Figure 5. (a) Cumulative monthly runoff and (b) median total monthly runoff recorded at the Butmaroo Creek stream gauge. Bounding lines on (b) indicate 25th and 75th percentile total monthly discharge.

Modern hydrology

Lake George is the focus of drainage of five main sub-catchments of small surface water systems (Figure 4): Collector Creek to the north; Allianoyonyiga Creek to the northeast; Taylors Creek to the east; Butmaroo Creek to the southeast; and Turallo Creek to the south. The lake also receives minor runoff from drainage off the fault scarp. The lakebed of Lake George, which is approximately 10 km wide by 20 km long, occupies about 150 km^2 of the 940 km^2 basin. The lowest point on the lake is on the eastern side, to the southwest of Rocky Point (Figure 4).

All of the creeks in the Lake George Basin are ephemeral, only sustaining flow into the lake during wetter periods. Butmaroo Creek is the only creek that has been gauged by the NSW Government, from 1979 until the present. The gauge (ID: 411003) is located at the Kings Highway crossing (Figure 4).

Two other small tributaries, Moura Creek and Dry Creek, join with Butmaroo Creek downstream of the gauge (*i.e.* between the gauge and the outlet to Lake George; Figure 4). Thus, the gauge does not account for all of Butmaroo Creek's runoff into Lake George. However, the pattern of runoff recorded at the gauge (Figure 5a) gives a good indication of the general pattern of runoff into Lake George for the last four decades.

The median monthly discharge (Figure 5b) indicates that Butmaroo Creek runoff systematically increases over the winter months to a maximum in August and September. This is in contrast to median monthly rainfall, which has no distinct pattern, and is likely explained by low evaporation rates during winter allowing for soils and creeks to become more saturated and runoff to be sustained.

The five-year period of greatest cumulative runoff for Butmaroo Creek, and presumably the entire catchment, was April 1988 to March 1993. Over this time, a total of 61 GL of runoff was recorded at the stream gauge and also corresponds to the last time Lake George had a water depth greater than 2 m.

The bathymetry of Lake George is quite flat with small changes in water-level resulting in relatively large changes in lake surface area at low water levels (*i.e.* <1.5 m). This feature is illustrated in Figure 6, in which the relationships between lake depth/elevation, surface area and volume are plotted. This feature is why the application of satellite imagery was investigated as a tool for monitoring low water levels.

The data in Figure 6 were generated by analysing the 1 m digital elevation model (DEM) of the lakebed (Geoscience

Australia, 2015) using the 3D Analyst extension in ArcMap (version 10.6.1; Esri, Redlands, USA).

Historic water levels

Lake George water-level observation records date back to 1820 (Russell, 1886) after European settlers first encountered it in August 1820. At that time, the lake was a 'noble expanse of water', as described by Governor Lachlan Macquarie (Barrow, 2012) and it was recorded in a watercolour picture by the convict artist, Joseph Lycett, in 1820. The picture was later reproduced as an aquatint etching, published after Lycett had returned to England in 1822 (Lycett, 1824, Plate 19; Figure 7). Both the watercolour and the aquatint are available at the National Library of Australia.

The water levels were not originally measured in any organised way but were instead reconstructed from local pastoralists' and settlers' notes of flooding extents, which were compiled by Henry Chamberlain Russell, NSW Government Astronomer, in his 1886 paper presented to the Royal Society of New South Wales (Russell, 1886). Since 1885, water levels have been directly, and almost continuously, measured by a series of Federal or State Government agencies, and more recently by the power and water company of the Australian Capital Territory (*i.e.* ACTEW and Icon Water). Table 1 and the following sections present a summary of the institution or individuals that recorded water levels and for what period.

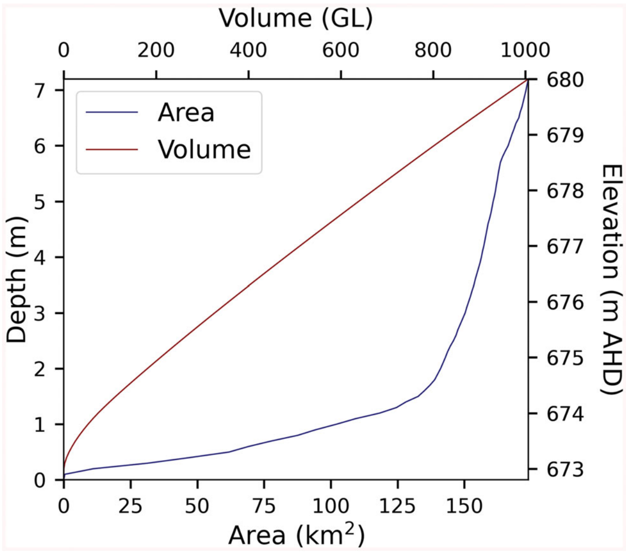

Figure 6. Lake George depth/elevation, surface area and volume relationships.

Henry Chamberlain Russell: 1820–1886

Henry Russell, NSW Government astronomer and meteorologist, made the following observation on the value of Lake George as a unique environment for scientific investigation in his 1877 text on the climate of NSW (Russell, 1877, p. 182):

> *… the history of Lake George is instructive, situated as it is in the mountains, with a well-defined catchment area, and no outlet. It forms a sort of rain-*gauge, *and should afford valuable information.*

Figure 7. Earliest recorded depiction of Lake George: an 1824 aquatint etching, based on an 1820 watercolour painting by convict artist, Joseph Lycett. Source: National Library of Australia (https://trove.nla.gov.au/version/262272810).

Table 1. Summary of institutions and individuals, and time periods of water-level monitoring.

Years	Monitoring institution or individual
1820–1886	Reconstructed by H.C. Russell
1886–1951	Department of Works and Local Government, and Water Conservation and Irrigation Commission of NSW
1951–1992	Bureau of Mineral Resources, Geology and Geophysics
1992–1998	Australian Geological Survey Organisation
1998–1999	Bureau of Rural Sciences
1999–2006	No on-site measurements
2006–2015	Icon Water (formerly ACTEW)
2013–2017	Research School of Earth Sciences, ANU
1987–2019	Satellite imagery (this study)

His 1886 presidential address, and subsequent paper (Russell, 1886), to the Royal Society of NSW was the first time the water-level records of Lake George had been compiled and presented to the public. In his study, anecdotal accounts of flood levels, observed rainfall records and detailed elevation surveying around the lake were used to reconstruct the lake level from the first settler encounter in 1820 until he installed his own datum and gauge in 1885 (Barrow, 2012), located on the southwestern shore of the lake (approximately 35.184°S, 149.400°E; Figure 4). Russell also attempted to reconstruct 1816–1820 water levels based on records of flooding in the nearby Hawkesbury River, but are speculative, albeit likely to somewhat resemble reality, and are not presented here.

The water levels presented by Russell (1886) include the three highest peaks in the lake's record: 1823 (7.3 m), 1864 (5.2 m) and 1874 (7.3 m). The two higher periods were depicted in popular artistic interpretations of the lake from *circa* 1820 (Figure 7) and 1886 (Figure 8), either side of the drier period during the middle of the nineteenth century.

The levels in Figure 9 have been digitised from Russell (1886), converted to metres, and referenced to AHD based on Russell's datum (672.879 m AHD). It is unknown how accurate these measurements are but is likely to be on the order of up to a metre, and probably even more uncertain for the earlier periods that are based on anecdotal accounts.

Figure 8. Hand-coloured engraving of a depiction of the southwestern shore of Lake George, illustrated by William Macleod (*ca* 1886). Scanned image from the private collection of Patrick De Deckker. Original appeared in multiple editions of Garran (1886).

