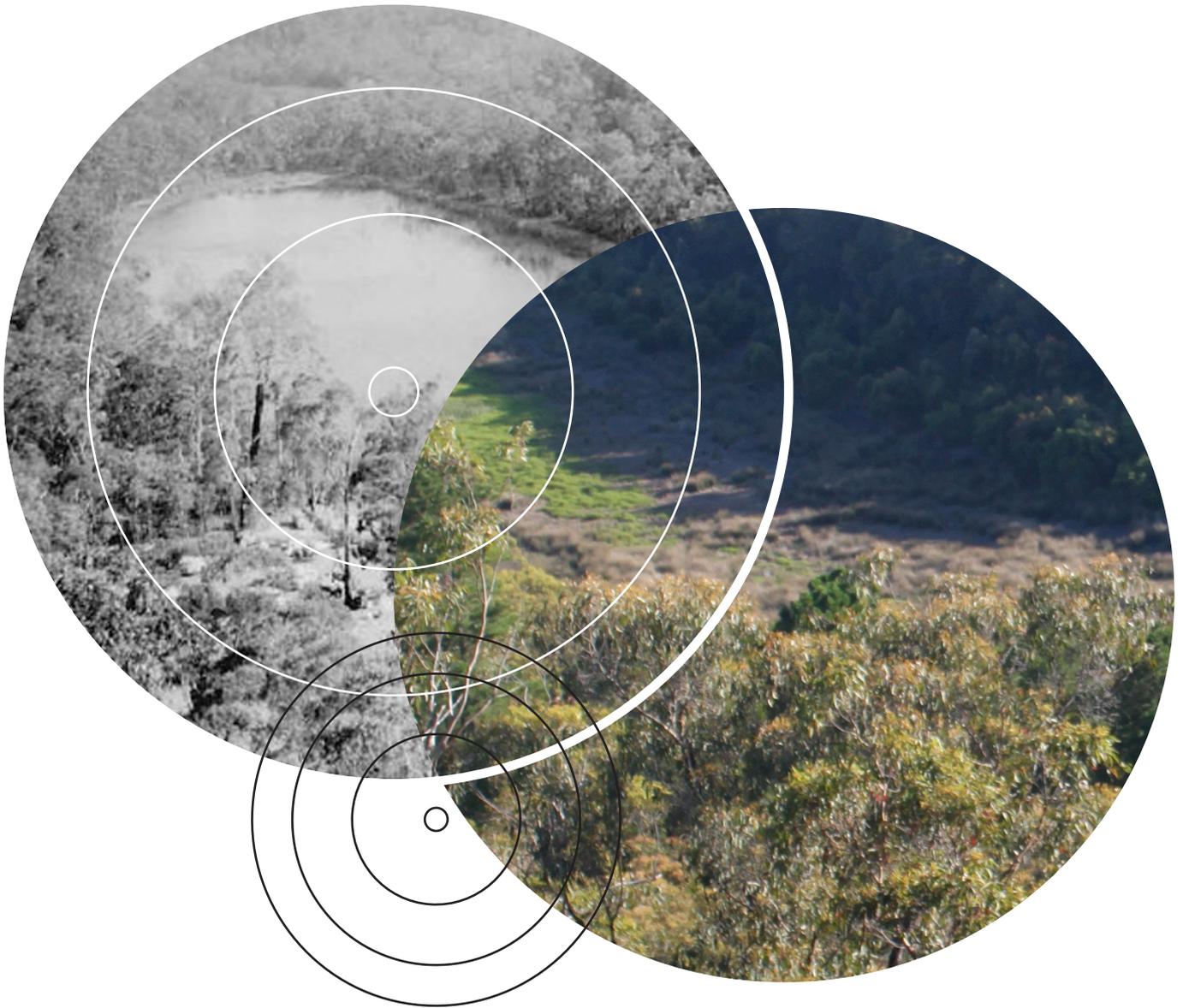


Long-term changes to water levels in Thirlmere Lakes — drivers and consequences



Centre for
Ecosystem
Science

Samira Schädler and Richard T. Kingsford

Centre for Ecosystem Science, School of Biological, Earth &
Environmental Science, University of NSW, NSW 2052, Australia

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Juxtaposition of a historical photograph of Lake Nerrigorang, taken in 1954 by Annette Bray with a recent photograph taken in 2012.

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Executive Summary

Many of the world's rivers and wetlands have degraded with alteration of flow regimes, when their water supply is modified. Mostly this is due to impacts of structures (i.e. dams and weirs), but increasingly mining and access to groundwater have affected flooding regimes of wetlands. We investigated water levels within Thirlmere Lakes, which are primarily filled by rainfall but interact with shallow groundwater.

We focused on the three of the five lakes with the most historical data, and compared inputs from rainfall and water levels over 115 years (1900–2015). This first step required development of three-dimensional models of the lakes, using topographic surveys. We then superimposed historical aerial photographs and ground photographs (1884–2012, n= 49 photographs/maps), allowing determination of water levels. We also investigated trends in groundwater levels (1999-2011), creating groundwater contour maps for two periods, before and after 1982, when longwall coal mining began. Rainfall and catchment inflow patterns were also examined at three nearby water bodies (Avon, Warragamba and Nepean Dams), acting as 'control sites'.

There were no significant long-term trends in rainfall at the three 'control sites', although rainfall increased significantly at Thirlmere Lakes (1900 – 2015). There were similar evaporation patterns at all sites and inflows at the three dams had not decreased. Contrastingly, there was a severe decline in water levels at Thirlmere Lakes. The disassociation of inflows and water levels (1930 -2015) had steadily increased, especially since the 1980's. In particular, we detected sudden drops in water levels in 1984, 1997 and 1998 in the three lakes. This did not coincide with the main period of water extraction for steam engines and Picton Tuberculosis Village at Thirlmere Lakes (1884-1910).

Groundwater levels in the shallow aquifer declined by up to 40m after mining commenced in 1982, also coinciding with an exponential increase in the number of groundwater bores (1940-2011). Although there were no publicly available data on how much groundwater was extracted each year, the serious decline in water levels coincided with increased groundwater development and longwall mining (29 longwall panels (2010)).

These serious declines in water levels in the three Thirlmere Lakes were not climate related and are best explained by anthropogenic impacts. There are two potential explanations for the draining of Thirlmere Lakes, which may have acted synergistically:

either there was considerable pumping of groundwater or longwall coal mining disrupted the groundwater aquifers, causing diversion of groundwater resources.

The implications are significant for the ecological character of the Thirlmere Lakes. There are many affected obligate aquatic species or species reliant on wet habitats, including five species of waterbirds (Australasian bittern *Botaurus poiciloptilus*, Australian painted snipe *Rostratula australis*, great egret *Ardea alba*, cattle egret *Ardea ibis*, and Latham's or Japanese Snipe *Gallinago hardwickii*) one fish species (Macquarie perch *Macquaria australasica*), two frog species (giant burrowing frog *Heleioporus australiacus*, Littlejohn's tree frog *Litoria littlejohni*) and two plant species (smooth bush pea *Pultenaea glabra*, Kangaloon sun orchid *Thelymitra Kangaloon*) that are listed as threatened. There are serious implications for governments and their responsibilities for managing the values of Thirlmere Lakes National Park along with the Blue Mountains World Heritage Area of which it is a part. These major changes in flooding regimes to Thirlmere Lakes will continue to degrade the Thirlmere Lakes National Park and its ecological, cultural and recreational values. Most importantly, identifying the relative importance longwall mining and groundwater pumping on this deterioration should be a priority, requiring detailed analyses of changes to groundwater pumping volumes and identifying flow paths for water supplies to Thirlmere Lakes.

Introduction

Wetlands continue to be lost, degraded and altered globally, more than other ecosystems (Millennium Ecosystem Report 2005). This reflects increasing human populations and economic development, associated with growing demand for food production, energy and water, mediated by climate change (Millennium Ecosystem Report 2005; Vörösmarty et al. 2010; Palaniappan & Gleick 2011; Bogardi et al. 2012; Junk 2012). The critical factor for all wetlands is the maintenance of a natural flow regime, including quantity, variability and quality (Mitsch & Gosselink 2000).

Natural flooding regimes are altered by flow interception, degrading wetlands and affecting dependent biodiversity (Bunn & Arthington 2002; Arthington & Pusey 2003; Nilsson et al. 2005a; Kingsford 2011; Watts 2011). Dams, weirs and direct pumping of water from rivers, wetlands and groundwater aquifers ubiquitously impact (Bernadez et al. 1993; Elmore et al. 2006) on freshwater ecosystems (Kingsford & Thomas 2004; Nilsson et al. 2005; Kingsford et al. 2006; Vörösmarty et al. 2010). Increasingly, there is also recognition of the impacts of mining on freshwater ecosystems, either through direct or indirect pollution, or alteration of surface and groundwater flow regimes supplying wetland systems (Whitfield 1988; Dawkins 1999; Itasca 2002; Booth 2006; Booth 2007; McNally & Evans 2007; Jankowski et al. 2008; Marandi et al. 2013). Concerns about the adverse effects of coal mining on the environment, especially rivers and wetlands continue to increase with the expansion of mining (Kay et al. 2006; Krogh 2007).

Thirlmere Lakes are in the Hawkesbury-Nepean Catchment (Fig. 1), affected by mining, agriculture, river regulation and urbanisation. Tahmoor Colliery, adjacent to Thirlmere Lakes National Park completed mining of 29 longwall panels by 2010, the closest only 600m from the lakes (Russell et al. 2010; Pells 2011; Riley et al. 2012; Gilbert & Associates 2012). Thirlmere Lakes were gazetted as Thirlmere Lakes National Park (630 ha), one of eight conservation areas within the Greater Blue Mountains World Heritage Area (National Parks and Wildlife Service NSW 1997). The lakes are within a buffer zone (Schedule 2 Special Area; Sydney Catchment Management Act 1998), protecting them from peripheral development and recognizing that if they are filled, water could overflow into Sydney's main water supply (National Parks and Wildlife Service NSW 1997).

Geological stability has produced a diverse freshwater ecosystem at Thirlmere Lakes, supporting organisms restricted to the catchment and dependent on water, including

the freshwater sponge *Radiospongilla sceptroides* (National Parks and Wildlife Service NSW 1997). The lakes also provide habitat for two waterbird species protected by migratory bird agreements: the Australasian Bittern *Botaurus poiciloptilus*, also listed as an Endangered species under the *Environmental Protection and Biodiversity Act 1999* (EPBC Act, 1999) and the Latham's or Japanese snipe *Gallinago hardwickii*. Thirlmere Lakes were listed as a Wetland of National Importance in 2001 (Environment Australia 2001) and as a high priority critical habitat for the Australasian bittern and the Bush-stone curlew *Burhinus grallarius* in 2007 (DECC 2007).

Sedimentary analyses suggest that water levels at the Thirlmere Lakes have fluctuated over time, occasionally drying completely (Atkinson 2000). Alternating bands of black/grey and yellow/red/orange clay indicate alternating wet and dry conditions in one of the lakes, Lake Baraba (Fig. 1), from over 43,000 years ago until the early Holocene (~8,500 years ago) (Black et al. 2006). After ~8,500 years ago peat started to form indicating wetland vegetation and humid environmental conditions. The nearby Dry Lake (Fig. 1) similarly had fluctuating water levels from the beginning of the Holocene (~ 10'000 years ago), until 6000-5000 years ago, followed by swamp vegetation in the last 2000–1000 years, indicative of predominantly wet conditions (Rose & Martin 2007). Rapid recovery of water levels during predominantly wet conditions also produced the 'floating islands' in Thirlmere Lakes, first described in 1974 (Vorst 1974; Timms 1992). These are thought to be formed by large amounts of aquatic vegetation, mainly *Lepironia articulata* und *Eleocharis sphacelata*, dying back during dry periods, but becoming buoyant from the gases produced during the decomposition of the organic matter and forming small floating islands, when water levels recover (Vorst 1974; Timms 1992).

Anthropogenic impacts have affected water levels in the Thirlmere Lakes over time. Water was extracted for the steam trains and for the Picton Lakes Tuberculosis Village water supply in the late 19th and early 20th Century (Riley et al. 2012; Pells 2011; Picton Lakes Village 1952). Most recently, concern has increased about the potential impacts of longwall coal mining on groundwater and surface water, resulting in a Commission of Inquiry by the NSW Government (Riley et al. 2012). Longwall mining inevitably interferes with groundwater aquifer systems when removing blocks of coal (=longwall panels) of 250-400m width and 3-4km length from the strata (Altun et al. 2010).

During extraction, the roofs of longwall panels are supported by pillars, which are removed after mining of each section so that the overlying stratum collapses into the created void (McNally & Evans 2007). This extends through the different rock layers

and, depending on the depth of mining, possibly to the land surface. This horizontal and vertical movement of different strata layers above and sometimes adjacent to the area mined possibly results in cracking and fracturing, as well as subsidence or upsidence at the surface (Booth 2007; Holla & Buizen 2001, Jankowski et al. 2008). This alters hydrological pressure gradients and permeability of the different rock layers, affecting groundwater movements and connectivity. Groundwater regimes may be affected by longwall mining, changing vertically and horizontally over large areas, sometimes beyond the area mined (Booth 1986; Holla 1997; Dawkins 1999; Holla & Buizen 2001; Booth 2006; Booth 2007). Further, alterations to these groundwater flow paths can affect connectivity of surface water and groundwater (Whitfield 1988; McNally & Evans 2007; Jankowski et al. 2008; Pells 2011). Increased volumes of surface and groundwater can be drawn down deep into recharge areas (Lahm & Bair 2000), reducing pressures by this water loss. These processes and the effects of mining are complex and depend on the extent of the impact and geology.

The water in Thirlmere Lakes is predominantly derived from rainfall but the lakes are also connected to the groundwater system, naturally losing surface water to the groundwater aquifers (Pells 2011; Riley et al. 2012). There are two main groundwater systems (shallow and deep) underlying Thirlmere Lakes, separated by a low permeability layer (Bald Hill Claystone layer, Fig. 2). Usually, if groundwater is extracted, aquifers are replenished from water from adjacent strata including surface water. Speculation has increased that recent water levels in the Thirlmere lakes have remained low or receded more quickly than in the past, coinciding with the start of longwall coal mining. There are two contrasting assessments of the interaction between coal mining and water levels at Thirlmere Lakes.

The first maintains that the low permeability Bald Hill Claystone prevents replenishment of the deep aquifer from the shallow aquifer at Thirlmere Lakes, and so surface water levels should not be affected by coal mining (Russell et al. 2010; Riley et al. 2012). The second contends the Bald Hill Claystones' hydraulic conductivity is similar to the hydraulic conductivity of the Hawkesbury Sandstone, allowing the shallow groundwater aquifer to interact with the deeper aquifers and draining water from Thirlmere Lakes (Pell 2011). A NSW Office of Water investigation concluded that declining water levels were primarily due to climatic variability, with insufficient subsequent rainfall to fill the lakes (Russell et al. 2010). However, water levels were estimated to be 1.5m–2.5m lower than what would be expected if only natural climate drivers were responsible (Pells 2011). The NSW Government Commission of Inquiry concluded that there was

no strong evidence that mining activities by longwall coal mining directly affected Thirlmere Lakes (Riley et al. 2012).

