Department of Planning and Environment

Thirlmere Lakes – A Synthesis of Current Research

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Executive summary

Thirlmere Lakes, in the Greater Blue Mountains World Heritage Area, is a group of five waterbodies that comprise Lake Gandangarra, Lake Werri Berri, Lake Couridjah, Lake Baraba and Lake Nerrigorang. The Thirlmere Lakes National Park was established specifically to protect these five perennial freshwater lakes. The Aboriginal or First Nations People of Australia were custodians of the land surrounding Thirlmere Lakes long before European arrival. The Camden–Picton–Thirlmere area was at the intersection of three language groups: the Dharug, the Tharawal and the Gundungurra. To this day, Thirlmere Lakes National Park remains part of Country for Aboriginal people and provides opportunities for the maintenance and renewal of cultural practice and connections to Country. The local community are also heavily invested in Thirlmere Lakes, particularly in terms of recreation and appreciation of its natural surroundings. Thirlmere Lakes National Park is jointly managed by the NSW National Parks and Wildlife Service (NPWS) and WaterNSW, as the national park is within the Warragamba Special Area and part of Sydney's drinking water catchment.

Water levels in Thirlmere Lakes have fluctuated over time, but there has been a recent decline that is and remains of significant concern to the local community. In response to these community concerns, the NSW Government appointed a group of four independent scientists and a community representative to evaluate possible causes for the low water levels in the lakes (Independent Committee – Thirlmere Lakes Inquiry; Riley et. al. 2012). Their findings were reviewed by the State's Chief Scientist and Engineer, Professor Mary O'Kane (CSE 2013). Both the Independent Committee and the Chief Scientist and Engineer agreed that more research needed to be done to fully understand how the lake system works before there can be a proper understanding of what is affecting water levels. In 2014 instrumentation was placed in and around the lakes to monitor lake levels and local climate. The then NSW Office of Environment and Heritage (OEH) (now Environment, Energy and Science group of Department of Planning and Environment, the department) subsequently committed $1.9 million over four years to a research program designed to help provide an understanding of the fluctuating water levels. The *Thirlmere Lakes Research Program* was announced by Jai Rowell, MP for Wollondilly, on 20 October 2017.

The *Thirlmere Lakes Research Program* aimed to provide a much more detailed understanding of the hydrological dynamics, water sources and water flow pathways for Thirlmere Lakes than what had existed previously. This was achieved by detailed investigations of the geology, geomorphology, hydrogeology and hydrology of the system. From the outset it was agreed that the research findings were to be shared between the research agencies, stakeholders and the community to achieve a collegiate outcome and help answer the fundamental community concern about whether the Thirlmere Lakes were losing water due to the impact of mining at the nearby Tahmoor coal mine. In attempting to address the question of *Where has the water gone*? though*,* it is equally important to address the question of *Has there been less water getting in*?

The overall aims of the *Thirlmere Lakes Research Program* were to:

- provide a detailed understanding of the hydrological dynamics of Thirlmere Lakes
- use that knowledge to promote best management practices for Thirlmere Lakes and the national park
- collate existing and new knowledge on Thirlmere Lakes into a Thirlmere Lakes database
- transfer knowledge gained in the program to agencies, land managers, relevant stakeholders and the community, and
- maximise the educational and training opportunities of the program.

To achieve this, the department collaborated with research partners at the University of NSW (UNSW), University of Wollongong (UoW) and Australian Nuclear Science and Technology Organisation (ANSTO), to investigate the sensitivity of these wetland systems to external influences, including the potential effects of mining activity and groundwater extraction. Throughout the program regular updates to the community were provided through newsletters and a series of annual Science Days where information and results from the research program investigations were provided as they progressed. Community feedback on progress was sought and questions encouraged. Presentations and demonstrations were also given to school groups and community organisations.