NSW Government: 1886–1949

Noakes (1962) stated that no official records were kept of lake levels for the period 1928–1950, with measurements between 1886 and 1928 collected by the NSW Department of Works and Local Government, and measurements collected by the Bureau of Mineral Resources (BMR) from late 1950. However, an Australian Bureau of Transport Economics (BTE) report from 1979 provides annual lake levels (given as the lake level in December each year) for this entire period (*i.e.* 1886–1949) (Bureau of Transport Economics, 1979, pp. 63–65). The BTE report states, *'[s]ome uncertainty on datum for lake levels has existed in the past but this has been resolved following work by DMR* [*NSW Department of Main Roads*]*'* (Bureau of Transport Economics, 1979, p. 60). This statement indicates that the BTE data have undergone a reassessment and correction prior to the Noakes (1962) publication.

Additionally, a graphical water storage record for Lake George for this period (Figure 10) was produced by the NSW Water Conservation and Irrigation Commission (WC&IC). A copy of the original WC&IC report was obtained from the National Capital Development Commission (NCDC), Canberra, in 1965, during rainfall and hydrological investigations of Lake George (pers. com. C. Speldewinde, NCDC, to R. Usback, 1965). Lake levels estimated from the graphical storage record (converted using the relationship in Figure 6) broadly match the BTE record. However, the WC&IC data appear offset backwards slightly in time when compared with the Bungendore Post Office rainfall record (*i.e.* the lake-level increases before the onset of rain), whereas the BTE data are synchronous. Thus, the BTE data are adopted as the more accurate water levels for the period 1886–1949. These data fill a gap in Lake George's water-level record that is present in all previous publications.

The water levels observed at Lake George between 1886 and 1949 are characterised by a much drier period (Figure 11). Elevated water levels were experienced briefly in the mid-1890s, and to a lesser extent in the late 1910s and mid-1920s. However, by the end of the 1920s, the lake had receded and was only seasonally inundated until the late 1940s when increased rainfall began to flood the lake by the

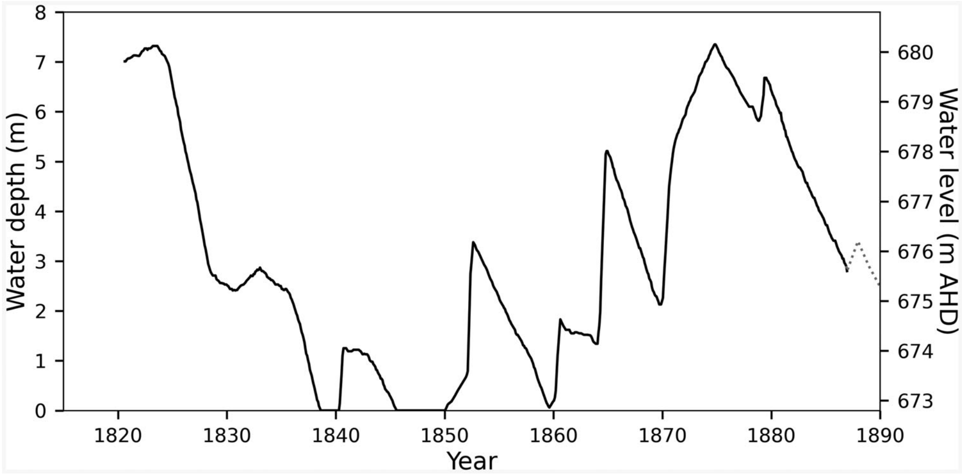

Figure 9. Early Lake George water levels reconstructed by H. C. Russell from 1818 through 1886. Grey line shows succeeding data.

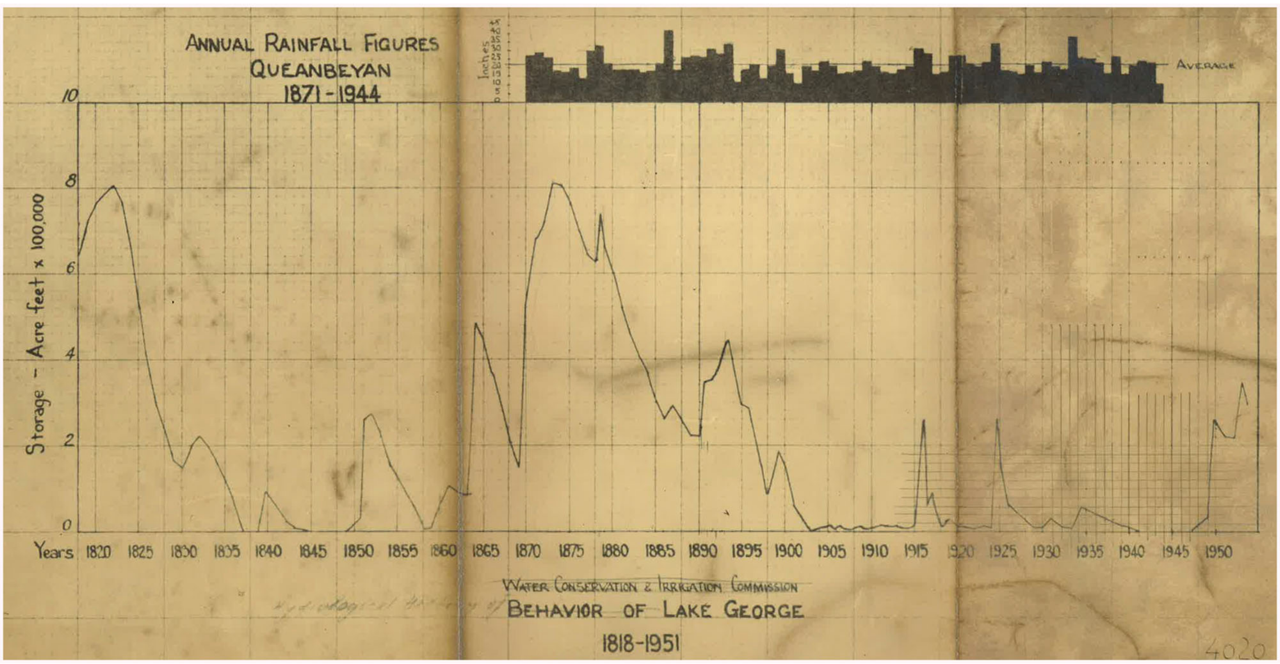

Figure 10. NSW Water Conservation & Irrigation Commission water storage records for Lake George, sourced from National Capital Development Commission research papers (*ca* 1965).

beginning of the 1950s. Confirmation of the dry period at the beginning of the 1940s is given by a series of aerial photographs taken in October 1941, which show a dry lakebed on both the eastern and western shores (Figure 12).

The lack of documentation of the measurements or a description of methods for the period of 1886–1949, make it impossible to give any indication of the uncertainty of the values but it is likely to be on a similar order, if not better, to the later measurements of H.C. Russell—that is, roughly 0.5–1.0 m.

Australian Government agencies: 1950–1999

Between 1950 and 1999, Australian Government agencies measured water levels at Lake George at an approximately monthly frequency from three gauges located at Rocky Point (35.093°S, 149.466°E), Kennys Point (35.050°S, 149.478°E) and Gearys Gap (35.080°S, 149.375°E) (Figure 4). Between 1950 and 1998, the various precursors of what is now Geoscience Australia (GA) (*i.e.* Bureau of Mineral Resources, Geology and Geophysics [BMR], and the Australian Geological Survey Organisation [AGSO]) collected the lake-level measurements. For the final two years, measurements were collected by the Bureau of Rural Sciences (BRS), which is now incorporated into Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES).