We aimed to further investigate any association between water level and climatic conditions, by obtaining historical photographs of water levels and climate data. We hypothesized that if there were no anthropogenic impacts, water levels should vary naturally over time, reflecting long-term rainfall patterns. To adequately do this, we had three specific objectives: 1) to develop an elevation model for three of the lakes to determine water levels; 2) to examine water level changes in relation to long term rainfall patterns at Thirlmere Lakes and 3) to compare these results with three other nearby 'control' sites for which similar changes to flow and rainfall patterns might be expected if changes have occurred for Thirlmere Lakes.

Methods

Study Site

We investigated long-term changes to water levels at Thirlmere Lakes and inflows at three other 'control' sites: Avon, Warragamba and Nepean Dams in the Hawkesbury-Nepean Catchment (21,710 km², Fig. 1a,b). These latter sites are large dams receiving water respectively from the Avon, Cordeaux and Nepean Rivers (Markich & Brown 1998; Pinto et al. 2012), and are part of the Upper Nepean Scheme and Sydney's main water supply (1888-1907) (Oberatu 2011). We chose these sites because there were no similar sized natural wetlands near Thirlmere Lakes with similar rainfall and evaporation. Flow data were also available to track potential run-off and likely filling patterns for these dams.

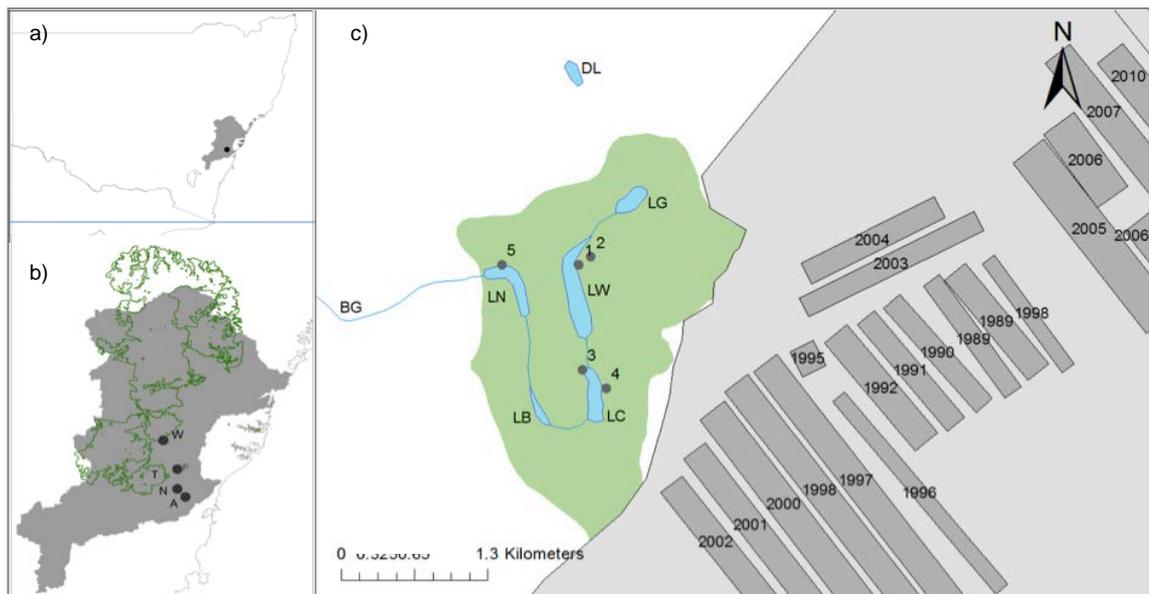


Figure 1: Location of Thirlmere Lakes in a) the Hawkesbury Nepean Catchment in NSW, b) and other sites (T-Thirlmere Lakes, A-Avon Dam, N-Nepean Dam, W-Warragamba Dam, P-Picton) with the Greater Blue Mountains World Heritage Area (green outline) and c) where Blue Gum Creek (BG) takes water from the five Thirlmere Lakes (LN-Lake Nerrigorang, LB-Lake Baraba, LC-Lake Couridjah, LW-Lake Werri Berri, LG-Lake Gandangarra), within the boundary of Thirlmere Lakes National Park (filled green), in relation to Tahmoor Coal Colliery Lease (grey area) and 20 nearby longwall mines (dark grey), identified by the date that they were established. The earliest longwall panel (1982) was ~4.5km east from the Thirlmere Lakes. Dry Lake (DL) lay ~1.5 km to the north and was also once connected to the system. There were 5 reference points used (filled circles, 1-5) to identify levels for determining water levels on ground photographs (see Appendix).

Most of the catchment area, for the four sites, is (max. elevation 1,290m) (Markich & Brown 1998; Hector 2011; Pinto et al. 2012), experiencing warm/hot summers and mild/cold winters with respective mean temperatures of 28.81 ± 1.99 °C (SD) (December-February, 1907-1975) and 17.43 ± 1.17 °C (SD) (June-August, 1907-1975) (Australian Government Bureau of Meteorology 2013). Mean annual rainfall for Picton (Fig. 1b) was 803.41 ± 254.97 mm (SD) (1880 - 2011), mostly over the summer and early autumn (Australian Government Bureau of Meteorology 2013).

The underlying geology shaped the surface and groundwater systems supplying Thirlmere Lakes. Thirlmere Lakes consists of five lakes (Fig. 1c), overlaying the Sydney-Gunnedah basin, accumulated between the Permian and Triassic (Herbert & Helby 1980). The lakes were probably formed with the Lapstone Monocline, about 15 million years ago, when a meandering stream was isolated from its channel by an uplift event (Bishop et al. 1982). Originally, a stream drained from Dry Lake into the Thirlmere Lakes and then west into Blue Gum Creek (Fig. 1c)(Rose & Martin 2007), which then flowed into Little River and then Warragamba Dam (Vorst 1974; National Parks and Wildlife Service NSW 1997; Pells 2011; Riley et al. 2012). Since the

formation of the Lapstone Monocline, water from Dry Lake no longer reaches Thirlmere Lakes. Thirlmere Lakes still overflows to the west into Blue Gum Creek and into Little River to reach Warragamba Dam, but they have not done so since 1974 (Vorst 1974).

It is thought that the water in Thirlmere Lakes is predominantly derived from rainfall but that the lakes are also connected to the groundwater system (Russell et al. 2010; Riley et al. 2012). A shallow and deep aquifer system occur at the Thirlmere Lakes, separated by a layer of low permeability, the Bald Hill Claystone (Fig. 2), which is a

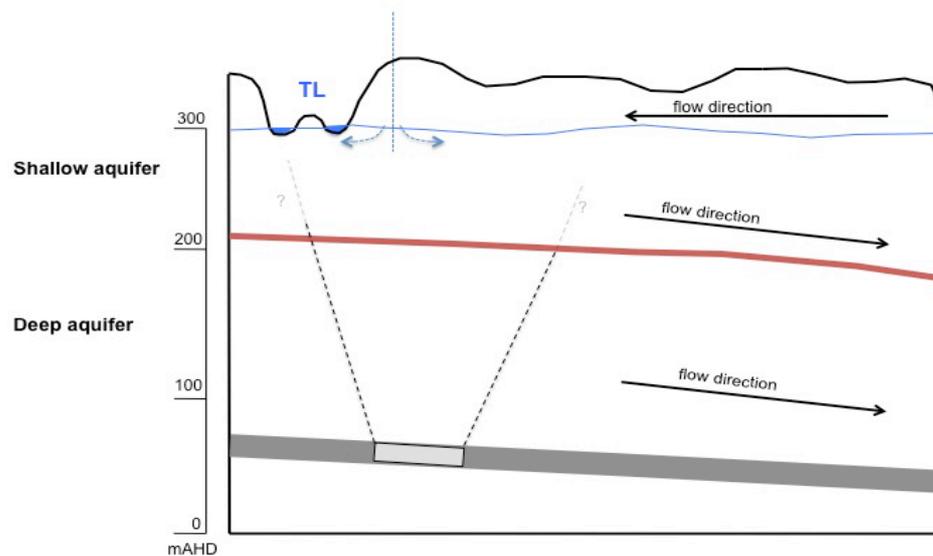


Figure 2: Conceptual diagram (not to scale) of interactions near Thirlmere Lakes (TL). The water table (blue) and interactions between surface flow and groundwater flow in the shallow and deep aquifers, separated by the Bald Hill Claystone layer (red), under which the coal seam lies (dark grey) where longwall (grey) mining occurs. The strata above the longwall (black dotted) will collapse into the newly created space (goaf) after the resources are removed (after Russell et al. 2010)

deposit of thick claystone/siltstone beds originating from exposed and weathered Permian volcanic rock (Branagan et al. 1979; Herbert & Helby 1980, Pells & Pells 2012). Groundwater in the shallow and deep aquifer generally flows to the east, opposite to surface water flow, along a hydraulic gradient caused by the eastward dip of the underlying bedrock (Russell et al. 2010; Riley et al. 2012)(Fig. 2).

Thirlmere Lakes are of high conservation importance, gazetted as a National Park in 1972, and providing habitat for dependent aquatic species. These include the freshwater sponge *Radiospongilla sceptroides*, endemic to the Warragamba Catchment Area. Thirlmere Lakes is the only location in Australia where the species does not produce gemmules, needed for sexual reproduction (NSW National Park and Wildlife Service, 1997). The threatened water lily species *Brasenia schreberi*, grey rushes *Lepironia articulata* and *Eleocharis sphacelata* grow in the deep water, possibly

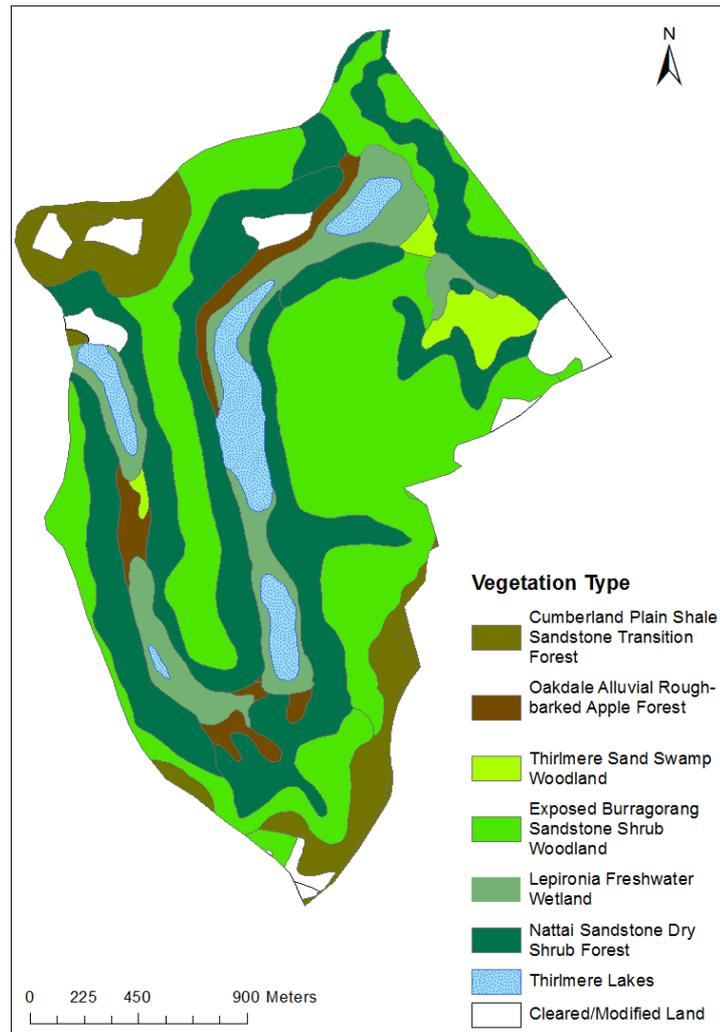


Figure 3: Thirlmere National Park with its lakes and six different vegetation communities and cleared land (NSW Department of Environment and Heritage 2003).

emerging on floating islands after water level fluctuations. Ivy duckweed *Lemna trisulca* floats on the water. Pithy sword-sedge *Lepidosperma longitudinale* and *Baumea teretifolia* grow on the water's edge or partially submerged, making up the Lepironia Freshwater Wetland Community (Fig. 3), providing habitat for the Australasian bittern *Botaurus poiciloptilus* (National Parks and Wildlife Service NSW 2003).

In the sandy drainage flats on the eastern lake boundaries, there is the unique Thirlmere sand swamp woodland (Fig. 3), characterised by the Parramatta red gum *Eucalyptus parramattensis* subsp. *parramattensis* and the flax-leaved paperbark *Melaleuca linariifolia* with an understorey of *Lepyrodia muelleri*. Further, the Oakdale alluvial rough-barked apple forest with the vulnerable mountain blue gum *Eucalyptus deanei* growing in drainage depressions may be dependant on the Thirlmere Lakes wetland (National Parks and Wildlife Service NSW 2003).

Other wetland dependent fauna include the common eastern froglet *Crinia signifera* and the brown-striped frog *Limnodynastes peronii* (NPWS 1997). There are several species listed as Vulnerable or Endangered possibly reliant on the Thirlmere Lakes including: the Australasian bittern *Botaurus poiciloptilus*, the Australian painted snipe *Rostratula australis* and migratory species like the great egret *Ardea alba*, cattle egret *Ardea ibis*, and the Latham's or Japanese Snipe *Gallinago hardwickii*, the Macquarie perch *Macquaria australasica*, the giant burrowing frog *Heleioporus australiacus* and Littlejohn's tree frog *Litoria littlejohni* and plant species also depending on swampy habitats like the smooth bush pea *Plutenaea glabra* and Kangaloon sun orchid *Thelymitra kangaloon* (Department of Sustainability Environment Water Population and Communities 2012).

Rainfall and evaporation

We collected annual rainfall for the four sites (Thirlmere Lakes, Avon, Warragamba and Nepean Dams, Fig. 1b), as an index of inflows to each water body. Long-term actual annual rainfall data were available for different periods for each of the sites: Thirlmere Lakes (Buxton, 1967 – 2015); Avon Dam (Dapto, 1908 – 2014); Warragamba Dam (Wallacia, 1944 – 2014) and Nepean Dam (Buxton, 1967 – 2015) (Australian Bureau of Meteorology, 2011). We used annual rainfall data from the Australian Water Availability Project (AWAP, www.eoc.csiro.au) for any location in Australia (5 km resolution), 1900 - 2011 (Raupach et al. 2008), to fill the gaps. We tested correlations (Pearson's) between annual actual (BOM) and AWAP data for all four sites (Thirlmere Lakes, $r = 0.97$; Avon Dam $r = 0.94$, Nepean Dam $r = 0.95$, Warragamba Dam $r = 0.97$). After filling data gaps with AWAP data, we had annual rainfall data sets for 1900-2014. We also used modelled pan evaporation data from AWAP for the same period (Raupach et al. 2008), estimating evaporation from the water bodies (Lowe et al 2009).

Annual rainfall was used to calculate cumulative rainfall residuals, the differences between annual and mean rainfall, to produce cumulative rainfall departure curves. We also ranked annual rainfall to identify quartiles of rainfall. We used the Mann Kendall

test for determining trends in rainfall data. We first tested for autocorrelation using the Breusch-Godfrey test (Breusch 1978). The Mann Kendall ranks data, detecting changes in the median value over time by calculating the Mann Kendall test statistic (S):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_k)$$

where:

$$\text{sign}(x_j - x_k) = \begin{cases} +1 & \text{if } x_j - x_k > 0 \\ 0 & \text{if } x_j - x_k = 0 \\ -1 & \text{if } x_j - x_k < 0 \end{cases}$$

An increasing or decreasing trend in annual rainfall is detected if the Mann Kendall test statistic (S) results in high or low values respectively. Given the high variability of annual rainfall data, we also used quantile regression analyses to investigate changes to high and low annual rainfall. Quantile regression detects different trends in portions of the probability distribution (Cade & Noon 2003; Mazvimavi 2010), as intercept and slope coefficient are calculated for each proportion (quantile) of the dataset separately.