The major findings of the *Thirlmere Lakes Research Program* are:

- Thirlmere Lakes are a unique and vulnerable ecosystem. The lakes are located near the top of the Blue Gum Creek catchment and have limited inflows from surrounding catchments. Their size and relatively shallow depths mean that minor changes in water levels can lead to the significant exposure of lakebed sediments.
- The recent droughts are not unprecedented and Thirlmere Lakes have dried intermittently over the last 120 years of records. Evidence of a major drying period for the lakes was also identified in the sediments and dated as far back as 12,000–21,000 years ago.
- Evidence from deep boreholes confirmed the presence of the Bald Hill Claystone approximately 100 metres below the lakes; however, it was found that the Bald Hill Claystone may not possess the aquitard properties previously assigned to it.
- No direct geological link (e.g. surface to coal seam faulting) between Thirlmere Lakes and Tahmoor Colliery was identified during the geological investigations. Faults and igneous intrusions have, however, been mapped in the seam-level workings of Tahmoor Colliery at a depth of about 400 metres. Further research is required into the potential for subsidence to interact with faults or cause regional movement on geological structures and the potential consequences this may have, especially in the vicinity of important natural wetlands like Thirlmere Lakes.
- Input into the lakes is primarily rainfall-runoff from very small localised catchments and the main water loss from the lakes is evapotranspiration; together these are referred to as climatic factors. The water balance assessment suggests the primary driver of water level variation over the period of study was climatic. The water balance model accounted for approximately 83–98% of lake level variation during the period studied.
- Whilst evaporation and transpiration dominated losses across all lakes during the drying period that persisted until early 2020, there remains a component of losses from each lake to groundwater. The proportions appear to be different for each lake and its stage of drying. While groundwater exchange is not the dominant process for the lakes, it can nevertheless still exert an influence on lake levels.
- It remains unclear how fast and how far groundwater depressurisation above Tahmoor Colliery longwalls has propagated to the west (i.e. towards Thirlmere Lakes). There is limited baseline data on groundwater levels prior to the mining that went closest to the lakes and there has been limited monitoring of groundwater levels between the mine and the lakes. Significant time lags in groundwater pressure response at distance and the slow movement of water through rock strata (i.e. low conductivities) may mean the full effects of such depressurisation are yet to express themselves.
- Over the last five years, Thirlmere Lakes have experienced three major filling events: the June 2016 east coast low rain event, and the February 2020 and March 2021 rain events. Under future climate projections, New South Wales is expected to become hotter, and wetter in the north-east and drier in the south-west, with an increase in heatwaves and heavy rainfall.

- It is difficult to predict exactly how Thirlmere Lakes will respond to a changing climate, but it is likely the lakes will continue to oscillate between being dry (or nearly so) and maintaining higher water levels, largely dependent on the occurrence of droughts and the frequency, intensity and duration of major rainfall events.
- The lake vegetation and aquatic fauna populations vary considerably in their individual responses to major fluctuations in lake levels.

As a result of the *Thirlmere Lakes Research Program* investigations we can say:

- the Thirlmere Lakes can effectively be thought of as a set of 'leaky bathtubs'
- the primary driver of water level fluctuations over the period of study has been climate (rainfall and evapotranspiration)
- we can account for a high proportion of the water level variability without factoring in losses due to human activity
- whilst evaporation and transpiration dominated losses across all lakes during the drying period that persisted until early 2020, there remains a component of losses from each lake to shallow groundwater
- there is a clear separation in water levels in the shallow bores (at ~15 metres depth) and the deeper bores (at ~100 metres depth). There are also clear differences in water chemistry in the shallow bores, deeper bores and in mine water, and
- we cannot rule out smaller (relative to climate) impacts of human activities (mining and groundwater extraction) and we will probably never be able to do this because baseline data captured prior to mining are inadequate and groundwater extraction in the area has increased (i.e. there is no reliable benchmark against which we can measure change).

In the longer term (years to decades):

- mining impacts on regional groundwater may affect lake water levels by reducing inflows to the lakes and by increasing the hydraulic gradients away from the lakes. Such impacts may take decades to express themselves in a measurable way
- anthropogenic climate change may also impact lake levels by affecting patterns of rainfall, evapotranspiration, and fire frequency
- because Thirlmere Lakes are a dynamic system that is very responsive to climate, it is likely the lakes will continue to oscillate between being dry (or nearly so) and maintaining higher water levels, largely dependent on the occurrence of major droughts and the frequency, intensity and duration of major rainfall events, and
- during periods of no or low water, the peat underlying the lakes is extremely vulnerable to desiccation and fire. Management of recreational access and fire during such times is particularly important.

Acknowledgements

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The Traditional Custodians of the area who have cared for the lakes for tens of thousands of years.

The local community who care so much about the Lakes.

This report was written by Martin Krogh, Dr Kirsten Cowley, Dr Tsuyoshi Kobayashi and Dr Joanne Ling.