The first seven years of data were digitised from Jennings *et al.* (1964), with the remaining data sourced from archived field log books held at GA. The accuracy of

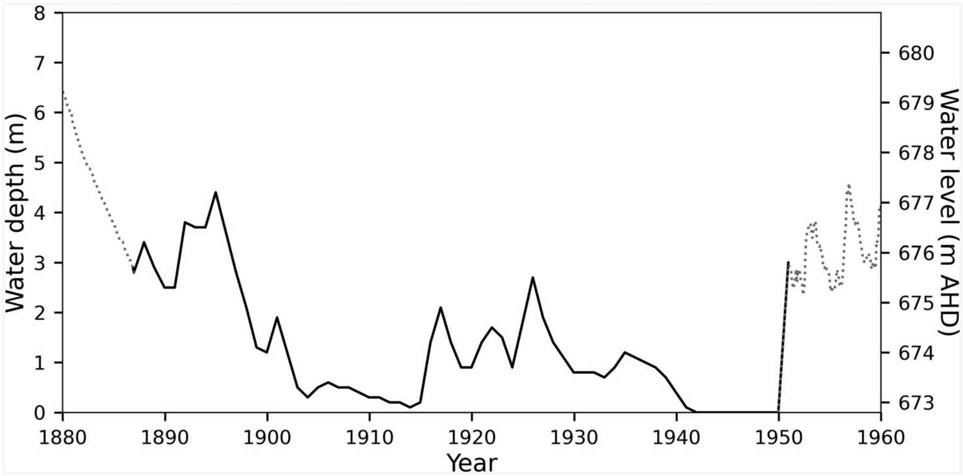

Figure 11. Lake George water levels collected by the NSW Department of Works and Local Government (1886–1928), and Water Conservation and Irrigation Commission (1928–1951). Grey lines show preceding and succeeding data.

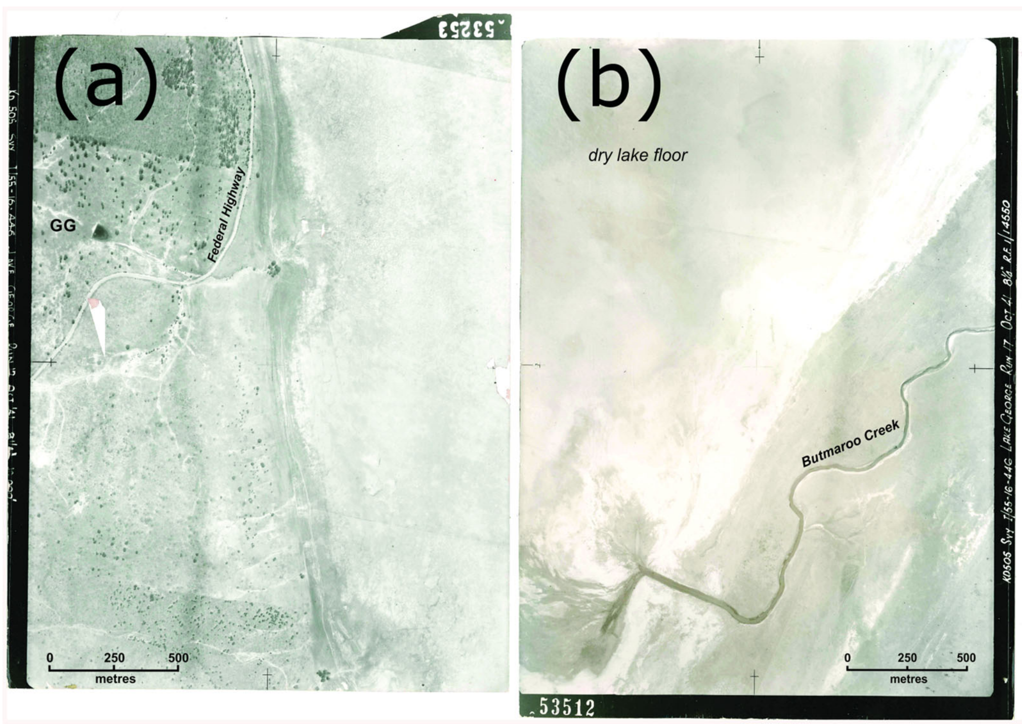

Figure 12. Aerial images of Lake George showing the western shore (left), where the old Federal Highway passes through Gearys Gap (GG), and southeastern shore (right), where Butmaroo Creek discharges to Lake George. Images taken in October 1941. Source: Geoscience Australia.

the measurements collected by the Australian Government agencies is estimated to be better than 0.5 m.

The water-level measurements collected during the period of measurement by Australian Government agencies show that Lake George fluctuated between approximately 2 and 4 m (Figure 13). Surface water was persistent enough during the 1950s and 1960s that the Canberra Yacht Club held sailing regattas (Figure 14) and water skiing was common (Figure 15). There were, however, two brief periods (*i.e.* less than a year each) in the 1980s when the lake was dry. After the final flooding event in the very late 1980s, the lake had been receding until the final measurements by BRS in April 1999.

From November 1960, electrical conductivity (EC) and temperature were also collected with most water-level measurements; pH was measured regularly from December 1988 (Figure 16). Lake salinity has been estimated by conversion of EC measurements based on the following formula:

$$S = 0.7677 \times EC^{0.9846} \quad (1)$$

where S is salinity [‰ as total dissolved solids (TDS)] and EC of the lake water is in the units of mS/cm.

Formula (1) was derived by compiling recent chemical analyses for the period 2013–2015 (Short, 2017) and historic data (Burton & Wilson, 1973; Jacobson & Schuett,

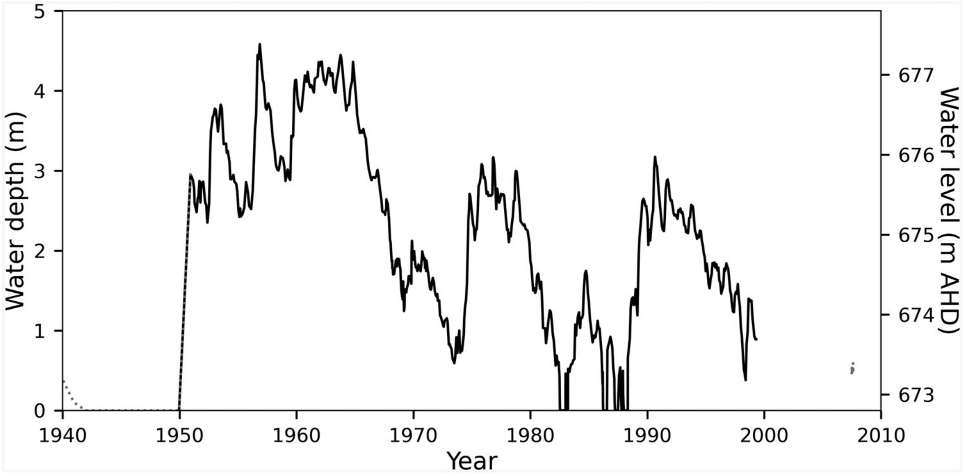

Figure 13. Lake George water levels collected by Australian Government agencies from 1951 through 1999. Grey lines show preceding and succeeding data.

Figure 14. Black and white photograph of Lake George taken on 30 September 1961 at the opening season regatta of the Canberra Yacht Club. Image courtesy of Peter Forster, Canberra Yacht Club.

1979; Jacobson et al., 1991). A total of 24 lake water samples were used with an EC range of 1.3–54 mS/cm, which covers most of the range of EC measured for the period 1960–1999 (*i.e.* 0.6–85 mS/cm).

These water quality data show that the lake is fresh to brackish (<1.0–10‰) when it fills but the salinity increases exponentially (note the logarithmic y-axis for salinity in Figure 16) as it recedes and becomes as saline as seawater (*i.e.* 35‰) and occasionally up to almost twice the salinity of seawater. The highest measurement was 61‰ recorded in August 1985 when the lake was 1.07 m deep.

The final decade of measurements during this period, when both EC and pH were measured, coincided with the lake receding from a wet period in the late 1980s. During

Figure 15. Power boats and water skiing on Lake George in the summer of 1964/1965. Photograph courtesy of Bradley Pillans.