The first order quantile regression model for the random variable Y is:

$$Y(\theta | x) = \beta(\theta)_0 + \beta(\theta)_1 X + \xi$$

where:

$Y(\theta | x)$ is the θ th quantile of Y, $\beta(\theta)_0$ the intercept, $\beta(\theta)_1$ the slope coefficient, X the covariate of Y and ξ the error. The θ th quantile regression estimate can then be found by minimizing:

$$\min \frac{1}{n} \left\{ \sum_{i: y_i \geq x_i \beta} \theta |y_i - x_i \beta| + \sum_{i: y_i < x_i \beta} (1 - \theta) |y_i - x_i \beta| \right\}$$

where:

n = sample size, $i = 1, 2, \dots, n$, y_i = value of Y and x_i = value of X (Koenker & Bassett 1978; Cade & Noon 2003; Mazvimavi 2010).

A trend in rainfall quantiles was detected if the slope coefficient was negative/positive and significantly different from zero. All tests were performed in Rstudio using the

packages “*Kendall*”, “*lmtest*” and “*quantreg*” (McLeod 2011; Koenker et al. 2013; Hothorn et al. 2014) .

Water levels - Thirlmere Lakes

Water levels at Thirlmere Lakes were not routinely collected, until recently (NSW Department of Environment and Heritage 2013). We therefore used indirect methods to estimate historical water levels in the lakes (1884-2012) using available imagery (historical aerial and ground photographs), maps (n = 49 photographs and maps, Appendix) and oral history records. We focused on three lakes, Lake Couridjah, Lake Werri Berri and Lake Nerrigorang (Fig. 1c), as data were primarily available for these more frequented lakes.

To systematically access all available historical imagery, we searched for photographs in relevant libraries including the National and State Library, State Records and the Historical Society in Picton. We also interviewed researchers and asked holidaymakers for material on Thirlmere Lakes. Photographs from flickr.com and taken by the community (with permission) were used. The key criterion for use was unequivocal specification of dates and inclusion of reference points (Fig. 1c). We identified 30 ground photographs, with reference points and dates, from different origins (1884–2012, Appendix).

We also identified 15 aerial photographs (1937-2010) from the NSW Government Land and Property Information, the National Library and the NSW State Records (Appendix 1). In addition, we used Parish Maps from Land and Property Information, 1897-1953 (NSW Government Land & Property Information 2012) and other maps from libraries, including the National Library in Canberra and the NSW State Library (Appendix).

Where we used oral history records stating water levels were low, we used the levels when the lakes were filled to one quarter to ensure we did not underestimate the levels.

We also developed a digital three-dimensional elevation model from topographic survey data of the three lakes (Fig. 4), by surveying 612 points over six months: Lake Werri Berri (249), Lake Couridjah (138) and Lake Nerrigorang (225). We focused on the natural break points in the environment (lake bed, slope, high point), ensuring capture of the bathymetry of the lakes. This involved measuring elevation at 3-4 points along a line of sight of the surveyor, repeated about every 25m, using a digital elevation surveyor (Sokkia Total Station, Set 5 50rx, Fig. 4). The Total Station used laser beams to measure horizontal and vertical angles and slope distances to a prism

(Advanced Prism AP Series), mounted on an adjustable pole held upright at the natural break points (Fig. 4). Prisms provided high accuracy ($\pm 2\text{mm km}^{-1}$, (Sokkia Topcon Co. Ltd. 2009), even over the greatest distance recorded (685.297m). Zenith angle, collimation error, Earth curvature and refraction were automatically adjusted for each calculation of elevation (Sokkia Topcon Co. Ltd. 2009).

We also tested for potential bias to elevation estimates, caused by swelling and expanding peat, with different moisture content by repeating six measurements at each lake over the six-month period; all points were within 0.28% of each other.

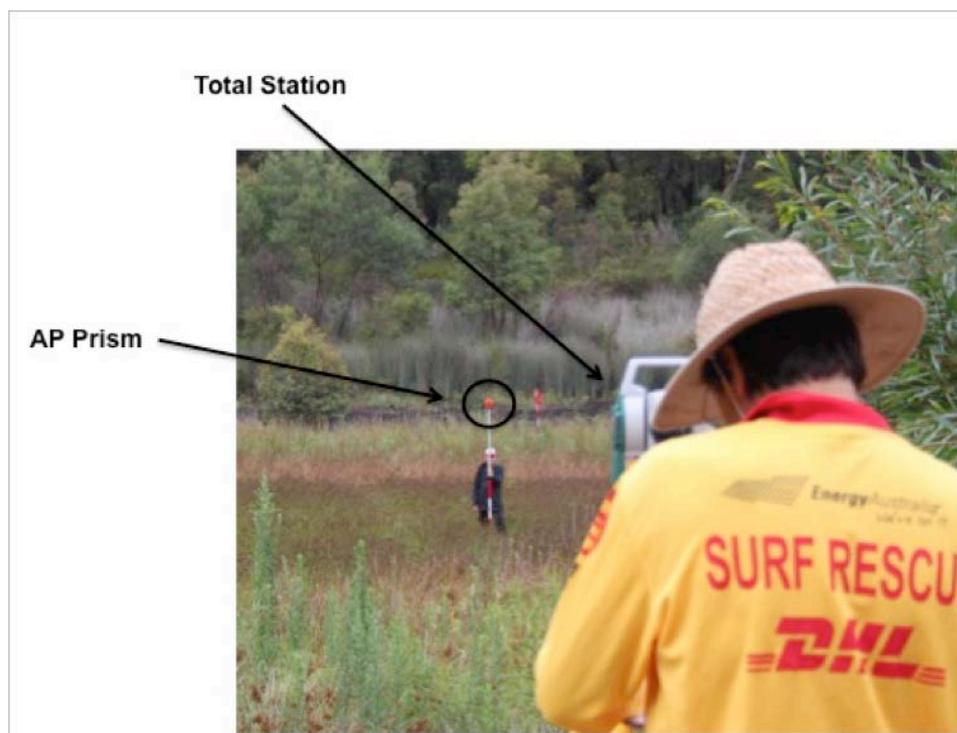


Figure 4: Measurement of bathymetry of three lakes, Lake Couridjah, Lake Werri Berri and Lake Nerrigorang, surveyed to develop a three dimensional model of lake levels, using a digital elevation surveyor (Sokkia Total Station, Set 5 50rx), focused on an AP Prism (photo S.Schadler).

We also established survey benchmarks at the three lakes (Lake Couridjah (2), Lake Nerrigorang (9), Lake Werri Berri (7)), allowing us to combine data and produce a digital elevation model across all three lakes. These were pegs in the ground, left at the site during the whole period of the survey, and were remeasured over time. The number of benchmarks for each lake was based on the size of the lake and visibility. We also surveyed three survey points established by the NSW Office of Water in May-June 2011 for the three lakes (Russell 2012), and included these in the digital elevation model (DEM). Each survey point was converted from a relative measurement (distances and bearings) into real coordinates. The measured changes in northing,

easting and elevation, relative to the previous point surveyed, were converted into coordinates using the following formulae:

$$\Delta\text{North} = \cos \alpha * d$$

$$\Delta\text{East} = \sin \alpha * d$$

$$\Delta\text{Level} = L_n - h$$

where d was the distance, α the bearing, L the level and h the height (Ghilani & Wolf 2012). We then used contouring and surface modelling software, Surfer 8 (Golden Software Inc 2002), to produce contour and three dimensional maps of lake surfaces from the survey data, interpolated between points with kriging analysis (Kao & Hung 2003; Nansen et al. 2003). Each map was exported and georeferenced in the Geographic Information System ArcMap10 (Environmental Systems Research Institute Inc 2010). Total lake volumes for the Thirlmere Lakes were also calculated, using the Software Surfer8. The maximum water levels were already established by a thalweg survey (Riley et al. 2012).

To link our photographs to the DEM and identify historical lake levels, first all aerial photographs were scanned in colour or gray scale, matching the original image, at a resolution of 600 dpi and then georeferenced in ArcMap10, using a high-resolution (0.7 m) georeferenced base layer provided by Nearmap (Nearmap Pty Ltd. 2012). We identified invariable locations (roads, crossings, train station, building), as ground-control points (GCPs) on the aerial photographs, as well as on the georeferenced base layer. This allowed us to warp and georeference all aerial images. We used 9-12 GCPs, concentrating on the Thirlmere Lakes (Hughes et al. 2006). To permanently georectify the aerial photographs, we applied a first order-polynomial transformation which produced similar results to a second-order transformation (Hughes et al. 2006). We similarly georectified historical maps with 6-9 points, as GCPs were limited.

Water levels at the three Thirlmere Lakes (Lake Werri Berri, Couridjah and Nerrigorang) were measured using the digital elevation model (aerial photographs, maps) and reference points (ground photographs).

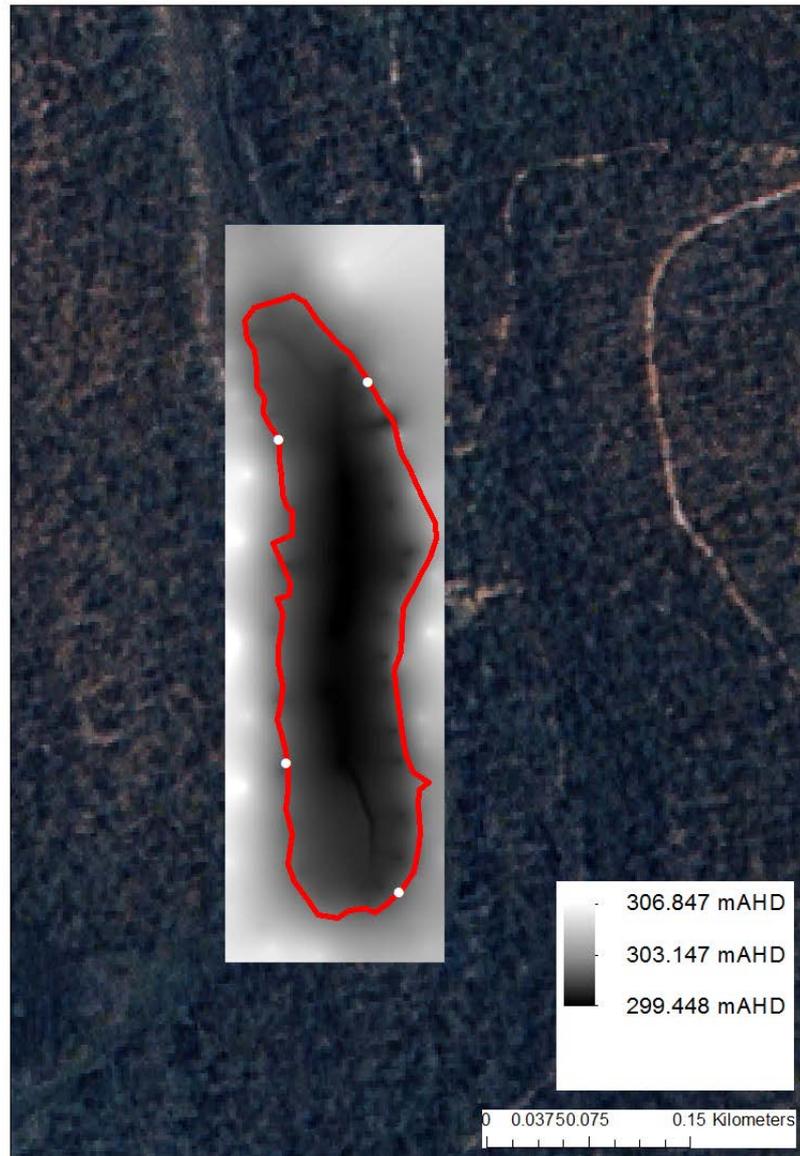


Figure 5. An example of how water levels were calculated for Lake Couridjah in February 2002. The digitised water coverage (red line) was overlaid on our DEM and then four random points used (white circles) to estimate water levels of lakes. Grey shading shows different water levels (mAHD).

The georectified aerial photographs and maps were integrated with the digital elevation model (DEM) in ArcMap, to estimate water levels. We digitised the area covered by water on each photograph or map and lake, producing separate shapefiles in ArcMap10. We then draped the shapefile of water coverage over the DEM (Fig. 5).

Each cell of the DEM was associated with an elevation value that could be retrieved. We identified elevation on the DEM of the water edge (=water level) at four random points along the outline of the water coverage polygon (Fig. 5). Georeferencing errors caused by elevation, angle distortion and obstructed views of the lake edge meant that sometimes these four estimates did not coincide and so we adjusted the water

coverage layer in relation to the DEM, until the four random points were within ± 0.1 m (Fig. 5).

We estimated water levels for two maps of the Parish of Couridjah (1894-1951) and three historical maps (Appendix), by comparing them to a similar aerial photograph. For these historical maps, the lakes were shown as full and all connected, indicating that water level was the same or higher than the water level of the aerial photograph from 1955, when the lakes were similarly connected. All water levels on historical maps had the water levels for the three lakes from the 1955 aerial photograph: Lake Couridjah (302.85 mAHD), Lake Werri Berri (304.45 mAHD) and Lake Nerrigorang (302.4 mAHD).

To determine water levels from the 30 ground photographs (Appendix), we used a reference point (Fig. 1c) with another measureable object to scale each photograph (Fig. 6). Reference points were points with a fixed location where elevation was measured during our survey (Fig. 1). These were visible on the photographs with the lake level and included two stonewalls, the jetty, the base of a bench and the base of a tree; all their heights were surveyed during bathymetric surveys. In most photos, water levels did not reach reference points, requiring identification of another measureable object to scale the photograph and measure the distance between reference points and water levels (Fig. 6).

Each photograph was imported to Photoshop (Adobe Systems Inc), where a vertical or horizontal line could be measured in units. The person standing on the jetty was estimated to be of average height (Australian Bureau of Statistics 2012), providing a measure in Adobe Photoshop. The ratio of units to average height was then used to calculate the distance between the jetty and the top of the water (Fig. 6). We also compared four ground and aerial photographs taken at the same time. Where we used estimates (e.g. height of person), we tested the sensitivity of the analysis by re-evaluating the water levels but varying measures by 10% and calculating the difference.

We derived an index for relative change between rainfall and water levels, using the differences between standardized annual rainfall departure from the mean and water levels (Larsen & Marx 2011). Three options were possible over time with this index: no change, decrease and increase. If neither variable changed its relationship over time, nor their relationship increased or decreased over time but this was synchronous between the variables, then no trend would have been detectable in our index. Only if



Figure 6: An example of how we estimated water levels on historical photographs (April 1988, Lake Couridjah), using a combination of a reference point (see Fig. 1c, Appendix), with known height (i.e. wooden jetty), and a measurable object (i.e. male). We had the surveyed height of the jetty (305.7m AHD). The height of an average male (red line, 1.75m) corresponded to 82.5 units on the image and so the water level was calculated as the height of the jetty above the water level (green line), corresponding to 77.5 units on the image. The ratio of the measurable object (male, 82.5 units/1.75m) was equivalent to water level below the jetty ratio (i.e. 77.5 unit/x), where x was 1.64m. This allowed estimation of the water level (305.7m - 1.64m = 304m).

water levels decreased in relation to rainfall over time was our index expected to increase over time, as the differences between the variables increased. The Mann Kendall test (see 2.2 for more details) was used to investigate changes in the trend of our index.