1. Introduction

Thirlmere Lakes are a system of five freshwater lakes (Lake Gandangarra, Lake Werri Berri, Lake Couridjah, Lake Baraba and Lake Nerrigorang) in a small Hawkesbury Sandstone valley in the NSW Southern Highlands, approximately 90 kilometres south-west of Sydney and 10 kilometres from Picton (see Figure 1.1). Thirlmere Lakes National Park was established to protect these lakes and the surrounding park supports a unique assemblage of terrestrial and aquatic native plants and animals, including a range of threatened species, three endangered ecological communities and one vegetation community found only in the park (DPIE 2019). Thirlmere Lakes National Park itself encompasses a total area of 660 hectares. The topography of the area has the lakes' surfaces at approximately 305 metres above sea level, with the surrounding ridges rising to 378 metres in the west, 350 metres in the east and 408 metres in the north; the ridge that forms the central axis of the valley rises to 335 metres above sea level (Vorst 1974).

The park is adjacent to the villages of Thirlmere, Buxton and Couridjah and was first reserved as a state park in March 1972 under the *National Parks and Wildlife Act 1967* and managed by Wollondilly Shire Council. It was redesignated a national park in 1974 under the *National Parks and Wildlife Act 1974*. The national park was subsequently included within the Greater Blue Mountains World Heritage Area (listed in December 2000). Two inholdings, which were private land, were added to the park in 2008. Thirlmere Lakes National Park is jointly managed by the NSW National Parks and Wildlife Service (NPWS) and WaterNSW, as the national park is within the Warragamba Special Area and part of Sydney's drinking water catchment (DPIE 2019).

1.1 Thirlmere Lakes level controversy

Water levels in Thirlmere Lakes have fluctuated over time, but in 2010 there was a notable decline that was of significant concern to the local community (DECCW 2010; ABC 2010). Community concerns about lake levels were expressed by the then local member Jai Rowell MP, Wollondilly Shire Council and community groups. In response, the NSW Government, through the Minister for the Environment and then Office of Environment and Heritage (OEH) (now the Environment, Energy and Science group of the Department of Planning and Environment, the department), commissioned the Thirlmere Lakes Inquiry. A group of four independent scientists and a community representative were appointed to evaluate the possible causes of the low water levels in the lakes (Independent Committee – Thirlmere Lakes Inquiry; see Riley et al. 2012). The community presented a number of concerns about Thirlmere Lakes to the Independent Committee established to undertake the inquiry and some members of the community suggested that the drying was directly related to longwall coal mining immediately to the east of the lakes.

The Thirlmere Lakes Inquiry published their findings in 2012 (Riley et al. 2012). Their findings were subsequently reviewed by the state's Chief Scientist and Engineer (CSE), Professor Mary O'Kane (OCSE 2013). Both the Independent Committee for the inquiry and the OCSE agreed that more research was needed on how the lake system worked before there could be a proper understanding of what was affecting lake water levels. As a direct response to the findings of the inquiry, a new monitoring network was established to provide near real-time information on the water levels[1] in each of the five lakes in Thirlmere Lakes National Park. An inter-agency working group (IAWG), which included scientists from the department, the Office of the Chief Scientist and Engineer (OCSE), Department of Primary Industries (DPI) Water (now the Water group in Department of Planning and Environment, DPE Water) and Sydney Catchment Authority (now WaterNSW), oversaw the establishment

[1] As well as local rainfall, solar radiation and wind speed.

of the new monitoring program[2], which was funded by the department (Parks and Wildlife Division) and implemented by WaterNSW (formerly by NOW). The IAWG was also tasked with providing the strategic direction for further research into the complex hydrology of Thirlmere Lakes.

Subsequent to the inquiry and establishment of the lake level monitoring program, further studies extended the historical record of estimated lake water levels and investigated correlations with possible drivers of water level variability. Schädler and Kingsford (2016) concluded that declining water levels coincided with establishment of longwall mining and groundwater extraction from bores, but noted that these effects were difficult to distinguish without a good understanding of connectivity between surface and groundwater systems; which at the time did not exist. Pells and Pells (2016, 2017) speculated that extraction of water from nearby mines had impacted lake water levels, based on the inability of their model to adequately simulate water level variability both before and after mining activities nearby. Conclusions drawn from models were clearly dependent on an adequate understanding of the system under investigation, much of which remained uncertain at the time. At that time, there was still much that was unknown about Thirlmere Lakes and the geology, geomorphology, hydrogeology and hydrology of the area and, as a result, it was difficult to determine what the primary drivers of surface water loss were. The IAWG summarised these knowledge gaps in a report entitled *The Mysterious Hydrology of Thirlmere Lakes* (OEH 2016). In attempting to address the question of *Where has the water gone*?, it is equally important to address the question of *Has there been less water getting in*?.