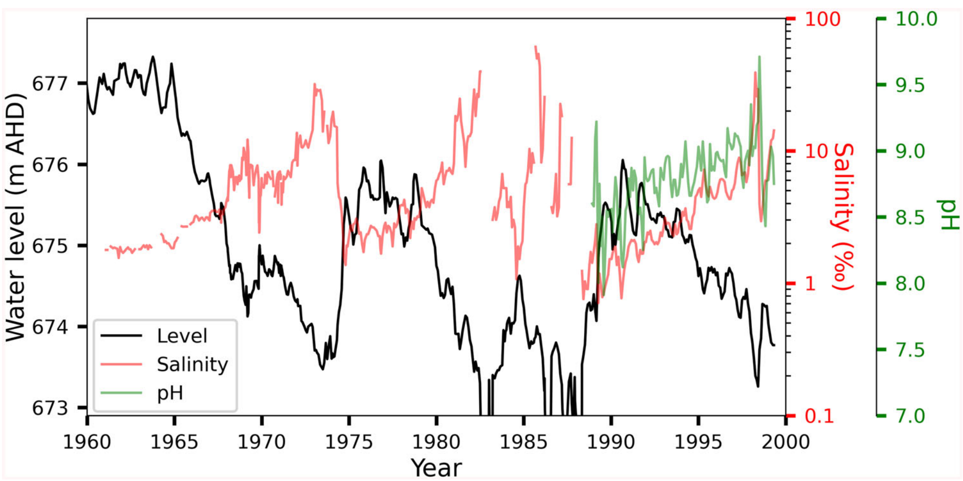

Figure 16. Lake George water levels and water quality measured by Australian Government agencies.

this recession phase (1990–1999), both pH and salinity increase as the water-level declines. The overall pH of Lake George for the period 1988–1999 is high, with a range of 7.9–9.7, which is comparable with the pH recorded by Short (2017) of 8.8–9.9.

ACTEW/Icon Water: 2006–2015

On-site water-level measurements at Lake George did not begin again after April 1999 until early 2006 when Icon Water (formerly the ACT Electricity and Water Corporation [ACTEW]) collected water-level measurements from a pressure sensor located on the lakebed at the base of Rocky Point (35.092°S, 149.465°E). The lowest water-level measurement possible (*i.e.* the level below which only atmospheric pressure was measured) for the sensor was 673.25 m AHD. Although the Icon Water measurements continued until mid-2015, only data up to 2013 are included. This is because the subsequent measurements by the ANU, beginning in 2013, were able to measure slightly lower water levels, as well as simultaneous EC and temperature measurements.

The hydrograph for this period (Figure 17) indicates the lake level was either very low (*i.e.* less than the 673.25 m AHD detection limit) or dry for the majority of the time. The highest recorded water-level for the period 2006–2013 was in August 2012 at a depth of 1.25 m. This was towards the end of a period of relatively high water levels for the entirety of 2012 where water levels were consistently at about 1 m. Only three other periods of inundation were recorded during this period: briefly in mid-2007, 2010–2011 and in mid-2013.

The Australian National University: 2013–2017

The most recent on-site water-level monitoring undertaken at Lake George formed part of a multidisciplinary study by researchers and students at the Research School of Earth Sciences, ANU. In August 2013, a combined pressure, conductivity and temperature sensor (CTD-Diver; van Essen Instruments B.V., the Netherlands) was installed on the lakebed (35.089°S, 149.462°E) and began collecting hourly measurements. The sensor was located about 400 m northwest of the ACTEW/Icon Water sensor at Rocky Point. The water-level measurements were corrected using a separate barometric pressure transducer (Baro Diver; van Essen Instruments B.V., the Netherlands), located onshore at Rocky Point. The lowest water-level measurement possible at the ANU sensor was 673.18 m AHD.

During the period 2013–2017, the lake level was still either very low or dry (Figure 18). Only towards the end of the monitoring period, in October 2016, did the lake begin to fill up to a depth of almost 1.6 m. This was the most water seen in Lake George since the wet period during the late 1980s/early 1990s. No more measurements were available after February 2017 because of instrument malfunction.

In January 2014, a shallow piezometer (nicknamed 'Russells bore') was installed next to the surface water sensor site at Rocky Point during a period when the lakebed was completely dry (see Figure 19). The piezometer was constructed of 50 mm-diameter PVC pipe installed to a depth of approximately 1.4 m below the lakebed in a hand-augered hole. The annulus space was then backfilled with washed 2–5 mm silica gravel to 10 cm above the inlet, followed by lakebed sediment and topped with bentonite powder to the surface. An extension piece of PVC was later added (see Figure 20) when the lake surface started to become inundated again.

Lakebed porewater was able to enter Russells bore through hand-cut slots at the deepest 10 cm of the pipe. Another CTD-Diver was installed in Russells bore in February 2014 and began collecting hourly measurements.

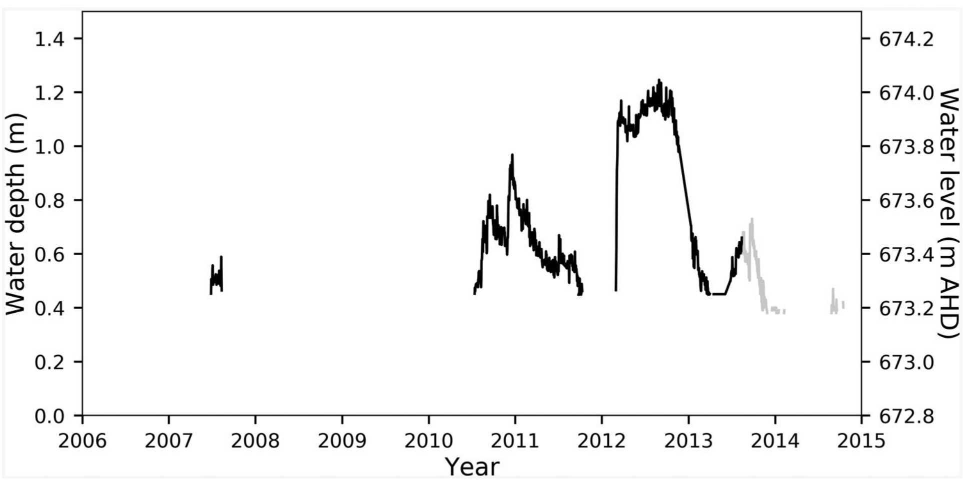

Figure 17. Lake George water levels collected by Icon Water (formerly ACTEW) from 2006 through 2013. Grey line shows succeeding data.

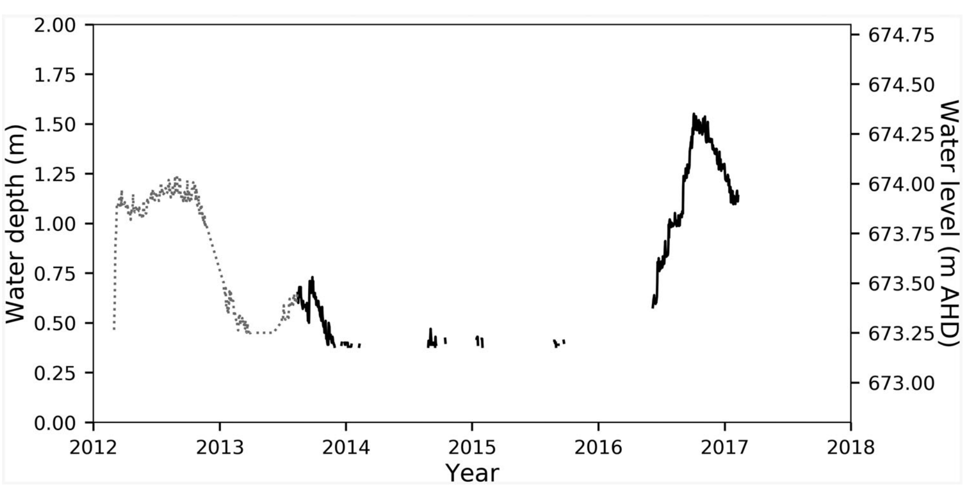

Figure 18. Lake George water levels collected by researchers of the ANU from 2013 through 2015. Grey line shows preceding data.