Sudden changes in patterns of water levels over time were also examined using broken-stick regression or segmented regression (Toms & Lesperance 2003; Muggeo 2003). Broken stick regression detects if systems are in 'shock' and identify the change point (=year) when the ratio between rainfall and water levels changed. The broken stick regression model was:

$$Y = \beta_0 + \beta_1(X) + \beta_2(X - C)^+ + \epsilon$$

where Y was the response variable (difference), X the covariate (year), β_0 the intercept, β_1 the slope before the Change point C and β_2 the difference in slope after C . We tested the null hypothesis $H_0: \beta_2 = 0$: that the slopes of the two proportions (before and after the change point) had not changed. R packages “*Sizer*” and “*segmented*” were used (Muggeo 2010; Sonderegger 2011). Prior to all regression analyses, normality was investigated using probability plots for all rainfall, evaporation and inflow data (and data transformed where necessary) and tested for heteroscedasticity using the Breusch-Pagan test (Breusch & Pagan 1979). Given the potential errors in oral water level estimates, only water level estimates from photographs or maps were used.

Water extraction

Water was extracted from the Thirlmere Lakes during the late 18th and early 19th century to supply steam trains passing Thirlmere (1885–1964) and for irrigation and domestic use by the Picton Village Tuberculosis Settlement (1927–1952) (Riley et al. 2012; Pells 2011; Picton Lakes Village 1952). The steam engines filled their tanks at Thirlmere Station, using water pumped from Lake Couridjah. To estimate water use, we obtained historical data on locomotives, their tank size and timetables listing frequency of public and goods trains (1891 and 1916) from the Australian Railway Historical Society New South Wales Division (ARHSNSW), providing an estimate of the number of locomotives per week. Between 1890s-1915, the J(483) and the B(55) steam trains were used, subsequently changing to the D(50), with respective tank size capacities of 13865l, 11250l and 16590l (W. Phippen, ARHSNSW member, pers. comm.). We estimated annual (Jan-Dec) water use, based on number of goods locomotives per week and their respective tank capacities.

Picton Village Tuberculosis Settlement also extracted water from Lake Couridjah (1927-1952), detailed in annual reports (1934, 1936, 1938-1940, 1942-1944, 1953-1954) (Picton Lakes Village 1952). It subsequently obtained water from elsewhere (Picton Lakes Village 1952). We estimated the total volume of water used each year, using annual expenditure on water, linked to volume.

Groundwater

Given probable connections between groundwater and surface water at Thirlmere Lakes, we also examined changes to groundwater extraction, linked to the number of bores installed and changes to groundwater contour levels that may have been affected by underground coal mining. We obtained data on the number of groundwater bores sunk each decade, using their installation date, which provided the number of

bores within radii of 5km, 10km and 20km of Thirlmere Lakes (NSW Office of Water 2010). Data on water allocations or volumes extracted were not publicly available.

We evaluated groundwater levels in the shallow groundwater system near Thirlmere Lakes and Tahmoor Colliery (Fig. 1c), by comparing contour maps of groundwater levels before and after longwall mining began in 1982 (Fig. 1c).

To create the groundwater maps, we used groundwater levels from borehole data from the NSW Office of Water (PINNEENA), within 30km of Thirlmere Lakes. These water levels accessed either the deep or the shallow groundwater system (Fig. 2) and so we compared bore depth with surface elevation and the height of the Bald Hill Claystone. The height of the Bald Hill Claystone was previously modelled and we accessed the data using Digital Imaging Geological Systems (DIGS) Report Viewer (NSW Department of Trade & Investment 2014). We divided bores into two groups for the shallow aquifer, those sunk before 1983 and afterwards, and imported coordinates and water levels of each bore into Surfer 8 (Golden Software Inc 2002). We then created two contour maps for the shallow aquifer in Surfer8, using kriging interpolation between data points (Kao & Hung 2003; Nansen et al. 2003). Contour maps of the deep groundwater system could not be created and compared due to the lack of data.

We also used the same data set to investigate groundwater changes by calculating trends in average groundwater levels (5 year periods). To examine the spread of sample points, the physical locations of the bores sunk within the 5-year segments were plotted. We only used years with >10 sample points, to maximise accuracy of the estimates with limited spatial bias, restricting analyses to the period, 1999 – 2011.

Other sites

We used catchment runoff as a surrogate for water levels at the other three 'control' sites (Avon, Warragamba and Nepean Dams). We used modelled annual catchment runoff which included inflow, storage diversions, rainfall, evaporation and data of other known losses to each water body system, available from 1909 -2011 (SCA unpubl. data; BOM National Water Account, 2011). Annual runoff was also compared to annual precipitation at each site. Besides investigating if there were trends in rainfall, we also analysed for trends in catchment runoff at Avon, Warragamba and Nepean Dams.

Results

Bathymetry

We created contour and 3D surfaces from the topographic survey data for the three lakes: Lake Couridjah, Lake Werri Berri and Lake Nerrigorang (Figs 7 & 8). The bathymetry of all three lakes was confined by the surrounding sandstone ridge, resulting in elongated lakes with steep edges following a horseshoe shaped bend along the ridge. Lake Werri Berri, the longest of the three surveyed lakes, and Lake Couridjah, the smallest of the three lakes occupied similar elevations, while Lake Nerrigorang was slightly lower. Lake Nerrigorang had its three lowest points at 298.6m when it was dry, compared to Lake Werri Berri and Lake Couridjah where the lowest points, when they were dry, were at 299.5m and 299.4 (Table 1). All the lakes had reasonably similar bathymetry otherwise (Fig. 7).

Table 1: Water levels when lakes were empty/full (from Riley et al 2012). Lake Werri Berri and Lake Couridjah first form a lagoon, then overflow into Lake Baraba (Full level).

Lake	Full level		Dry
	AHD	Depth (m)	AHD
Lake Werri Berri	305.5	6	299.5
Lake Couridjah	305.5	6.1	299.4
Lake Nerrigorang	304.2	5.6	298.6

We then compared the lowest point of each lake with overflow points surveyed by Riley et al (2012), resulting in the maximal depth. This meant Lake Nerrigorang was almost six metres deep at its deepest point, compared to the other two lakes, which were slightly over 6m deep (Table 1), and already connected to a lagoon. Lake Werri Berri had the steepest bank of the three lakes and was also the longest of the lakes. These patterns were also clear in the three dimensional surfaces (Fig. 8). Lake Werri Berri and Couridjah form first a lagoon, and then overflow into Lake Baraba (Fig 1c). Lake Nerrigorang overflows into Blue Gum Creek at about 304.2 AHD (Riley et al. 2012). To fully understand flow directions at different water levels heights, also the remaining lakes would have to be surveyed.

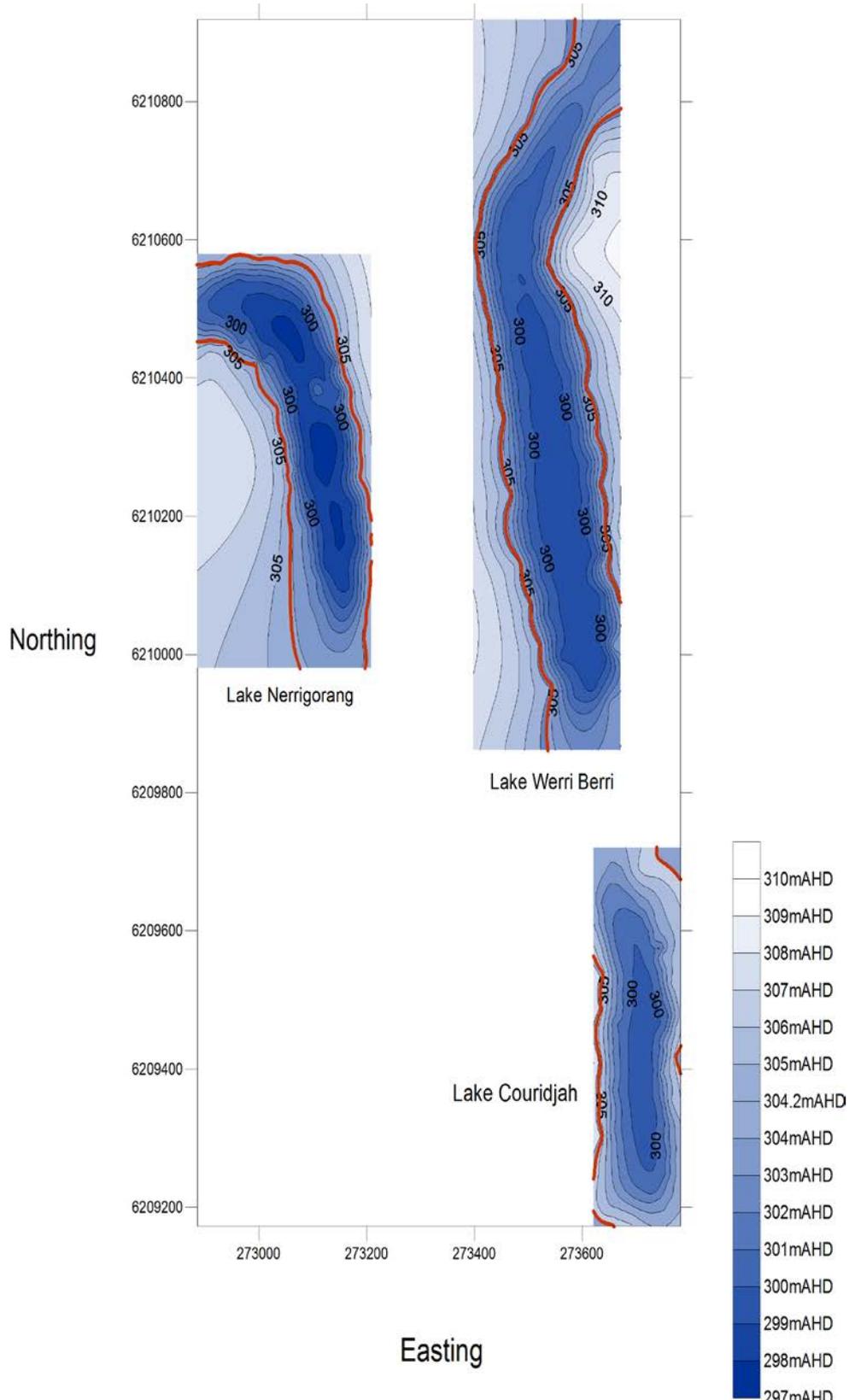


Figure 7: Contour maps, created from topographic surveys and labeled with 300m, 305 and 310m AHD contours (1m separation) for three Thirlmere Lakes (Lake Couridjah, Lake Werri Berri and Lake Nerrigorang), with their location (Easting and Northing) and bathymetry. Overflow of the lakes occurs above the red contour lines, when the lakes are at their maximum depth (Table 1).

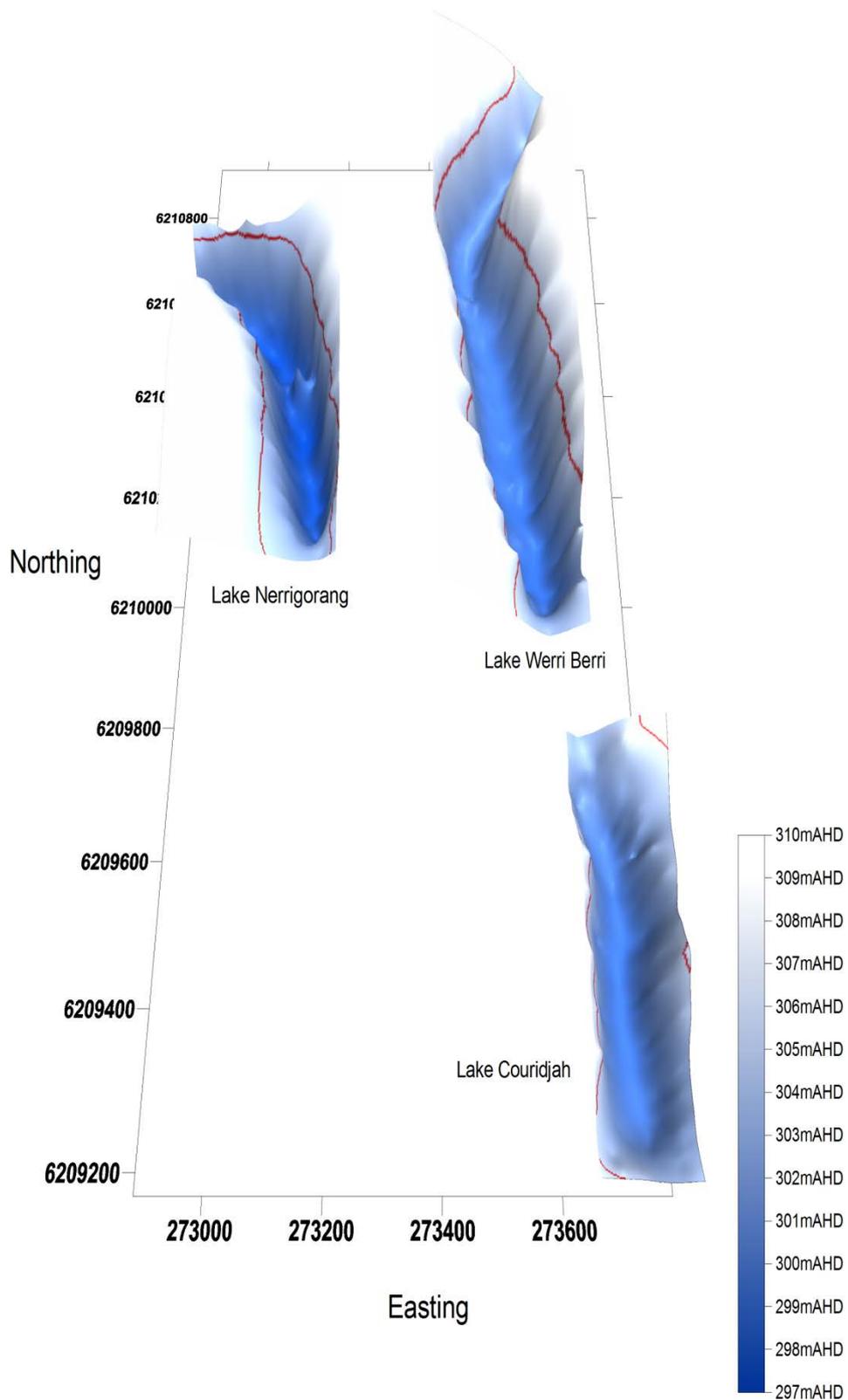


Figure 8: Three dimensional surfaces of three Thirlmere Lakes (Lake Couridjah, Lake Werri Berri and Lake Nerrigorang), created from topographic surveys and labeled with elevations 297-311 mAHd, with their location (Easting and Northing) and bathymetry. The lakes overflow at their maximum depth, above the red contour lines.

Abiotic drivers - rainfall patterns, 1900-2014

Similar rainfall patterns (1900 – 2014) were detected across all sites, with the highest correlations between Thirlmere Lakes and Warragamba Dam, and Thirlmere Lakes and Nepean Dam (Table 2). Annual rainfall at Avon Dam had a higher mean, median and variation, compared to the other three sites (Table 2).