1.2 Thirlmere Lakes Research Program

In response to the need for further research into the complex hydrology of Thirlmere Lakes, the department committed $1.9 million over four years to a research program to help provide an understanding of the fluctuating water levels. The *Thirlmere Lakes Research Program* was announced by Jai Rowell, MP for Wollondilly, on 20 October 2017. The new research program aimed to provide a more detailed understanding of the hydrological dynamics of Thirlmere Lakes than currently existed, including detailed investigations of the geology, geomorphology, hydrogeology and hydrology of the system. The department collaborated with research partners at the University of NSW (UNSW), University of Wollongong (UoW) and Australian Nuclear Science and Technology Organisation (ANSTO), to investigate the sensitivity of these wetland systems to external influences, including the potential effects of mining activity and groundwater extraction.

The five primary research themes addressed in the *Thirlmere Lakes Research Program* were:

- **TLRP1** – Thirlmere Lakes: the geomorphology, subsurface characteristics and long-term perspectives on lake-filling and drying (UoW Lead Researcher Dr Tim Cohen)
- **TLRP2** – Surface Water – Groundwater Interaction (UNSW Lead Researcher Dr Martin Andersen)
- **TLRP3** – Developing an Integrated Water Balance Budget for Thirlmere Lakes to Provide a Detailed Understanding of Hydrological Dynamics (UNSW Lead Researcher Associate Professor Will Glamore)
- **TLRP4** – Geological mapping and geophysical surveys of the Thirlmere Lakes area (UNSW Lead Researcher Dr Wendy Timms[3])
- **TLRP5** – Environmental isotopes investigations into periodic and recent water losses from Thirlmere Lakes (ANSTO Lead Researcher Dr Dioni Cendón).

[2] Near real-time data is available and plots of lake levels can be found on the WaterNSW Continuous water monitoring network website.

[3] Dr Wendy Timms subsequently moved to Deakin University and the lead role was taken by Dr Martin Andersen.

Additional studies were also undertaken opportunistically to investigate the peat water storage, limnology and vegetation at Thirlmere Lakes. The following chapters of this report detail relevant information for the Thirlmere Lakes area and the major findings of the *Thirlmere Lakes Research Program.*