Figure 19. Dust cloud and grazing sheep on the dry eastern shore of Lake George, with the Capital Wind Farm turbines in the background. Photograph taken in January 2014 from Rocky Point (looking south towards the mouth of Taylors Creek). Photograph courtesy of Michael Short.

The lowest porewater-level measurement possible by the sensor in Russells bore was 671.97 m AHD, approximately 1 m below the lakebed at that location. No water-level measurements were collected from Russells bore after late 2015 because of levels lower than the bottom of the sensor and a subsequent instrument malfunction.

The shallow porewater levels measured in Russells bore (Figure 21) are quite reactive to rainfall events of >15 mm/day, increasing by approximately 60 cm over only a few days. This is likely to have been facilitated by the large cracks that rapidly form on the clay-rich lakebed once the lake becomes dry.

The measurements from Russells bore also indicate that the porewater salinity is much more stable than that of the surface water. Over the one and a half years of measurements, the salinity of Russells bore had a relatively small range of 32–41‰, compared with the range of 0.5–61‰ for surface water during the period 1960–1999 (Figure 16). Historical data (Jacobson *et al.*, 1991) indicate that 30–40‰ is the typical porewater salinity found between the lake surface and a depth of approximately 10–15 m, below which point the salinity decreases approximately linearly by diffusion to 10–15‰ at a depth of 80 m.

Satellite-derived water observations

Despite the interest from local residents and scientists alike, at the time of publication (late 2020), the measurement of water levels at Lake George is not linked to any current projects that have the funding to maintain on-site measurement infrastructure and continue this unique water-level record.

Fortunately, GA has made large amounts of the Landsat and Sentinel satellite imagery archives for Australia open to the public, along with several derived Earth observation products. These products include temporal observations of all surface water bodies across Australia. The unique, flat bathymetry of Lake George means that it is likely to be a good candidate for applying satellite imagery methods to estimate lake water levels. At low water levels (typical for the current climate of the area), minor changes in water-level result in relatively large changes in lake surface area. Therefore, the resolution of Landsat (approximately 900 m^2 pixels) and Sentinel (approximately 100 m^2 pixels) data will be sensitive to small water-level fluctuations.

Water Observations from Space

One recently developed technique for remotely sensed open water identification is the Water Observations from Space (WOfS) product from GA. WOfS is a decision tree classifier algorithm that groups Landsat 5, 7 and 8 pixels into a number of descriptive classes, such as, water observed, cloud, shadows, high slope and sea (Mueller *et al.*, 2016). GA make available WOfS classifications for individual Landsat satellite passes or summary products, which aggregate observations

Figure 20. Bear McPhail (left) removing the cap of Russells bore with Bradley Opdyke (right) in November 2015. The housing of the surface water logger is located in the pipe to the left of Russells bore. Rocky Point can be seen in the background. Photograph courtesy of Bradley Pillans.

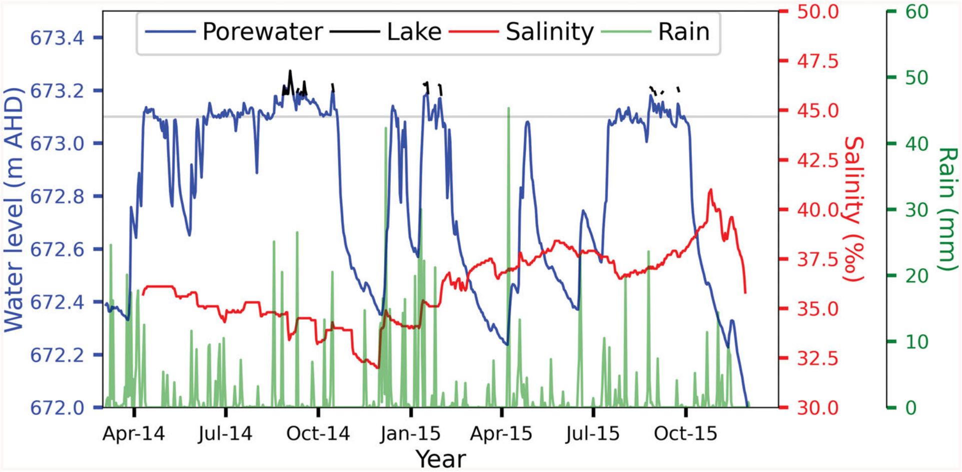

Figure 21. Porewater level and salinity recorded in Russells bore for the period of April 2014 to December 2015, plotted with lake levels and daily rainfall. Grey horizontal line indicates the ground surface.

over seasons and years. A summary of water observations for the period 1987–2018 is presented in Figure 22.

The filtered product includes only observations with a > 10% confidence for the presence of surface water. However, we found that there was very little difference between the filtered and non-filtered products for Lake George. The pattern of the WOfS data closely matches that of the bathymetry of Lake George (Figure 4) and indicates that only a small proportion of the lake's total extent (as typically indicated on maps) has been covered in water for more than 50% of observations over the past three decades.

Time-series water indices

In addition to the WOfS classifications, five satellite-derived water index methods were applied and compared: the tasselled cap wetness index (TCW; Crist, 1985); the normalised difference water index (NDWI; McFeeters, 1996); the modified NDWI (MNDWI; Xu, 2006); the automated water extraction index ($AWEI_{sh}$ and $AWEI_{ns}$ for with and without shadows, respectively; Feyisa *et al.*, 2014); and the water index (WI; Fisher *et al.*, 2016).

To implement each of the index methods, a query was performed on the Open Data Cube (ODC; Open Data Cube, 2020) Landsat and Sentinel archive in combination with Python scripts from the Digital Earth Australia Notebooks repository (Geoscience Australia, 2020). Between September 1987 and November 2019, 278 images (227 Landsat and 51 Sentinel) were produced covering the entirety of Lake George, consisting of pixels with a $<10\%$ cloud coverage (*i.e.* $>90\%$ clear pixels).

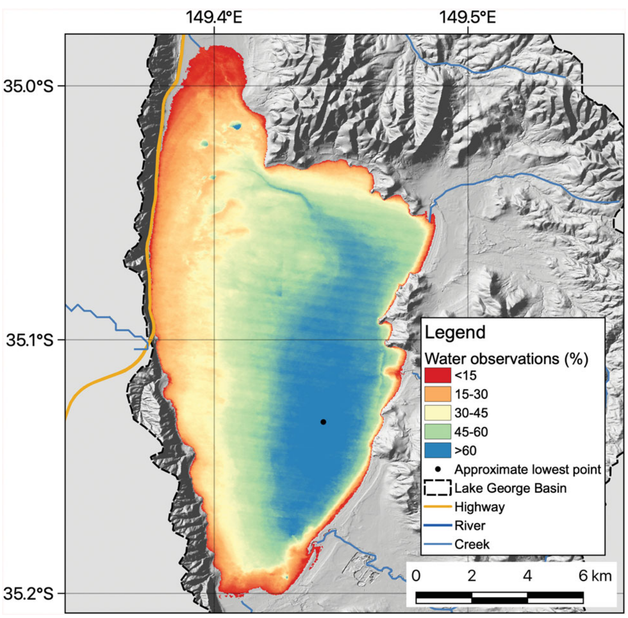

Figure 22. Lake George Water Observations from Space (WOfS) percentages for the period 1987–2018.