Table 2: Means, medians, standard deviations, ranges for annual rainfall and correlation coefficients between pairs of rainfall sites (see Fig. 1), across all years (1900-2014, n= 115).

Station	Annual rainfall (mmy-1)				Correlation		
	Mean	Median	Standard deviation	Range	Thirlmere Lakes	Avon Dam	Nepean Dam
Thirlmere Lakes	829.9	830.1	245.5	1357.8	-		
Avon Dam	1076.0	1001.5	371.5	1823.7	0.90**	-	
Warragamba Dam	819.9	793.3	255.8	1682.6	0.93**	0.87**	-
Nepean Dam	950.7	913.5	295.5	1572.7	0.94**	0.91**	0.92**

** p-value > 0.01

There were also similar patterns detected in cumulative rainfall departure for all sites (Fig. 9), showing periods of decreasing and increasing trends in rainfall (1900-2014). Distinct periods of low cumulative annual rainfall occurred at the beginning of the

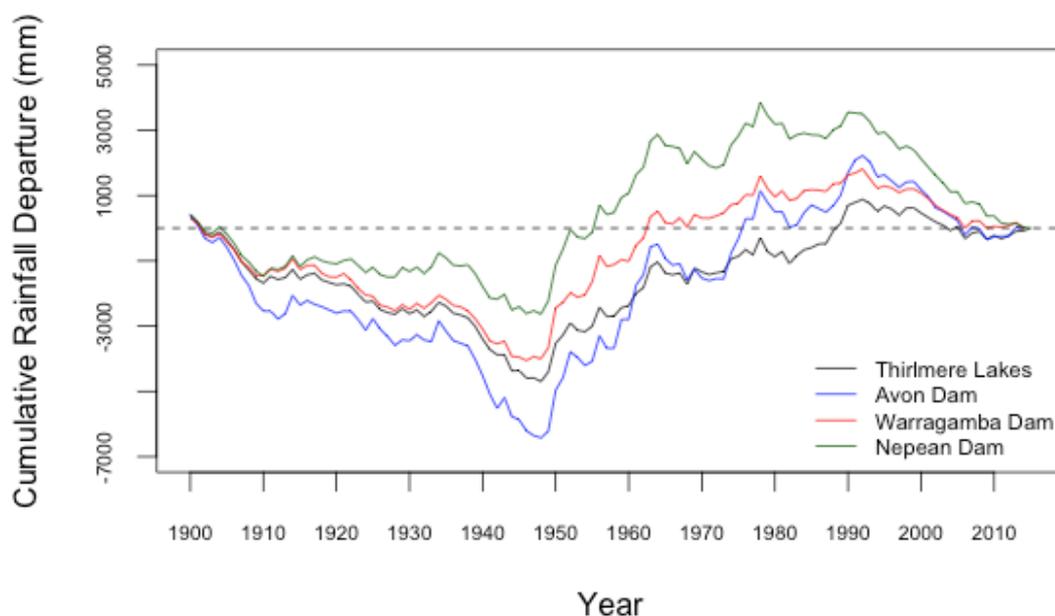


Figure 9: Cumulative annual rainfall departure curves (mm) for all four sites: Thirlmere Lakes, Avon Dam, Warragamba Dam and Nepean Dam, 1900–2014.

century and in the two periods: 1937–1947 and 1994–2009. These periods mark some of the worst droughts in Australia: the “Federation drought” (1895–1902); the “World

War II drought” (1937–1945) over eastern Australia and; the “Millennium drought” (2001–2009) over south-eastern Australia. The period 1937-1947 had lower cumulative annual rainfall than the other two periods identified (Fig. 9). The lowest years of rainfall (lowest quartile) for Thirlmere Lakes included the following 28 years: 1902, 1905-1909, 1915, 1918, 1923, 1924, 1926, 1932, 1936, 1939 – 1941, 1944, 1946, 1953, 1957, 1965, 1968, 1979, 1982, 1994, 1997, 2006 and 2009 (Fig. 18d). The six lowest years (and percentage of the mean) in increasing amount were 1944 (40.9%), 1979 (48.8%), 1940 (54.0%), 1982 (55.7%), 2006 (56.1%) and 1907 (56.2%). These coincide with strong signals in cumulative departure for rainfall (Fig. 9). Contrastingly, there were 28 years in the upper quartile, when rainfall was high: 1900, 1911, 1914, 1929, 1933 and 1934, 1949 – 1952, 1955, 1959, 1961 – 1963, 1969, 1974, 1976, 1978, 1983, 1984, 1988 – 1990, 1995, 1998 and 2007 (Fig. 18). These periods corresponded to increasing positive rainfall trends in cumulative departure from the mean (Fig. 9). No significant trends in annual rainfall were detected at the three control sites but rainfall increased at Thirlmere Lakes (Table 3).

Table 3: Mann Kendall's tau statistic and two-sided p-values for testing long-term trends in annual rainfall at the four sites, 1900-2014.

Site	Kendall's tau statistic ^a	Two-sided p-value
Thirlmere Lakes	0.128	0.04
Avon Dam	0.106	0.09
Warragamba Dam	0.064	0.32
Nepean Dam	-0.036	0.56

^aPositive value indicated an increase

Further, there was no significant trend in any quantile of annual rainfall for any of the four sites, with slope coefficients for each quantile within the confidence interval of the least square regression model (red dotted lines) (Fig. 10).

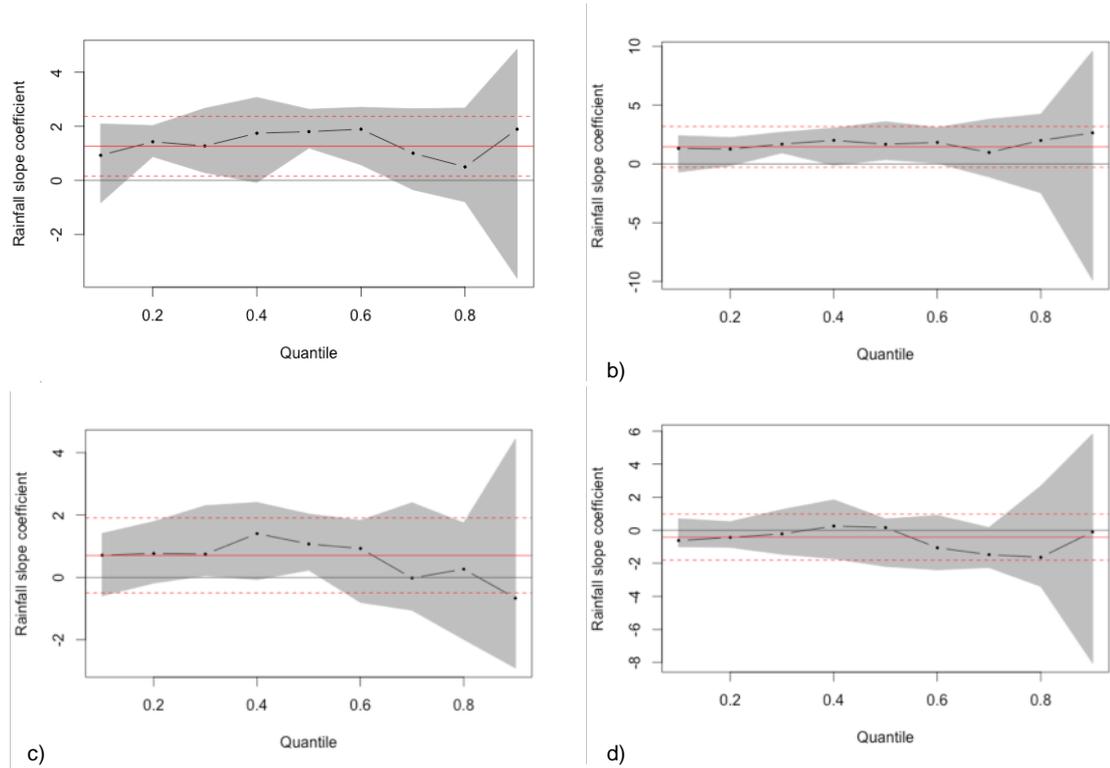


Figure 10: Mean rainfall slope coefficients ($\pm 95\%$ confidence interval (red dotted lines)) and quantile (0.1–0.9) rainfall coefficients ($\pm 95\%$ confidence interval (grey)) for the four sites: a) Thirlmere Lakes b) Avon Dam c) Warragamba Dam and d) Nepean Dam. Zero indicated no trend.

Abiotic drivers – inflows

Annual inflows (1906-2011) at the three ‘control sites’, the dams, were similar to rainfall patterns, with high interannual variability (Table 4). All three sites had different inflow volumes and variation, reflecting their catchment size and inflowing tributaries, with the highest inflows into Warragamba Dam (Fig. 11, Table 4). Inflows to Avon Dam and Nepean Dam were highly correlated but neither Avon Dam nor Nepean Dam inflows were correlated to inflows at Warragamba Dam (Fig. 11, Table 4).

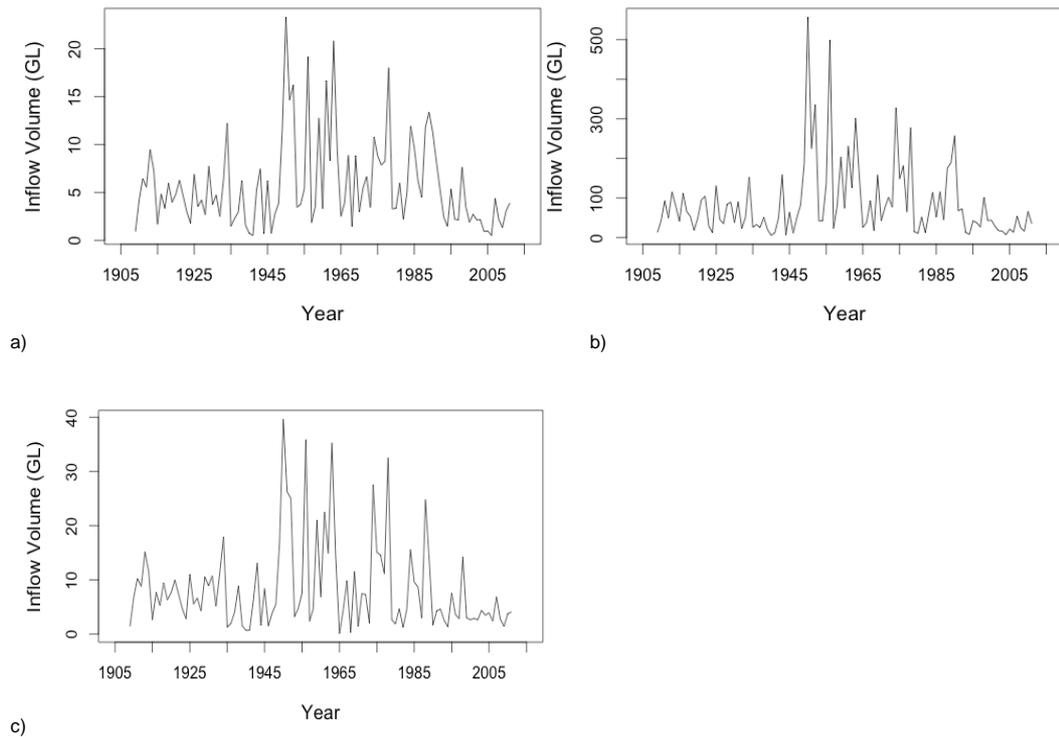


Figure 11: Annual inflows to a) Avon Dam, b) Warragamba Dam and c) Nepean Dam, (1906–2011). Data were based on inflow models for each of the reservoirs (Sydney Catchment Authority, unpubl. Data).

Table 4: Means, medians, standard deviations, ranges for annual inflow and correlation coefficients between pairs of inflow sites (see Fig. 1), across all years (1906 – 2011, n=105).

Station	Inflow (MLy ⁻¹)				Correlation	
	Mean	Median	Standard deviation	Range	Avon Dam	Warragamba
Avon Dam	5782.7	4392.9	4660.3	22779.7	-	-
Warragamba Dam	87946.3	52364.7	95902.0	551275.0	0.11	-
Nepean Dam	8450.6	5528.2	8206.9	39593.8	0.93	0.01

There were no significant trends in annual inflows over time (Table 5). There were also no detectable trends in inflows for different quantiles at Avon Dam, but inflows increased significantly at Warragamba Dam and Nepean Dam in the 80th and 90th quantiles (Fig. 12). Quantile regression lines, except the two highest ones at these two dams were similar to the least square model (Fig. 12a,c): they were not significantly different. This was also reflected in the slope coefficients (Fig. 12b,d).

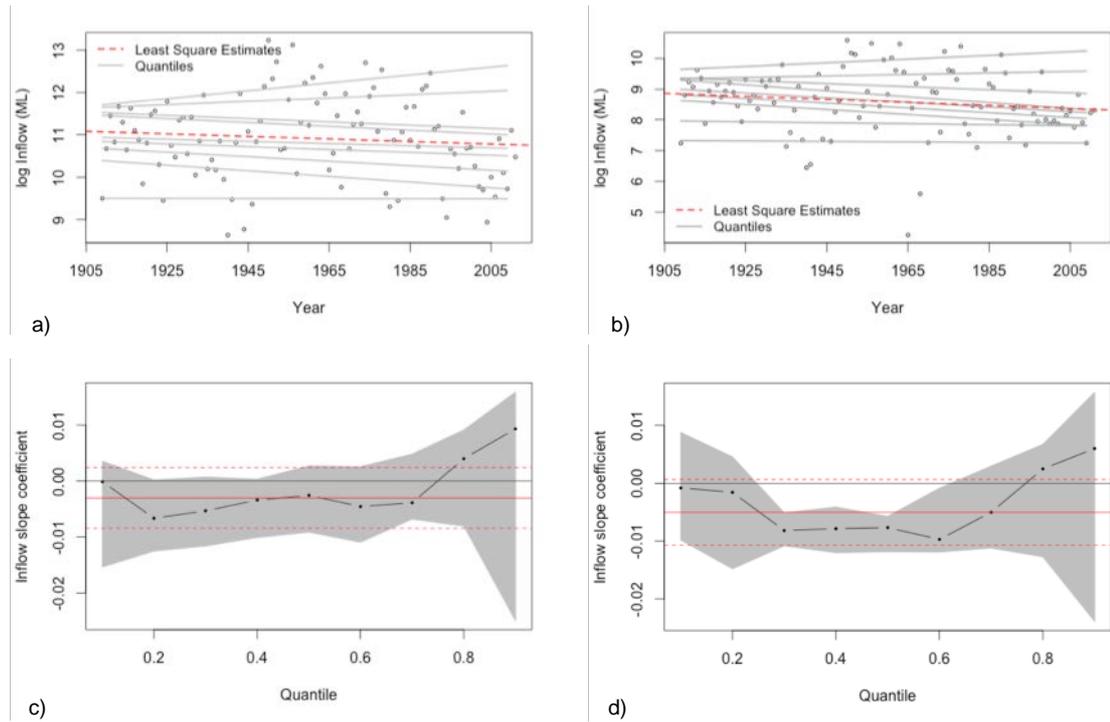


Figure 12: Inflows (log-transformed) over time (1906-2011), showing quantile regression lines (grey lines) and simple linear regression (red dashed line, least square estimate) for a) Warragamba Dam and b) Nepean Dam. Changes in coefficients of slope ($\pm 95\%$ confidence limits) for inflows to c) Warragamba Dam and d) Nepean Dam for each quantile.