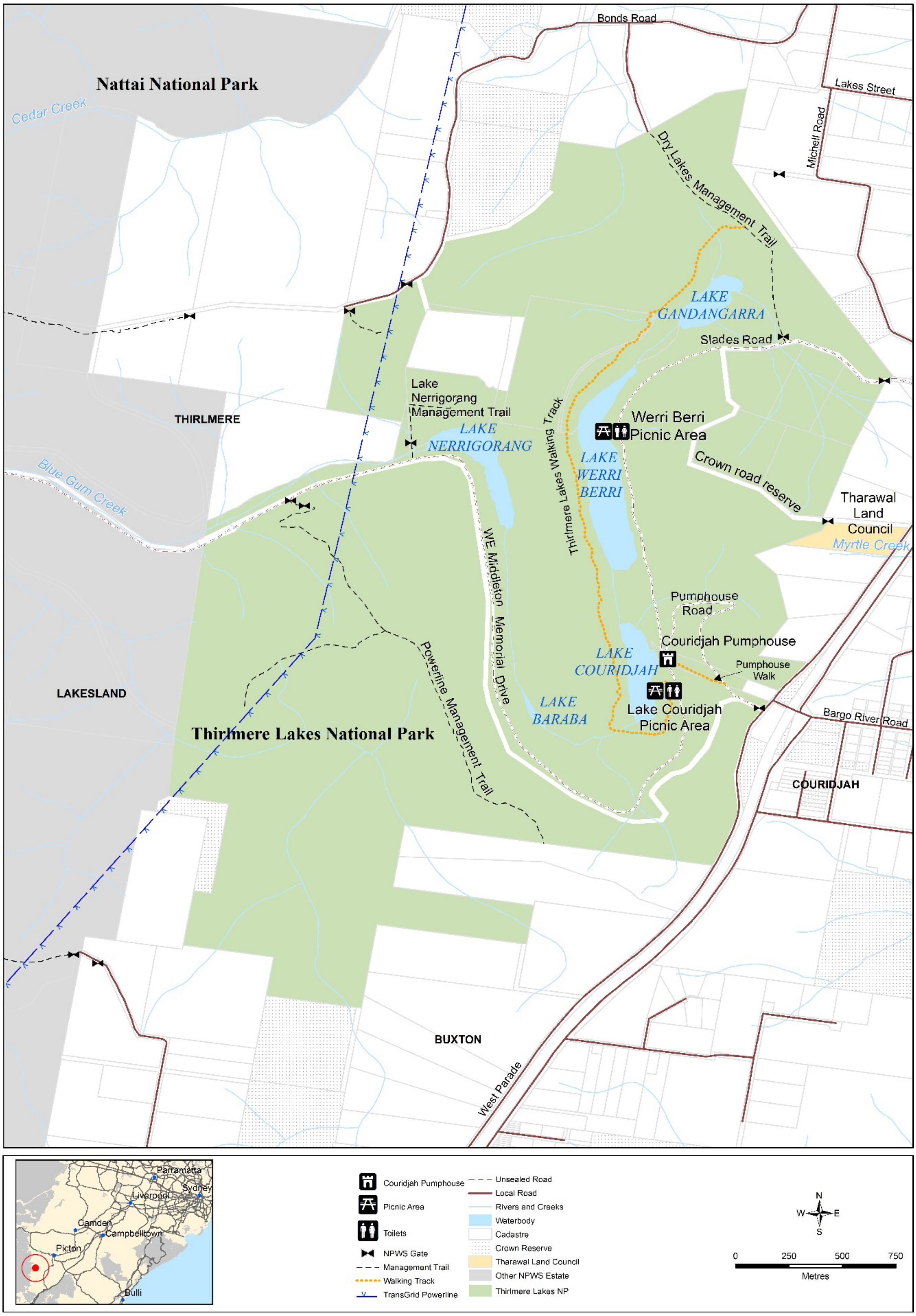

Figure 1.1 **Map of Thirlmere Lakes National Park**

Source: DPIE 2019

2. Background

2.1 Aboriginal history

The Aboriginal or First Peoples of Australia have been custodians of the land surrounding Thirlmere Lakes long before European arrival, settlement and subsequent displacement. The Camden–Picton–Thirlmere area was at the intersection of three language groups: the Dharug, the Tharawal, and the Gundungurra (Before Camden: Settlement and Conflict). This is evidenced by the different names for the region, it being called Baragil (or Baragal) in one language, and Benkennie, meaning the dry land, in another.

The Gundungurra (also spelled Gandangara) language group lived to the south-west of Sydney. Their country included the catchments of the Wollondilly and Cox rivers and some adjacent areas west of the Great Dividing Range. Their neighbours were the Dharug, Darkinung, Wiradjuri, Ngunawal and Thurrawal speaking peoples (Smith 2009). Most published references point to the area being within the domain of the Gundungurra people; however, the Gundungurra Indigenous Land Use Agreement (ILUA) area map (PDF 8.9MB) does not actually include Thirlmere Lakes. William Russell (or *Werriberrie*), a Gundungurra man born on the banks of Werri-berri[4] Creek, drew a distinction between the Cubbitch Barta or white pipe-clay Cowpasture or Camden tribe, stating they were different to those of Burra-ga-rang (Figure 2.1; Russell 1914).

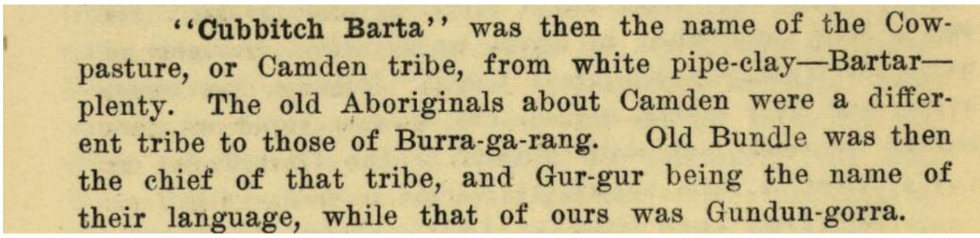
"Cubbitch Barta" was then the name of the Cowpasture, or Camden tribe, from white pipe-clay—Bartar—plenty. The old Aboriginals about Camden were a different tribe to those of Burra-ga-rang. Old Bundle was then the chief of that tribe, and Gur-gur being the name of their language, while that of ours was Gundun-gorra.