Each of the 278 satellite passes were converted to images with red, green and blue (RGB) bands, and all of the above calculated water indices. Several of these passes were then inspected at different lake levels to manually calibrate the open-water threshold for each index (*i.e.* the value above which open water is classified as present) based on the true-colour (RGB) extent of the lake's surface area. The open-water thresholds for each of the indices are presented in Table 2 (note that open water is identified by WOfS as a classification method not a value threshold).

The inundated area estimates determined by the indices were converted into water levels based on the relationship presented in Figure 6. It was found to be more accurate to perform this conversion by using the linear regression between each 10 cm interval in the water-level range 0–4 m (672.8–676.8 m AHD), instead of attempting to fit the entire intricate curve to a complex polynomial (or other) regression.

After conversion to water levels, all of the wetness indices performed satisfactorily in estimating the measured water levels (typically <0.5 m from the measured value). The estimated water levels calculated using the indices were compared with the value of the measured water-level. The dates of the indices and the water-level measurements rarely coincided (especially prior to 2007 before data logging sensors were used), which made it difficult to determine commonly used comparative statistics directly.

By visual inspection of the matches (Figure 23), the WOfS and NDWI were the worst performing while the

Table 2. Open-water thresholds used to identify the surface area of Lake George.

Water index	Open-water threshold
TCW	0.03
NDWI	−0.20
$AWEI_{sh}$	0.05
$AWEI_{ns}$	0.15
MNDWI	0.60
WI	3.00

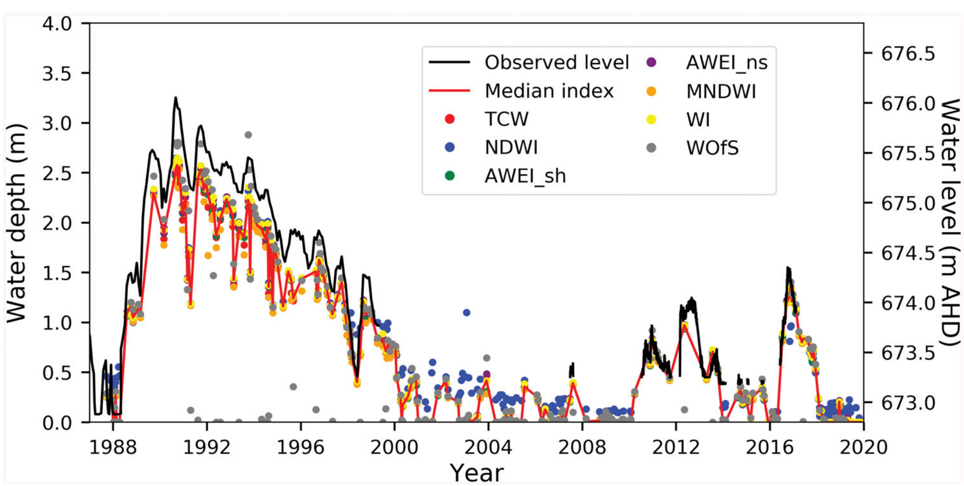

Figure 23. Estimated Lake George water levels from satellite imagery compared with measured water levels. Index abbreviations explained in text.

others were all comparable. The WOfS estimates produced several false-negatives (*i.e.* underestimates of open water) and the NDWI produced several false-positives (*i.e.* overestimates of open water). At higher water levels, all of the indices consistently underestimate the surface area of the lake. During the process of visual calibration of the open-water thresholds, this was found to be an effect largely attributable to cloud cover over the water—larger open-water areas are more likely to be affected by the 10% allowance of cloud cover than smaller ones, which leads to an underestimate.

Table 3. Summary of goodness-of-fit statistics for the water index estimates compared with the observed water levels.

Water index	R^2	RSS	Average error (cm)	Median error (cm)
TCW	0.94	12	−33	−34
NDWI	0.92	10	−25	−27
$AWEI_{sh}$	0.95	11	−33	−33
$AWEI_{ns}$	0.94	10	−31	−31
MNDWI	0.94	13	−36	−35
WI	0.94	10	−30	−29
WOfS	0.51	41	−52	−29

An allowance of seven days was used to determine coincident timesteps. Out of the 278 satellite images of Lake George for 1987–2019, only 65 (55 for WOfS) were within a week of a water-level measurement. The range of water levels for those 65 covers the full range of observations for that period (*i.e.* 0.08–3.25 m). Four classical comparative statistics were then applied to broadly summarise

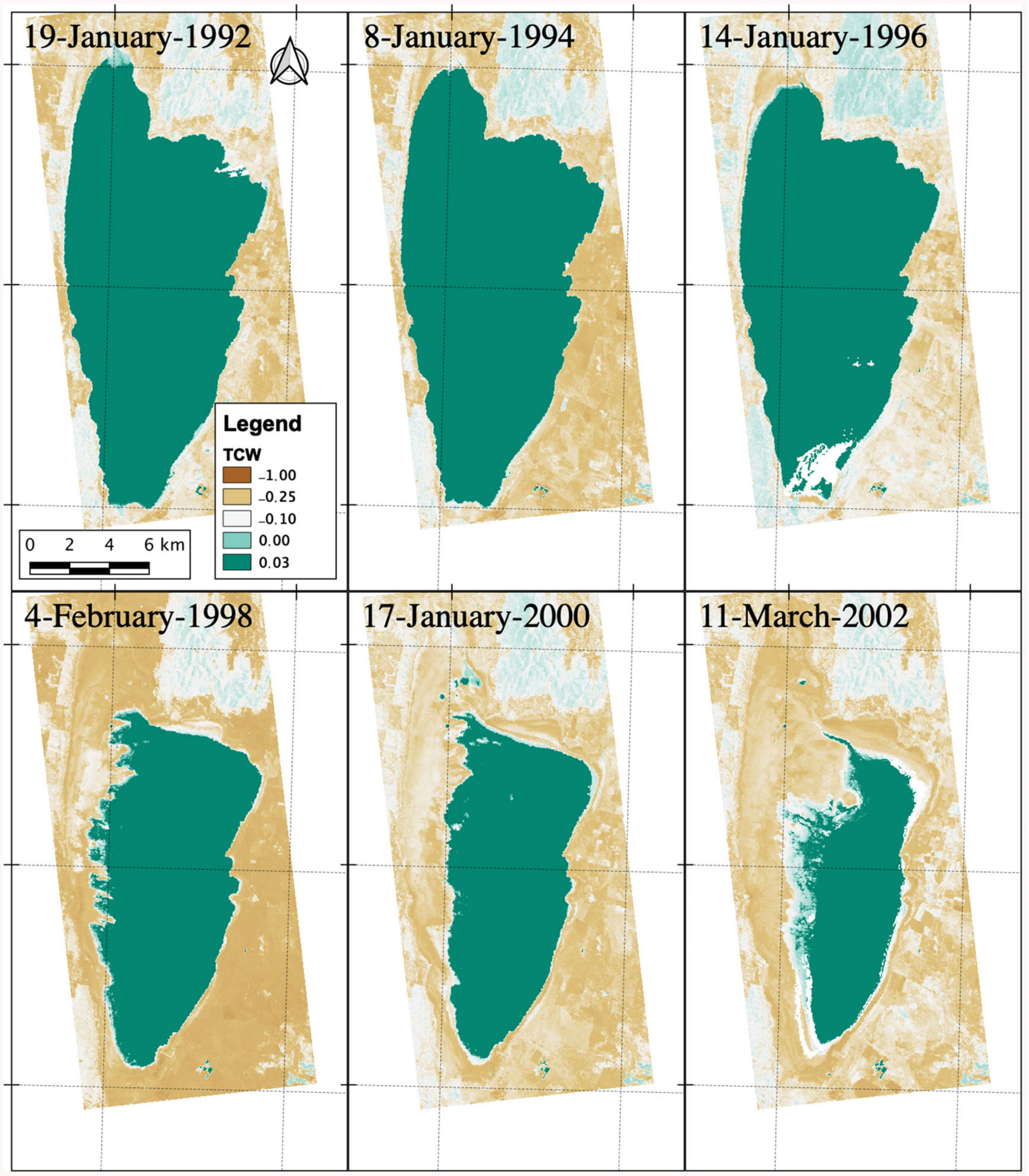

Figure 24. A sequence of Landsat imagery for Lake George showing the tasselled cap wetness (TCW) index values during a recession from flooding in the early 1990s to near dryness in the early 2000s.