Table 5: Mann Kendall's tau statistic and two-sided p-values for testing long-term trends in annual inflow at three sites, 1906-2011.

Site	Kendall's tau statistic ^a	Two-sided p-value
Avon Dam	-0.06	0.36
Warragamba Dam	-0.07	0.32
Nepean Dam	-0.12	0.06

^aPositive value indicates an increase

Abiotic drivers – evaporation patterns, 1900-2013

Like rainfall patterns, the increasing and decreasing trends in cumulative annual evaporation were similar among the four sites (Fig. 13), producing high correlations between sites (Table 6). Mean and median lake evaporation were highest at Warragamba Dam and lowest at Nepean Dam, which was also reflected in patterns of variation (Table 6). There were no overall trends in annual evaporation, detected at any of the sites (Table 7).

Table 6: Means, medians, standard deviations, ranges for annual lake evaporation and correlation coefficients between pairs of sites (Fig. 1), across all years (1900-2013, n= 114).

Station	Lake Evaporation (mm y ⁻¹)				Correlation		
	Mean	Median	Standard deviation	Range	Thirlmere Lakes	Avon Dam	Nepean Dam
Thirlmere Lakes	1259.0	1253.0	37.0	207.0	-		
Avon Dam	1227.5	1221.6	35.9	218.4	0.99**	-	
Warragamba Dam	1323.0	1317.0	38.5	191.9	0.99**	0.97**	
Nepean Dam	1227.3	1221.6	36.4	227.8	0.99**	0.99**	0.98**

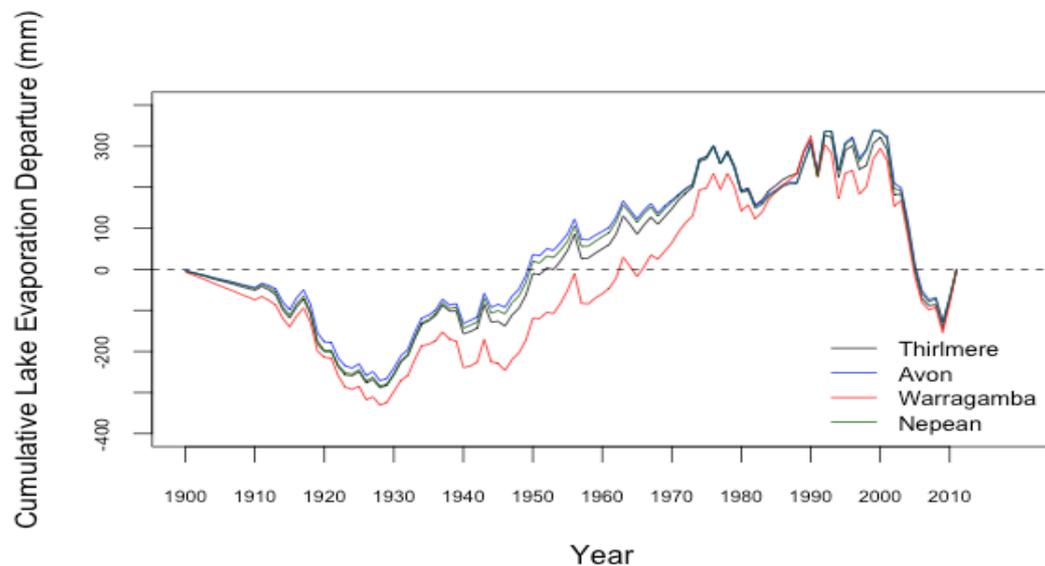


Figure 13: Cumulative annual evaporation departure curves (1900–2013) for all four sites: Thirlmere Lakes, Avon Dam, Warragamba Dam and Nepean Dam.

Table 7: Mann Kendall's tau statistic and two-sided p-values for annual evaporation at all four sites

Site	Kendall's tau statistic ^a	Two-sided p-value
Thirlmere Lakes	-0.08	0.23
Avon Dam	-0.05	0.41
Warragamba Dam	-0.12	0.06
Nepean Dam	-0.06	0.32

^aPositive value indicated an increase

Despite this, there were clear trends in the low and high quantiles for evaporation, at all sites (Fig. 14). The upper quantiles (80th and 90th) showed an increasing trend while the lower quantiles (10th, 20th, 30th and 40th) showed a decreasing trend (Fig.14).

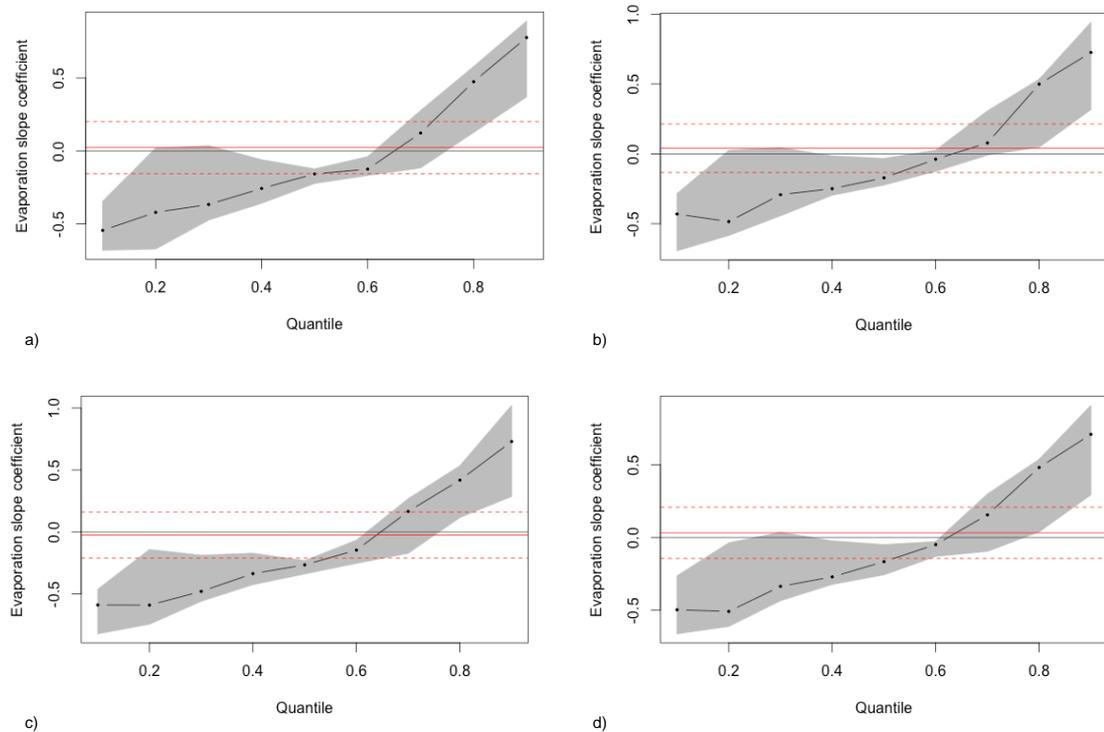


Figure 14: Mean evaporation slope coefficient ($\pm 95\%$ confidence interval (red dotted lines)) and 0.1 – 0.9 quantile evaporation coefficients ($\pm 95\%$ confidence interval (grey)) for the four sites: a) Thirlmere Lakes b) Avon Dam c) Warragamba Dam and d) Nepean Dam.

Water extraction from Thirlmere Lakes

Most of the water extraction from Lake Couridjah (Fig. 1c), primarily to refill steam engines, occurred between 1884 and 1910, averaging 85.2 ± 35.9 (SD) MLy^{-1} , about 22.4% of the total lake volume (Fig. 15). Peak water extraction was approximately in 1884, when 124 MLy^{-1} or 35% of the total lake volume was estimated to be extracted but this volume declined with improved networks and engines until no water was extracted when steam trains were no longer in use in 1964 (Fig. 15). Small amounts of water (mean 3.4 ± 1.4 SD MLy^{-1}) were also extracted for the Picton Village Tuberculosis Village (1934-1948). In 1934, 1.7 MLy^{-1} was extracted for the village, reaching 4.95 MLy^{-1} in 1943. In the following 5 years, the water demand decreased again until water from Thirlmere Lakes was no longer used in 1964 (Fig. 15).

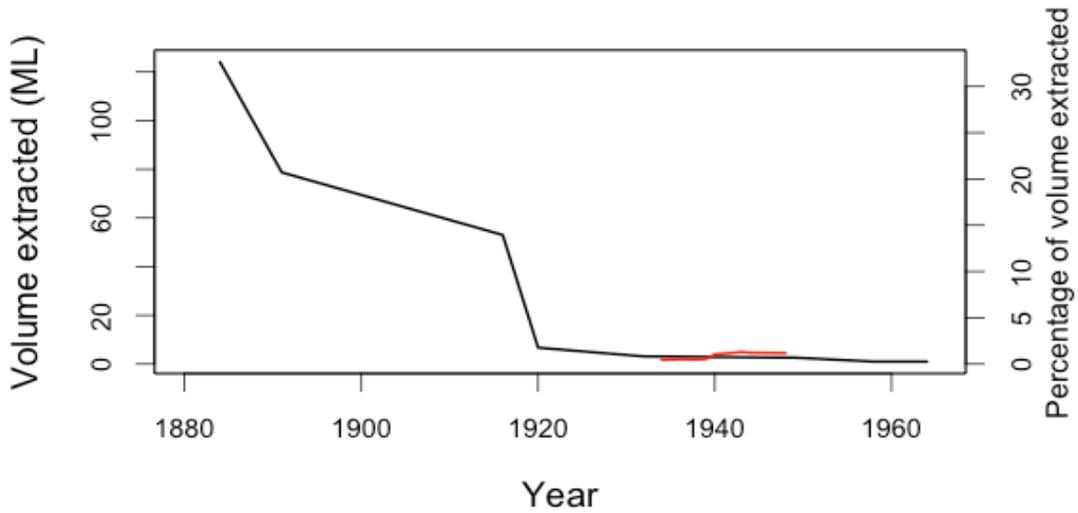


Figure 15: Annual volume (ML) and percentage of lake volume extracted from Lake Couridjah for steam trains (black) and the Picton Village Tuberculosis Village (red).

Groundwater

The number of bores sunk within 20km of Thirlmere Lakes has increased exponentially, since the 1930s (Fig. 16). Only two bores existed in the decade 1930–1940, within 20km and none within a 10 km or less of Thirlmere Lakes. By 1970–1980, there were 40 bores within 20km. After the 1980’s the number of bores grew with 20, 96 and 235 bores respectively within 5, 10 and 20km by 2011. (Fig.16).

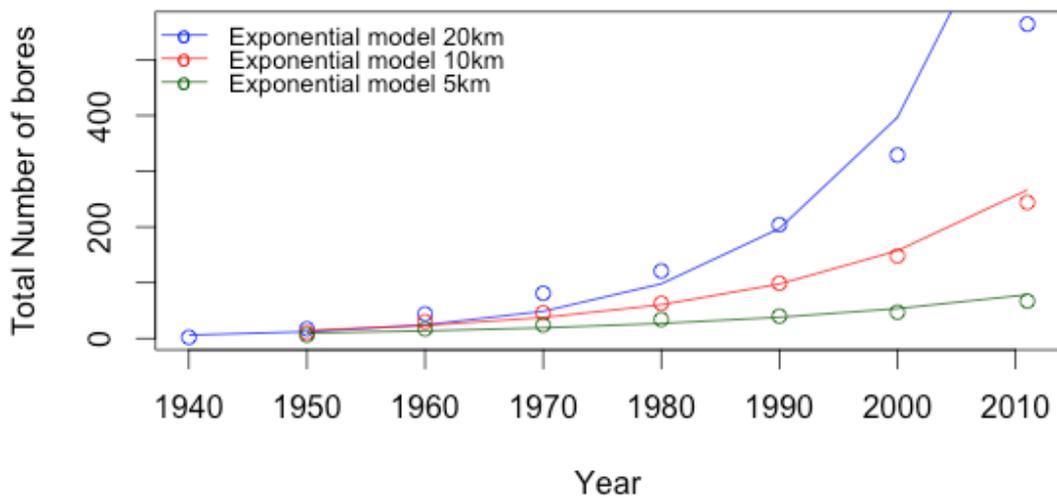


Figure 16: Number of groundwater bores (circles) sunk within 5km (green), 10km (red) and 20km (blue) of compared to exponential models (lines) at Thirlmere Lakes (data 1930–2011).

There were changes to shallow groundwater levels after 1982, when longwall mining began at Tahmoor Colliery (Fig. 17). Groundwater contour lines near Thirlmere Lakes have shifted to the east, compared to before 1982, and had dropped by 0 – 40 m (Fig. 17).

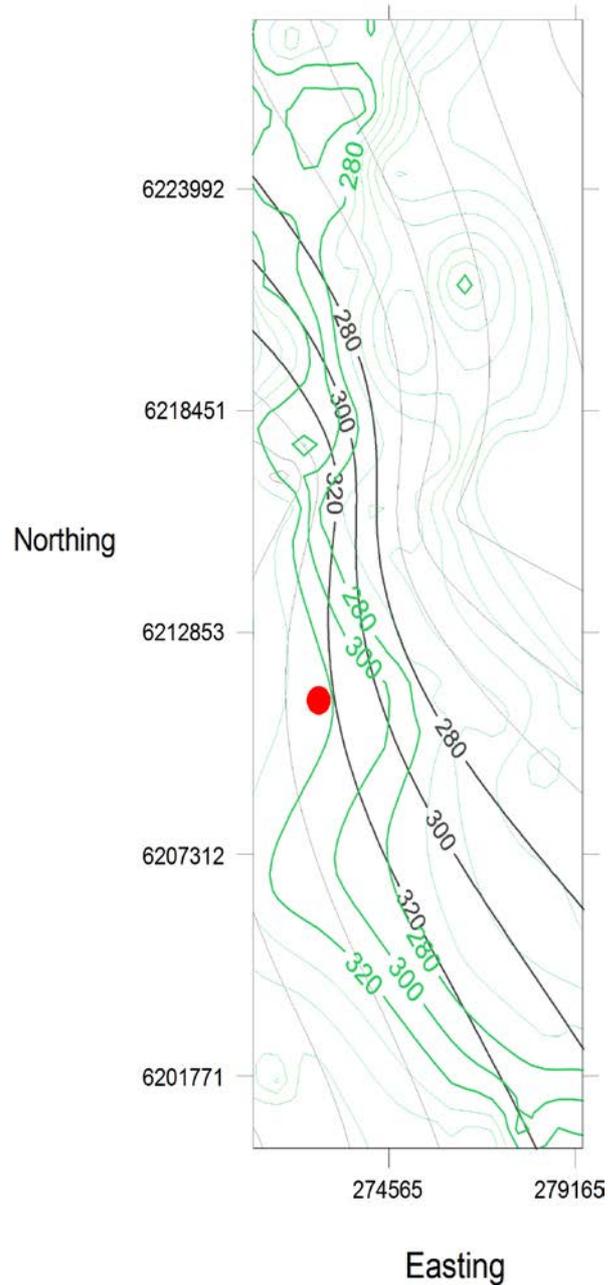


Figure 17: Groundwater contours of water levels (20 m separation) before longwall coal mining began in 1982 (black) and afterwards (green), in relation to Thirlmere Lakes (red circle).