Figure 2.1 Extract from Russell (1914) about the Cubbitch Barta tribe

Jim Smith (2017) recently provided a detailed account of the Gundungurra people of the Burragorang Valley, noting that the Cowpastures tribe of the Camden district were Dharug speakers who called themselves the Muringong. Fowler et al. (1998) suggested there was evidence the Nepean River was used as the borderline with the Thurrawal tribe and that the Gundungurra and Dharug tribes used to meet at Emu Plains to arrange or celebrate marriages. After the Dharug tribe was driven from this end of their territory by settlement and punitive expeditions, the Gundungurra were reported to inter-marry with the Thurrawal people (Fowler et al. 1998).

Relatively little is recorded in the published literature in terms of Aboriginal stories of Thirlmere Lakes, or the original Aboriginal names for the five lakes[5]. Some anecdotal reports suggested that Aboriginal people would not camp at the lakes believing that *it contained a bunyip or some horrible creature that screamed occasionally during the night.* [6] Apparently early settlers also came to believe that *it contained a banshee after hearing the terrible screams that sounded like a woman in her death throes; even the dogs bristled and cowered*

[4] Near The Oaks. According to Smith (2009), werriberri is a reference to 'tree ferns'.
[5] If they were indeed identified separately.
[6] Undated letter from EM Brodie. Brodie suggested it was a screech owl, but hand written notes on the letter suggested that this might actually be due to the barking owl. However, it is noted elsewhere that the Australasian bittern (recorded from Thirlmere Lakes) was also known as the 'bunyip bird' and may have been the original cause of the noise. Brodie goes on to note that these birds *are not very numerous in these parts and seem to have disappeared from the district*. Surveys have also failed to record bitterns at Thirlmere Lakes in recent times.

near the camp-beds and so it was avoided at night.[6] Despite such stories, there are a number of sites around Thirlmere Lakes that indicate extensive Aboriginal usage of the area (DPIE 2019).

In 1974, Mr C Wilder spoke to the Geographical Names Board about the naming of the five lakes within the then Thirlmere Lakes State Park. In its response, the Geographical Names Board (1974) elected to record the following names:

Lake Gandangara; named after the local Aboriginal tribe.

Lake Werri Berri; named after Billy Russell – *one of the last surviving members of the Gandangara tribe, was said to have been known by the natives as Werri-Berri* (Geographical Names Board 1974). AL Bennett helped record William Russell's (aka 'Werriberrie') recollections of the area in 1914, when William Russell was aged 84 (Russell 1914).

Lake Couridjah; named for *the lake from which water was pumped for railway purposes when the railway line was constructed nearby, in 1867. The adjacent railway stopping place was known as 'Couridjah', said to mean 'the place where banksia trees grow'* (Geographical Names Board 1974). The word *Couridjah* originates from an aboriginal word but actually has many documented translations. According to Chalk (2007), George Caley recorded *Couridjah* to mean '*the place where Banksia trees grow*'. *Couridjah* has also been translated as meaning '*honey*' and '*home of the white ants*'; although its similarity to the Aboriginal word '*kooradgie*', meaning medicine man and '*coradgery*', meaning magic, are also apparent (Chalk 2007). Chalk (2007) concluded that the original meaning for the word '*Couridjah*' was actually, with specific reference to Thirlmere Lakes, '*a place for Aboriginal magic*'. An interesting similarity though can also be seen in Jim Barratt's (2015) word list where the Gundungurra word *guuridyaa* (said to be sourced from the word *courigah*) is translated as 'a big lagoon'.

Lake Baraba; named after the word 'Baraba', *meaning bullrushes in the vocabulary of the nearby Dharruk tribe* (Geographical Names Board 1974; see support for this translation in Friends of Berowra Valley Regional Park 2001).