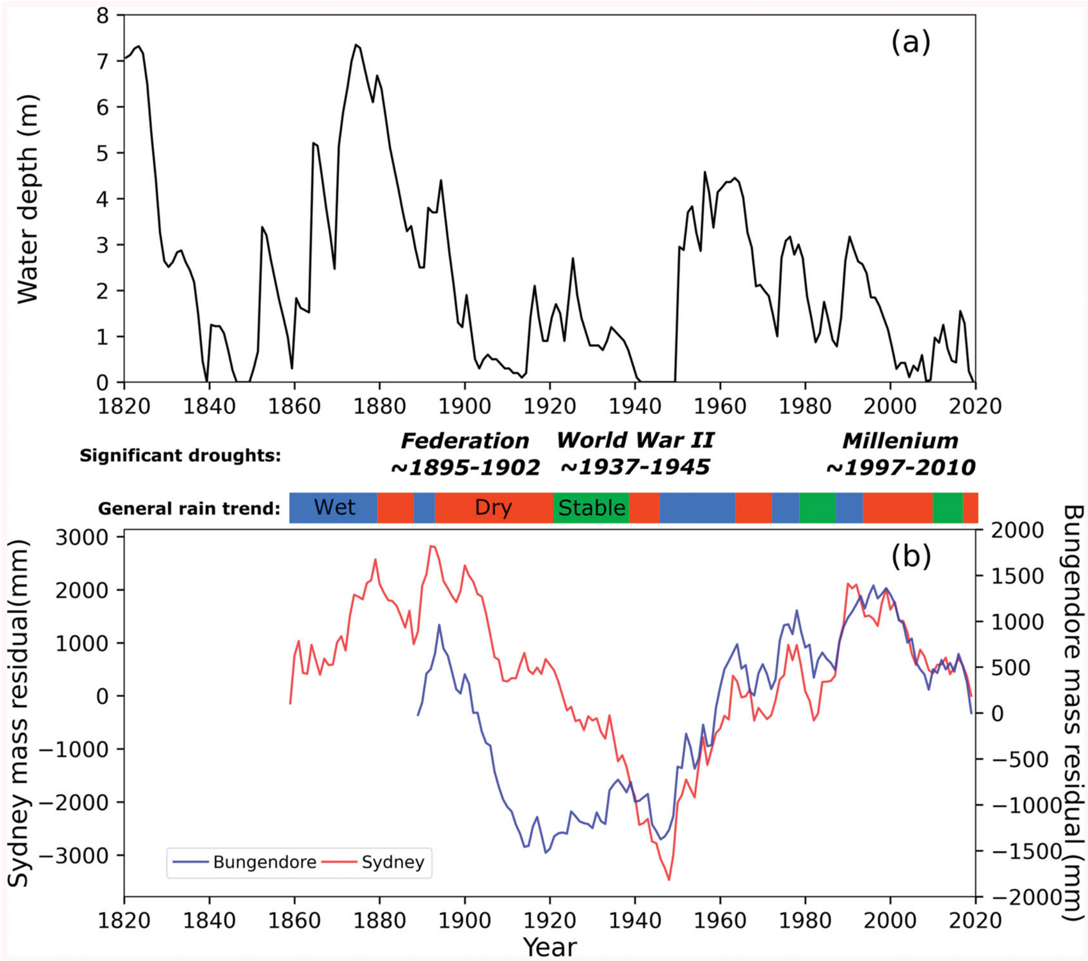

Figure 25. (a) Annual maximum Lake George water levels and (b) annual rainfall cumulative mass residual curves for Bungendore and Sydney Observation Hill.

how well each index estimated the observed water-level. These statistics were the R^2 value of an ordinary least-squares regression, the residual sum of squares (RSS), the average error and median error of near-coincident observations (Table 3).

The WOfS and NDWI estimates were discarded owing to their obvious false-negatives and false-positives, respectively, and a median of the remaining indices was used for the satellite imagery estimate because they all performed more or less the same. The comparison plot (Figure 23) shows that the median of index estimates are in good agreement with the observations—this is despite the numerous potential sources of error such as conversion of the bathymetry DEM into the area-depth relationship, error in the water-level measurements, and visual determination of open-water thresholds (among many others). This method of water-level estimation is very promising for ensuring that the hydrographic record of Lake George can be maintained. In fact, it has provided coverage for a period where no levels were recorded (1999–2006), albeit confirming that the lake level was very low and seasonally dry.

As an example of the output produced by the WI analysis, several images of the TCW imagery are shown in Figure 24 of the recession of Lake George from flooding in 1992, to near dryness in 2002.

The rain gauge of southeastern Australia

The annual maximum levels of the complete record for Lake George between 1820 and 2019 is shown in Figure 25 and the annual maximum levels are tabulated in Table 4 (note that this plot does not show seasonal drying). The levels experienced at the lake over the last two decades are some of the lowest in the record.

The relationship of Lake George's water-level fluctuations and the drought/flood conditions of SE Australia is shown by plotting the hydrograph (Figure 25a) with the cumulative mass residual curves of monthly rainfall at Bungendore and Sydney Observatory Hill (Bureau of Meteorology site 066062) (Figure 25b). Cumulative mass residual curves provide an indication of medium- and long-term trends: positive slopes indicate periods of above average rainfall, and *vice versa* for negative slopes.

Table 4. Annual maximum water depths (m above lakebed) recorded at Lake George for the period 1820–2019.

Year	Depth (m)	Year	Depth (m)	Year	Depth (m)	Year	Depth (m)	Year	Depth (m)
1820	7.07	1860	1.83	1900	1.90	1940	0.10	1980	1.87
1821	7.13	1861	1.62	1901	1.20	1941	Dry	1981	1.40
1822	7.27	1862	1.57	1902	0.50	1942	Dry	1982	0.87
1823	7.32	1863	1.52	1903	0.30	1943	Dry	1983	1.07
1824	7.16	1864	5.21	1904	0.50	1944	Dry	1984	1.75
1825	6.49	1865	5.15	1905	0.60	1945	Dry	1985	1.36
1826	5.38	1866	4.50	1906	0.50	1946	Dry	1986	0.92
1827	4.43	1867	3.81	1907	0.50	1947	Dry	1987	0.78
1828	3.25	1868	3.20	1908	0.40	1948	Dry	1988	1.41
1829	2.64	1869	2.47	1909	0.30	1949	Dry	1989	2.65
1830	2.51	1870	5.15	1910	0.30	1950	2.95	1990	3.17
1831	2.62	1871	5.88	1911	0.20	1951	2.88	1991	2.89
1832	2.83	1872	6.40	1912	0.20	1952	3.70	1992	2.63
1833	2.87	1873	7.00	1913	0.10	1953	3.83	1993	2.57
1834	2.62	1874	7.35	1914	0.20	1954	3.25	1994	2.37
1835	2.44	1875	7.28	1915	1.40	1955	2.86	1995	1.85
1836	2.18	1876	6.86	1916	2.10	1956	4.58	1996	1.84
1837	1.45	1877	6.45	1917	1.40	1957	4.13	1997	1.66
1838	0.46	1878	6.10	1918	0.90	1958	3.37	1998	1.40
1839	Dry	1879	6.68	1919	0.90	1959	4.14	1999	1.15
1840	1.25	1880	6.40	1920	1.40	1960	4.24	2000	0.74
1841	1.22	1881	5.78	1921	1.70	1961	4.36	2001	0.29
1842	1.22	1882	5.12	1922	1.50	1962	4.36	2002	0.42
1843	1.07	1883	4.66	1923	0.90	1963	4.45	2003	0.42
1844	0.70	1884	4.21	1924	1.80	1964	4.36	2004	0.11
1845	0.27	1885	3.72	1925	2.70	1965	4.02	2005	0.36
1846	Dry	1886	3.29	1926	1.90	1966	3.26	2006	0.25
1847	Dry	1887	3.40	1927	1.40	1967	2.94	2007	0.59
1848	Dry	1888	2.90	1928	1.10	1968	2.09	2008	0.02
1849	Dry	1889	2.50	1929	0.80	1969	2.12	2009	0.05
1850	0.30	1890	2.50	1930	0.80	1970	1.99	2010	0.97
1851	0.67	1891	3.80	1931	0.80	1971	1.88	2011	0.86
1852	3.38	1892	3.70	1932	0.70	1972	1.46	2012	1.25
1853	3.20	1893	3.70	1933	0.90	1973	1.00	2013	0.73
1854	2.68	1894	4.40	1934	1.20	1974	2.71	2014	0.47
1855	2.23	1895	3.60	1935	1.10	1975	3.08	2015	0.43
1856	1.78	1896	2.80	1936	1.00	1976	3.17	2016	1.55
1857	1.40	1897	2.10	1937	0.90	1977	2.78	2017	1.28
1858	0.99	1898	1.30	1938	0.70	1978	3.00	2018	0.24
1859	0.30	1899	1.20	1939	0.40	1979	2.70	2019	0.02