Groundwater contour levels (1999 – 2013) averaged in five-year blocks within a 20km Radius of Thirlmere Lakes, also showed about a 40m reduction in water levels (Fig 18).

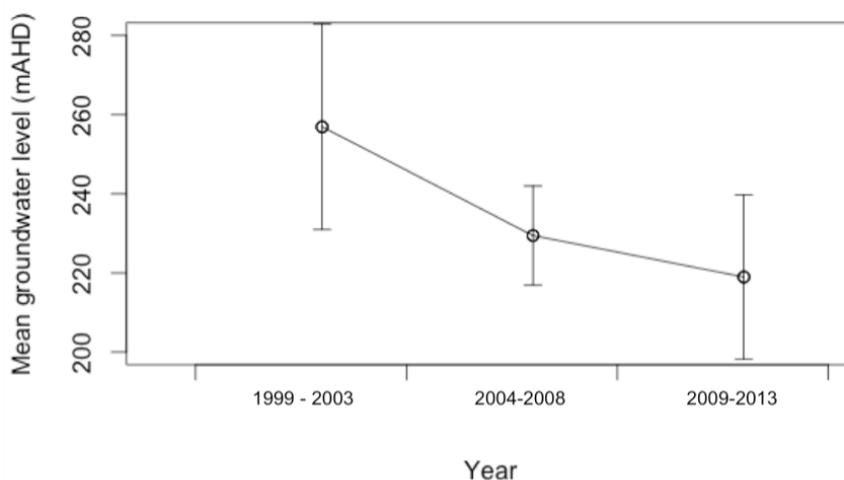


Figure 18: Mean (\pm SE) groundwater levels (averaged over 5 year periods 1999 – 2013) within 20km of the Thirlmere Lakes. Data were from levels encountered when bore holes were first established (NSW Office of Water data).

Water levels at Thirlmere Lakes

Water levels at all Thirlmere Lakes: Lake Werri Berri, Lake Couridjah and Lake Nerrigorang were highly variable over time (Fig. 19a,b,c), but showed similar patterns. Until the late 1980s to the early 1990s, water levels at all lakes primarily reflected rainfall patterns with peak water levels occurring in years of above average rainfall (Fig. 19). Previous periods of low rainfall, such as 1937–1947 (Fig. 9), resulted in low water levels at the three Thirlmere Lakes. Since 1994, water levels have consistently fallen. The reasonably close relationship between rainfall and water levels separated after 1990, with average or even above average rainfall not reflected in rising water levels (Fig. 19). This decoupling of rainfall and water levels at Lake Nerrigorang may have occurred even earlier, possibly early 1980s, compared with water levels at Lake Werri Berri and Lake Couridjah (Fig. 19).

This was reflected in the increasing disassociation between rainfall and water levels (ie index of change) over time, for all three lakes, particularly recently (1985–2015, Fig. 20). Given that the index was the difference between rainfall departure from the mean and water level, a trend in the index reflected an altered relationship between the two

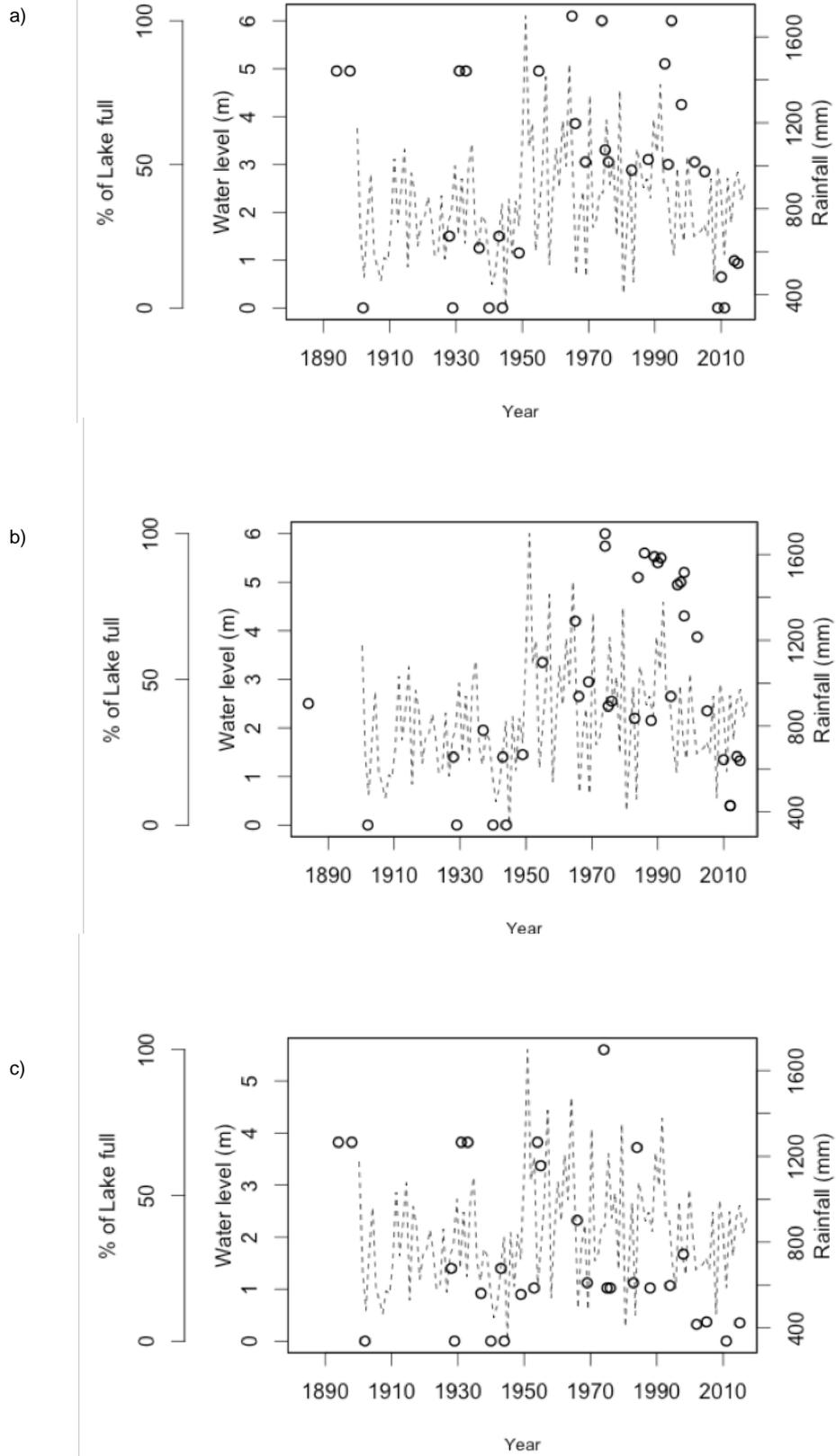


Figure 19: Water levels at a) Lake Werri Berri, b) Lake Couridjah and c) Lake Nerrigorang in relation to annual rainfall (dashed line).

variables. If water levels and rainfall had tracked similarly over time, there would be no trend in the index.

The increasing trend (Fig. 20) suggested that differences between rainfall and water level z-scores constantly increased. The significant trend became increasingly positive since the mid 1980's. Either rainfall increased and water levels were stable; rainfall was static and water levels decreased or rainfall increased and water levels decreased. Because there were no long-term changes in rainfall (Table 3, Fig 10), this increasing trend in the index was probably attributable to reductions in water levels (Table 8, Fig. 20).

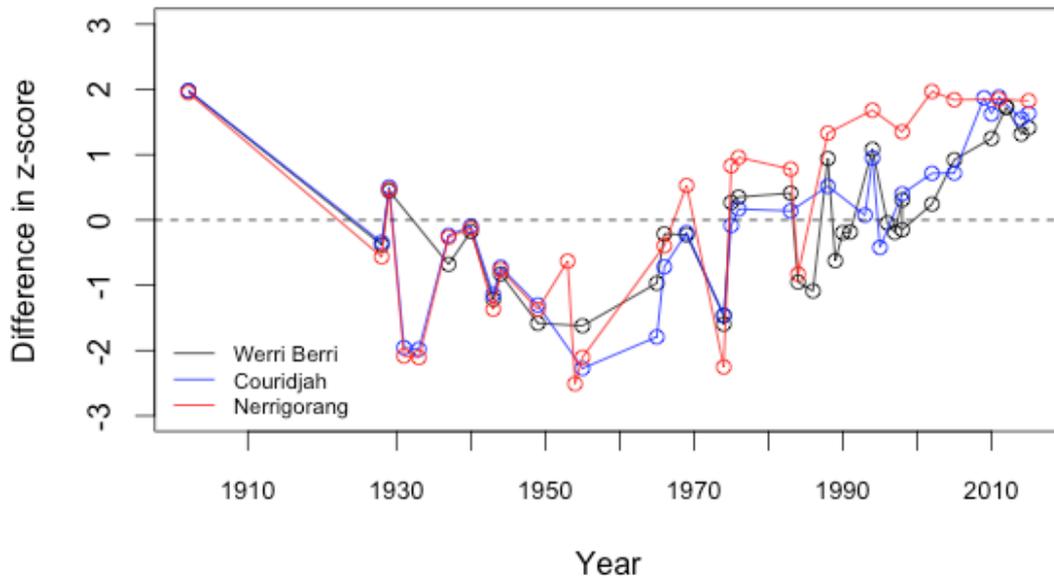


Fig 20: Increasing index of change, being positive for all Lakes since approximately 1980.

Sensitivity analyses of the potential error on water level estimates from ground photographs indicated a maximum of 0.06% change in estimates.

Table 8: Mann Kendall's tau statistic and two-sided p-values for differences in z-scores at the Thirlmere Lakes

Site	Kendall's tau statistic ^a	Two-sided p-value
Lake Werri Berri	0.49	< 0.01
Lake Couridjah	0.41	< 0.01
Lake Nerrigorang	0.40	< 0.01

^aPositive value indicates an increase

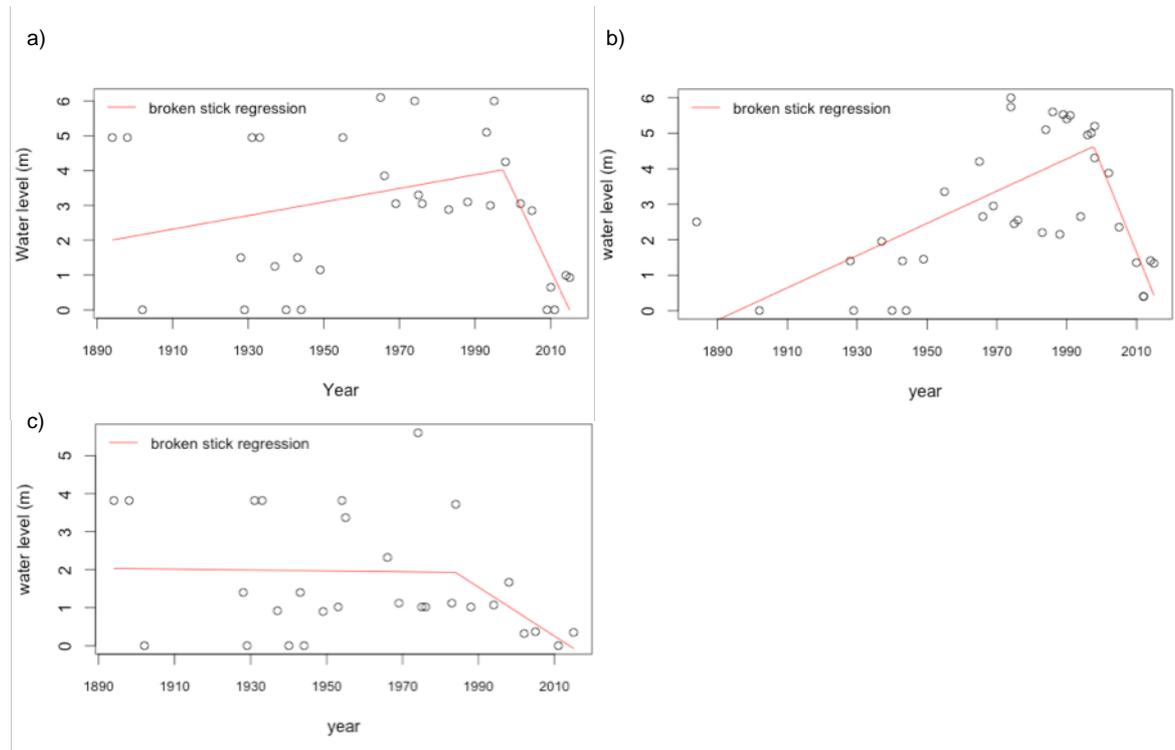


Figure 21: Broken stick regression lines (red) for water levels, showing change points when relationships between water levels change at a) Lake Werri Berri (1997), b) Lake Couridjah (1998) and c) Lake Nerrigorang (1984).

We identified clear change points in water levels at the three lakes: Lake Werri Berri in 2004 (Fig. 21a), Lake Couridjah in 2000 (Fig. 21b) and Lake Nerrigorang in 1998 (Fig. 21c, Table 9). Broken stick regression showed clear change points at the three lakes, after which there were rapidly falling water levels (Fig. 21).

Table 9: Broken stick regression estimates for the three Thirlmere Lakes showing variance explained (R^2), estimated year of breakpoint and associated Standard Error.

Site	R^2	Breakpoint estimate	Standard Error
Lake Werri Berri	0.27	1997	6.37
Lake Couridjah	0.55	1998	3.19
Lake Nerrigorang	0.14	1984	22.4

Discussion

There was good evidence for significant changes to long-term natural water level patterns at Thirlmere Lakes (1880–2015), reflecting alteration of filling and drying recently (Fig. 19). Water levels in Thirlmere Lakes have considerably declined recently, probably since the 1980s, a trend not explained by natural variation in climate. We reconstructed historical water levels in three of the lakes (Fig. 19), not previously available, using constructed digital elevation models of the lakes. Our results suggest an increasing trend of disassociation between rainfall and water levels since 1980, when rainfall no longer seemed to affect water levels in the lakes (1980–2015, Figs 19 & 20). The magnitude of this change was unlikely to be explained by increasing temperatures or increasing evaporation. Such altered filling patterns were probably due to changed surface and groundwater flows, caused by anthropogenic impacts (longwall coal mining and/or increased groundwater pumping), as we found no such breaks in climate or inflow patterns at our three ‘control’ sites (Fig. 11).

Rainfall patterns (1900–2014) were strongly correlated at all four sites (Table 2), with no significant trends at the three ‘control’ sites (Fig. 9 & 10), and an even some indication of increasing rainfall at Thirlmere Lakes (Table 3), which would be expected to increase the volume of water in the lake. Evaporation patterns (1900–2011) at all four sites were also strongly correlated (Fig. 13, Table 6) with no trends in overall mean (Table 7) but increasing trends in the high evaporation quantiles (Fig. 14), indicating increased variability. Contrastingly, there was evidence that evaporation decreased in the low quantiles (Fig. 14). Reflecting rainfall patterns, inflows (1906–2011) to the three large dams (Avon, Warragamba and Nepean Dams) were strongly correlated with few detectable trends (Table 5), except for increased high volume inflows (Fig. 12), similar to the increased high rainfall at Thirlmere Lakes (Table 3). Absences of any strong trends in rainfall, evaporation or inflows at any of the three ‘control’ sites and rainfall and evaporation at Thirlmere Lakes indicated little evidence for a decline in hydrological inputs (i.e. rainfall) were the cause of the drying out of Thirlmere Lakes (Fig. 19).