Lake Nerrigorang; named after the area of the lakes being known as Nerrigorang to Billy Russell, *said to mean shaky or unstable ground*. Russell (1914) identified that 'Narre-ga-rang' was the name of Picton Lakes because the soil around the lakes is not firm, or a 'shaky place'[7].

To this day, Thirlmere Lakes National Park remains part of Country for Aboriginal people and provides opportunities for the maintenance and renewal of cultural practice and connections to Country. Evidence of this connection to Country within the park includes art sites, artefact scatters and shelters. Stories and mythology, cultural resources and the landscape itself also provide strong cultural links to the park for the Aboriginal community (DPIE 2019).

2.2 Early European exploration

In 1798 under the direction of Governor Hunter, John Wilson was sent to help disprove a rumour that '*there was a colony of white people at no great distance in the back country – 150 or 200 miles – where there was abundance of every sort of provision without the necessity of so much labour*' (Cambage 1920). Wilson was a former convict who later spent much of his time in the bush among the Aboriginal people, who had given him the name Bunboee. Another member of the party is recorded as a lad called Barracks[8] who was credited with recording the journeys in a diary (Cambage 1920). The first journey took the party to the Wollondilly River near Bullio (see Figure 2.2).

[7] Jim Barratt's (2015) word list cites the Gundungurra word *narrigarang* translating as 'soil which is not firm'. This was easily corroborated over the last few years when the lakes were dry at the surface, where jumping up and down on the dried peat was somewhat reminiscent to bouncing on a trampoline. In contrast, Chalk (2007) suggested that *Nerrigorang* meant 'water with a sandy bottom'. It is noted though that Lake Nerrigorang does not actually have a 'sandy bottom'.

[8] Barracks was reported to have arrived in the colony with Governor Hunter as a boy servant. He later returned to England with Governor Hunter (taking with them the diary of the trips).