Water elevations (in metres AHD) can be calculated by adding 672.8 m to the depth value.

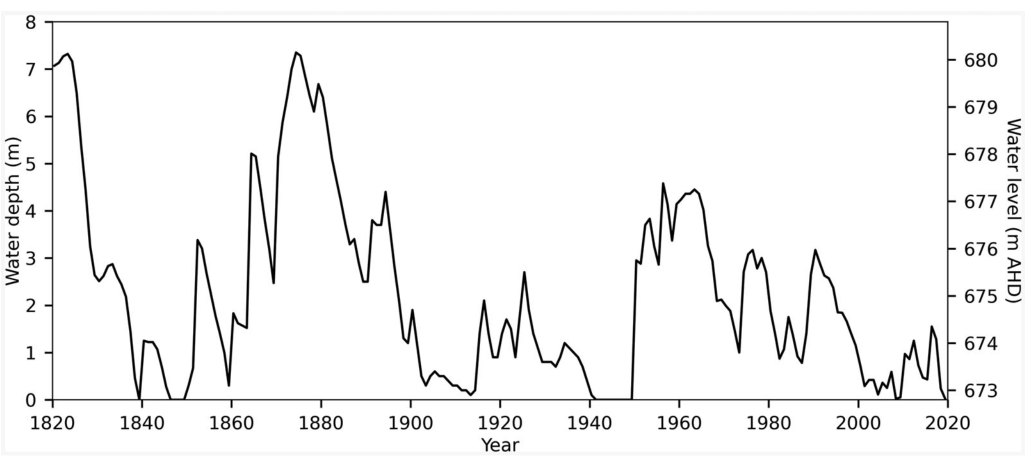

Figure 26. Annual maximum water levels recorded at Lake George between 1820 and 2019 (data in Table 4).

The water-level observations display a very close resemblance to the rainfall trend. This is unsurprising given that it has been shown numerous times previously that the lake level is a simple water balance consisting primarily of rainfall, runoff and evaporation (Jacobson & Schuett, 1979; Noakes, 1962; Russell, 1877, 1886; Short, 2017), and does not have the benefit of being sustained by groundwater.

The curves presented in Figure 25 also demonstrate that the water-level trends observed at Lake George are typically a good indicator for the prevailing climate in the region. This provides support to H.C. Russell's early assertion that Lake George would be an important scientific resource because it acts almost as a natural rain gauge (Russell, 1877). It also highlights the importance of preserving this record and continuing to uncover insights into Lake George's past through study of its hydrological, geological and human occupational history.

Conclusion

The almost continuous water-level record of Lake George spans two centuries (Figure 26; annual maximums are plotted to smooth seasonal variations)—this is the longest record of its type in existence for the Southern Hemisphere. The fluctuating water levels recorded over those two centuries display a high sensitivity to the prevailing climatic conditions in SE Australia. This supports an early assertion by the pioneering meteorologist/astronomer, H.C. Russell, that Lake George acts as a 'natural rain gauge'. It is therefore, of great scientific and historic value.

Since 2017, on-site monitoring of the water-level at Lake George has not been undertaken because, unfortunately, it is not considered a funding priority by entities that would typically have an interest in ensuring that this valuable record is continued (*e.g.* federal and state government agencies, or universities, *etc.*). The relatively low water levels of the last two decades have likely increased the disinterest.

Here we have shown that it is possible to continue the Lake George water-level record using remote sensing techniques—at least for water levels that are less than 4 m. Of the most commonly used water indices, we find that a median of the TCW, $AWEI_{sh}$, $AWEI_{ns}$, MDWI and WI is reasonable and should be adopted for estimating the water-level at Lake George *in lieu* of on-site measurements.

Data sources

Elevation data were sourced from the Australian Government's ELVIS (Elevation Information System) national elevation data portal (Geoscience Australia, 2019b). The two datasets accessed were: the Shuttle Radar Topography Mission (SRTM) One Second DEM (Gallant *et al.*, 2011), and the Lake George 1 m Lidar DEM (Geoscience Australia, 2015). These data are licensed under the Creative Commons (CC) Attribution 4.0 International Licence.

Climate data were sourced from the from the Queensland Government's SILO data portal (Queensland Government, 2020), which is licensed under the CC Attribution 4.0 International Licence.

Butmaroo Creek streamflow data were obtained from the WaterNSW real-time water data portal (WaterNSW, 2019), which are publicly available for reproduction but copyrighted by the State of NSW through WaterNSW.

Icon Water has given permission to use the lake-level data for their period of collection (2006–2015). The data are publicly available through the Lake George Super Science Data Portal (NCRIS, 2019).

Summary WOfS products are publicly available from the Geoscience Australia Digital Earth Australia data portal (Geoscience Australia, 2019a), available to the public through an Apache License 2.0.

The ODC data (Open Data Cube, 2020) are made available by Geoscience Australia through implementing scripts available on their online GitHub repository (Geoscience Australia, 2020). The data and scripts are available to the public through an Apache License 2.0.

Acknowledgements

We wish to acknowledge the First Nations people of the Ngunnawal, Ngambri and Ngarigo who have deep connections to the land upon which Lake George is situated. We also repeat the call of numerous people before us for the return of the lake's original name—whether that be Weereewa or Ngungara. As people of non-indigenous descent, we are in no place to say, but either would be preferable to the name of a monarch who never stepped foot in Australia, let alone on the shore of the lake.

During the course of this work, Bear McPhail passed away. His academic guidance, passion for Lake George and friendship were pivotal for the production of this work. We miss him tremendously, and we dedicate this work to his memory.

For the early stages of this research, M. Short received financial support from the Australian Government in the form of an Australian Postgraduate Award, and from the Australian National University in the form of a research scholarship.

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The Keatley family, of the Luckdale property on the eastern shore of Lake George, graciously provided access to collect samples and install sensors at Rocky Point between 2013 and 2017. Peter Keatley was an especially valuable source of information and history because of his many years living on the edge of the lake.

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Data availability statement

The data used in this paper are available online from the PANGAEA data repository (Short *et al.*, 2020) at https://doi.pangaea.de/10.1594/PANGAEA.922463, and are available for use under a CC Attribution 4.0 International Licence. Michael Short will endeavour to update this dataset with the satellite-derived water levels on an annual basis.

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