There was an increasing disassociation between rainfall and water levels since 1980, coinciding with reductions in water levels in the lakes (Table 8, Fig. 20). There were also obvious change points, indicative of sudden drops in water levels, varying for each lake: Lake Werri Berri in 1997, Lake Couridjah in 1998 and Lake Nerrigorang in 1984 (Table 9, Fig. 21). This suddenness implicates a pulse disturbance, rather than a press disturbance (Lake 2000), indicative of a sudden decrease in water supply potentially caused by increasing groundwater extraction or alteration of inflows from changes to the aquifer caused by mining disruption. In the early part of the 20th Century, there was no evidence for any decline in long-term water levels when significant amounts of water (15–35% of total lake volume) were extracted from Lake Couridjah for steam trains (until 1920, Fig. 9), during a period of low rainfall, despite relatively few data points in this period (Fig. 19).

Thirlmere Lakes clearly dry naturally, with records of extremely low water levels and drying at the beginning of the 20th century and in the early 1920s (Rose & Martin 2007; Pells 2011; Riley et al. 2012). Such drying events coincided with severe dry periods, with low rainfall (Fig. 19). Separating natural drying periods from increased drying from anthropogenic impacts is critical. Given the relative simplicity of the hydrological system (i.e. no large catchment), the relationship between rainfall and water levels was expected to be close, reflected in the differences between standardised water levels and rainfall before 1980 (Fig. 20). The most recent drying period reflected a separation of this relationship. Despite the paucity of data, water levels were reasonably stable during the period 1910–1930 (Fig. 19), a sequence similar in rainfall to the last 20 to 30 years. The dramatic recent decline in water levels clearly did not occur in the previous period with similar rainfall. Water levels previously recovered quickly after dry spells. After the World War II drought, with rainfall among the lowest six years on our record (1940, 1944), water levels in the lakes had recovered by 1949, at the beginning of a period of high rainfall. This did not happen after the Millennium drought, despite the ranking of 2007 among the years of rainfall within the highest quantiles.

Another study reached a similar conclusion, estimating that water levels were 1.5–2.5m lower than expected from natural climate drivers (Pells 2011). Contrastingly, New South Wales Government and Gilbert & Associates (2012) analyses concluded that water levels at Thirlmere Lakes were low due to below average rainfall (Russell et al. 2010; Riley et al. 2012). None of these studies statistically analysed long-term rainfall patterns. Two examined long-term changes (Russell et al. 2010; Gilbert & Associates 2012), while Riley et al (2012) only examined the last 23 years, and did a detailed

drought analysis. Only Pells (2011) and Gilbert & Associates (2012) reconstructed water levels, but had a limited number of data points, compared to our study. Modelling by Gilbert and Associates (2012) replicated current levels based on climate alone but this did not adequately predict past droughts. The historical levels used did not examine the effects of Federation and World War II droughts but are critical to predict current levels. There were other inaccuracies regarding water levels at the three lakes; Lake Nerrigorang was predicted from their modelling to dry in 1960, 1972, 1980-1988 and 1996-2007. Further, Lake Werri Berri was predicted to be dry in 1982, mostly dry in 1984-1986, 1997-1999 and 2003-2007. These predictions were false, given available photographic data and reliable anecdotal evidence, some of which was used by Gilbert and Associates (2012).

Clearly, our detailed analyses of rainfall data for the site suggests that a conclusion that lower water levels were due to low rainfall was unfounded. The Millennium Drought (2002-2009), with low rainfall throughout eastern Australia, may have contributed to this interpretation but it was not drier than the Federation Drought (1895 - 1902) or World War II Drought (1937 - 1945) at Thirlmere Lakes (Pells 2011; Riley et al. 2012), illustrated by rainfall patterns (Fig. 9). Therefore, these drier periods should have produced similarly low water levels at the Thirlmere Lakes than the Millennium Drought. This occurred but water levels usually recovered rapidly, following significant rainfall, unlike the most recent period (Fig. 19). Our long-term analyses of rainfall clearly showed that, during similar significant dry periods, lake levels dropped but then recovered. Recent high rainfall events filled Thirlmere Lakes in 2012, but water levels then declined, a process with no historical precedent. Hydrological models were used by others to simulate water level response to rainfall, but relied primarily on assumptions and estimates from other areas, given the lack of available hydrological data (Pells 2011), with contrasting conclusions (Pells 2011; Riley et al. 2012; Gilbert & Associates 2012). We considerably extended and filled existing gaps in the water level record and updated and analysed rainfall data until 2013, when the Millennium drought had clearly broken, and yet drying of the lakes continued.

Given little evidence that drying of Thirlmere Lakes was related to the key natural drivers, identification of the cause remains critical, given the conservation importance of the system and its wetland values. Thirlmere Lakes fill from local rainfall and surface flow but they also rely on groundwater processes (Riley et al. 2012). The declining groundwater levels coincided with establishment of longwall mining and groundwater extraction. These two anthropogenic drivers have probably changed groundwater flow

patterns; both highly complex and their effects difficult to distinguish without good understanding of connectivity processes in the groundwater systems which currently do not exist. The effects of groundwater extraction and mining on surface water can both occur suddenly or with a significant time lapse, depending on several factors. However, the effects from groundwater extraction are more likely to be characterised by a press disturbance. It would be predicted that such an effect would be gradual over time and would still follow rainfall patterns (Barlow & Leake 2012). Contrastingly, mining impacts on groundwater may be more of a pulse disturbance, with a sudden onset and intense change (Bender 1983). In natural systems, such pulses can be recoverable. Water levels at the Thirlmere Lakes have likely been slowly declining since the 1980's from groundwater extraction, followed by the sudden break indicative of a pulse impact, as opposed to a press disturbance. It is likely that longwall mining development, rather than increasing groundwater access was also a significant factor in the relatively sudden decline in water levels.

Mining of coal resources disrupts groundwater flow paths, moving water to lower pressure areas, including extraction locations (Eade & Wood 2001; Booth 2006; DECC 2007). This problem is partly reflected in the need for coal mines to pump out groundwater, seeping into mine workings (Tahmoor Underground - Glencore 2013). In the Tahmoor Colliery, adjacent to Thirlmere Lakes (Fig. 1c), mine water discharge was 1200 -1600 MLy⁻¹, 1995-2011 (Pells 2011). At Thirlmere Lakes, the Bald Hill Claystone layer lies between the shallow and the deep aquifer, where mining occurs (Fig. 2), probably preventing downward vertical movement of water into the deep aquifer (Russell et al. 2010; Jankowski & Knights 2010), although this is contentious. However, coal mining has probably increased the permeability of the Bald Hill Claystone (Holla & Buizen 2001; Jankowski et al. 2008; Pells & Pells 2012), potentially increasing the connectivity of the aquifers (Fig. 2) and increasing groundwater loss from Thirlmere Lakes. The block of longwall panels closest to the lakes were established recently (1997 – 2004), coinciding with the significant drop in water levels of the lakes (Figs 19 & 20). There is clearly a need to apply the Precautionary Principle before the nature of this mechanism is further investigated.

Numbers of groundwater bores, mostly extracting water from the shallow groundwater aquifer, have also increased, contributing to declines in groundwater levels by 40m in the same period after longwall mining (Figs 17 & 18). These may have increased drying of the lakes, although unlikely to be the major cause as their increase does not

explain sudden change points (Fig. 14). Further, groundwater impacts are generally slow to materialise, with substantial time lags (Kelly et al. 2013).

Our estimates of historical water levels were critical to our conclusions. There were minor inaccuracies (<0.28%) produced by the swelling peat surface, from heavy rainfall during our surveys. Although greatest at Lake Couridjah, they minimally affected our estimates of lake levels, given the large lake volume. Our estimates of water levels, using historical ground photographs, were probably less accurate than estimates from aerial photographs, given effects of different angles and distances. Despite this, the discrepancies were low, given we found minimal differences between aerial and ground photographs for three dates and showed that there was less than one percent uncertainty in estimating the length of an object on the photographs (e.g. height of a male adult) introduced a maximum error of 0.06%.

There are clearly significant environmental impacts caused by this drying. Thirlmere Lakes is undoubtedly of high conservation value due to its old age and ecological importance (NSW National Park and Wildlife Service 1997; Environment Australia 2001). The area is listed in the Directory of Important Wetlands in Australia (Environment Australia 2001) for 5 out of 6 criteria, including playing an important ecological and hydrological role in the natural functioning of the wetland complex and providing important habitat for animal taxa at a vulnerable stage in their life cycle. However, the predominantly perennial wetland ecosystem is moving towards a temporary wetland or terrestrial ecosystem state. This will reduce resilience of key obligate aquatic species and communities highly dependent on past flow regimes and open water area (DECC 2007). The rare sponge *Radiospongilla sceptroides* may have already disappeared from the Thirlmere Lakes National Park (B.Owers, pers. comm.). Similarly, the floating islands, an unusual feature of Thirlmere Lakes connected to fluctuating water levels, relies on quickly recovering water levels (Vorst 1974; Riley et al. 2012). Also, Thirlmere Lakes provides habitat to many listed threatened wetland species: five species of waterbirds, a fish, two frog species and two plant species.

The New South Wales Government has pledged to protect the values of Thirlmere Lakes by gazetting the area as a National Park and committing in the Plan of Management to protect “*the lakes in a stable and unpolluted condition*” given the “*important physical and ecological features of the ancient [...] system*” and preserve the park because water flows into Sydney’s water supply (National Parks and Wildlife Service NSW 1997). The ecological character of Thirlmere Lakes is changing, affecting this commitment to the values in the Plan of Management. Furthermore, Thirlmere

Lakes National Park is part of the Greater Blue Mountains World Heritage Area (World Heritage Committee 2000), adding another commitment to protect, manage and monitor the Thirlmere Lakes National Park which is a site of special natural significance. Finally, the values of the lakes as a recreational and tourist destination are also affected by declining water levels.

Conclusion

Water levels at the Thirlmere Lakes have receded since the 1980s, despite few strong trends in climatic drivers or filling patterns at the lakes or three 'control' sites. These changes were reasonably sudden. The system is highly dependent on surface flow, which then flows into the groundwater system, lowering lake levels, which are replenished by high rainfall. We identified two potential anthropogenic causes: increased groundwater extraction and impacts of longwall mining leading to greater losses of groundwater and surface water from the lakes. There are significant implications for the long-term management and obligations of governments to an area that is gazetted as a National Park and part of the Blue Mountains World Heritage Area. It is also an important recreational area. The damage to the ecosystem are not easily reversed but will be exacerbated by increasing deleterious developments.

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Appendix

Ground and aerial imagery used to determine water levels at different Thirlmere Lakes, giving the type of imagery, its date of acquisition, source, relevant lake and reference point (see Fig. 1c) used to determine water levels.

Imagery type	Date	Source	Thirlmere Lake	Reference point	Water level (mAHD)	Accuracy
Ground photography	1974	Patricia Fanning	Lake Couridjah	Jetty	301.74	± 0.06%
	1984	David Hunt	Lake Couridjah	Stone Wall	301.1	± 0.06%
	1989	David Hunt	Lake Couridjah	Jetty	301.6	± 0.06%
	1989	David Hunt	Lake Couridjah	Jetty	301.7	± 0.06%
	1989	David Hunt	Lake Couridjah	Jetty	301.3	± 0.06%
	1990	Mall Juske	Lake Couridjah	Jetty	301.5	± 0.06%
	1997	NPWS	Lake Couridjah	Jetty	301.0	± 0.06%
	1998	NPWS	Lake Couridjah	Jetty	300.5	± 0.06%
	1996	Dr Scott Mooney	Lake Couridjah	Stone Wall	300.95	± 0.06%
	2012	Philip Pells	Lake Couridjah	Survey	296.47	± 0.06%
	2012	Philip Pells	Lake Couridjah	Survey	296.3	± 0.06%
	1991	Anon./Thirlmere Lakes Inquiry	Lake Couridjah	Stone Wall	301.5	± 0.06%
	2002	Jeff Patchett	Lake Couridjah	Stone Wall	301.7	± 0.06%
	1998	Jeff Patchett	Lake Couridjah	Jetty	301.86	± 0.06%
	1965	State Library	Lake Couridjah	Jetty	300.2	± 0.06%
	1986	Anon./Thirlmere Lakes Inquiry	Lake Couridjah	Jetty	301.6	± 0.06%
	1989	Anon./Thirlmere Lakes Inquiry	Lake Couridjah	Jetty	301.6	± 0.06%
	1884	Anon./Picton & District Historical Society	Lake Couridjah	Survey	298.5	± 0.06%
	1953	Oakes Historical Society	Lake Nerrigorang	Jetty	299.62	± 0.06%
	1954	Annette Bray	Lake Nerrigorang	Bench	302.42	± 0.06%

Imagery type	Date	Source	Thirlmere Lake	Reference point	Water level (mAHD)	Accuracy
	1955	P. Rackleyft	Lake Nerrigorang	Bench	302.32	± 0.06%
	1984	Anon./State Library	Lake Nerrigorang	Bench	302.32	± 0.06%
	1993	Angela Jansz	Lake Werri Berri	Stone Wall	304.6	± 0.06%
	1998	NPWS	Lake Werri Berri	Stone Wall	304.1	± 0.06%
	2011	Philip Pells Report	Lake Werri Berri	Survey	298.94	± 0.06%
	2010	Julie Shepard	Lake Werri Berri	Survey	300.1	± 0.06%
	1965	Anon./State Library	Lake Werri Berri	Tree	305.6	± 0.06%
	2011	Rosie Nicolai	Lake Werri Berri	Survey	298.94	± 0.06%
	2011	Tess Carrad	Lake Werri Berri	Survey	298.9	± 0.06%
	2011	Max Phillips	Lake Werri Berri	Survey	298.94	± 0.06%
					WB, C, N	
Aerial photography	1937	State Records NSW	All		300.75,301.45,299.51	±0.1m
	1949	National Library of Australia	All		300.65,300.95,298.46	±0.1m
	1955	NSW Land & Property Information	All		304.45,302.85,301.61	±0.1m
	1966	Pells Progress Report 2	All		303.35,302.15,300.91	±0.1m
	1969	NSW Land & Property Information	All		302.55,302.45,299.71	±0.1m
	1975	Pells Progress Report 2	All		302.8,301.95,299.61	±0.1m
	1976	State Records NSW	All		302.55,302.05,299.61	±0.1m
	1983	NSW Land & Property Information	All		302.4,301.15,299.61	±0.1m
	1983	Pells Progress Report 2	All		302.34,302.25,299.71	±0.1m
	1988	NSW Land & Property Information	All		302.6,301.65,299.61	±0.1m
	1994	Pells Progress Report 2	All		302.5,302.15,299.66	±0.1m
	1998	NSW Land & Property Information	All		303.4,302.05,300.26	±0.1m
	2002	NSW Land & Property Information	All		302.55,301.55,298.92	±0.1m

Imagery type	Date	Source	Thirlmere Lake	Reference point	Water level (mAHD)	Accuracy
Maps	2005	Pells Progress Report 2	All		302.35,301.85,298.96	±0.1m
	2010	Pells Progress Report 2	All		300.15,300.85,298.11	±0.1m
	1894	NSW Land & Property Information	All		304.45,302.85,302.41	
	1898	NSW Land & Property Information	All		304.45, 302.85,302.41	
	1931	State Library of NSW	All		304.45, 302.85,302.41	