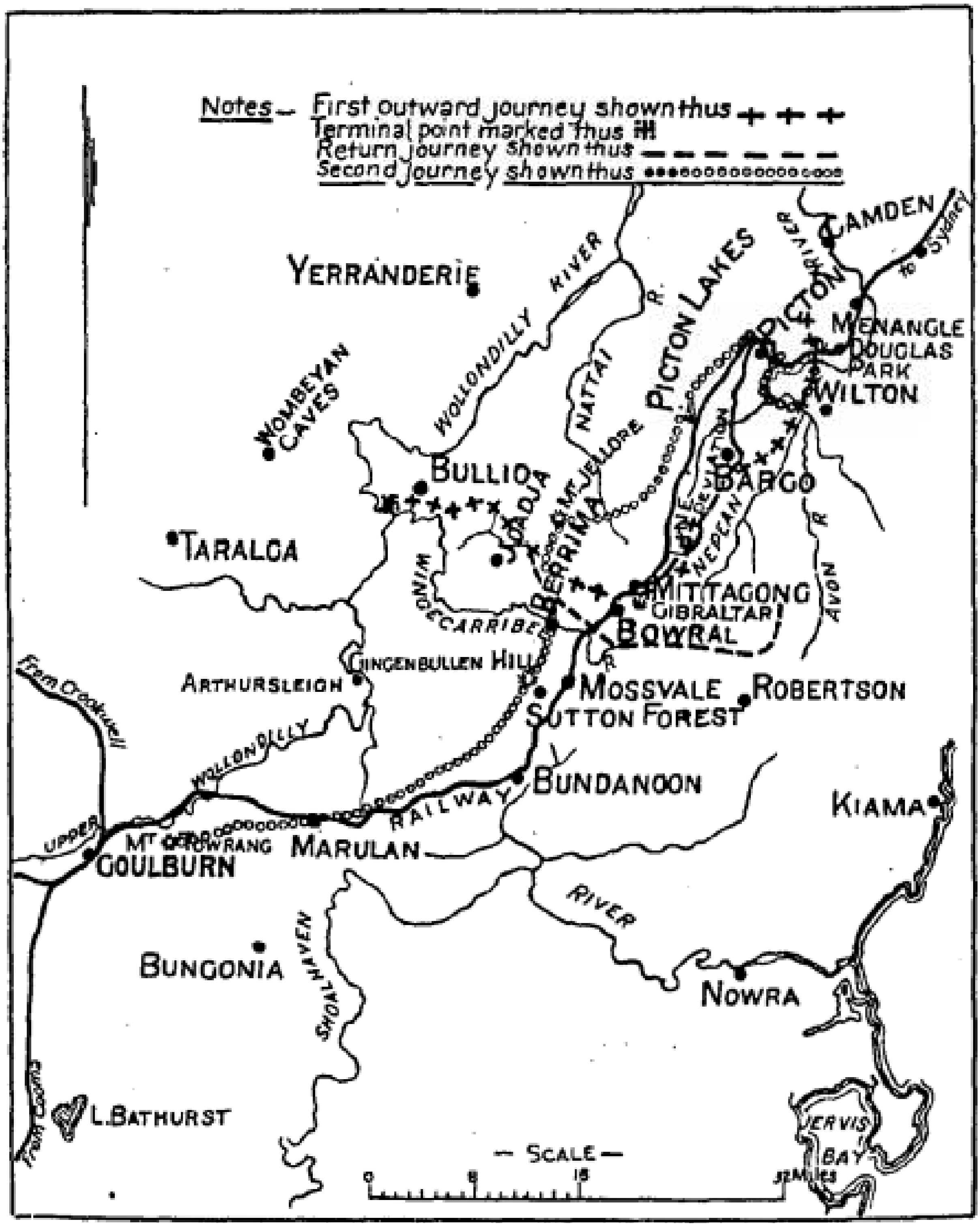

Figure 2.2 **Map of Wilson's expeditions of 1798**
Source: Cambage 1920

However, it was the second journey that led to the first recorded European visit to Thirlmere Lakes. The group on the second journey initially consisted of Wilson, Barracks, Henry Hacking (a quarter-master of the *Sirius*), and another man named Collins. The party left Prospect on Friday 9 March 1798 and travelled towards the Nepean River. After initially investigating the existence of salt deposits in the Bargo River gorge that had been noted on the first trip, the diary entry for Wednesday 14 March states:

"Wednesday, 14th.—Course, E. Having plenty of provisions, Wilson concluded to go to the eastward to see if he could get some skins of birds and animals. Collins went with him to keep him company. Hacking leaving us to return to Sydney. Wilson asked me if I was willing to go to the S.W. part of the country for nine or ten days. I told him I was willing to go to any part he thought proper. Then we altered our course and steered S.W. We had a fine open country for 7 or 8 miles. We saw the dung and marks of the cattle's feet all the way till we came to a rockey creek, then we had a nasty, scrubby, stoney country for the remainder of that day. We crosst three deep vallies, with large ponds of water in each of the vallies. We also crosst one deep gully; we then came to for the night. Distance, 13 miles."

Figure 2.3 Extract from the diary of Barracks (Cambage 1920)

In November 1802, Francis Barrallier was exploring the country at the headwaters of Stonequarry Creek in an (ultimately unsuccessful) attempt to cross the mountains (Macqueen 1993). When just north of Thirlmere, he turned first westerly and then north-westerly towards the Nattai River, eventually arriving at a spot on the high land overlooking the watershed of a tributary of that river[9]. Barrallier was close to, but does not appear to have actually reached, Thirlmere Lakes. Bayley (1974), however, stated that one of the party, Sergeant Buscombe, found '*one of the four*[10] *sheets of water known by the aborigines as "Coradgery"*'.

Bayley (1974) went on to state that:

> Lieutenant Dawes, on being told of the existence of the lake by the party on return, went and discovered the four of them. He named the district Thirlmere as it compared with Thirlmere in England's lakes district.

It appears that this could not have been Lieutenant William Dawes of First Fleet fame though, since that Lieutenant Dawes is reported[11] to have sailed back to England with the marines in December 1791, arriving in England in 1792.

Shortly afterwards, George Caley, who was following the tracks of Barrallier, became disoriented and headed southward thereby coming upon the lakes which he named '*Scirpus Mere'*. He believed that he was the first white man to discover them as the diaries of Wilson's expedition had already been taken back to England with Governor Hunter. The details of Caley's travels are given in Else Mitchel (1939a) as:

> At Stonequarry Creek Caley saw the tracks of Barralier's wagons, and he knew from the natives that "at Nayti the furthest point reached by him he had built a bark hut" and established a depot. Caley was not aware of the exact location of this depot, and set out to find it, taking, firstly, a course a little to the west of south. He met nothing in this direction, but saw no more

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[9] This was suggested to be near Sheas Creek, approximately six miles from Thirlmere (Cambage 1915).

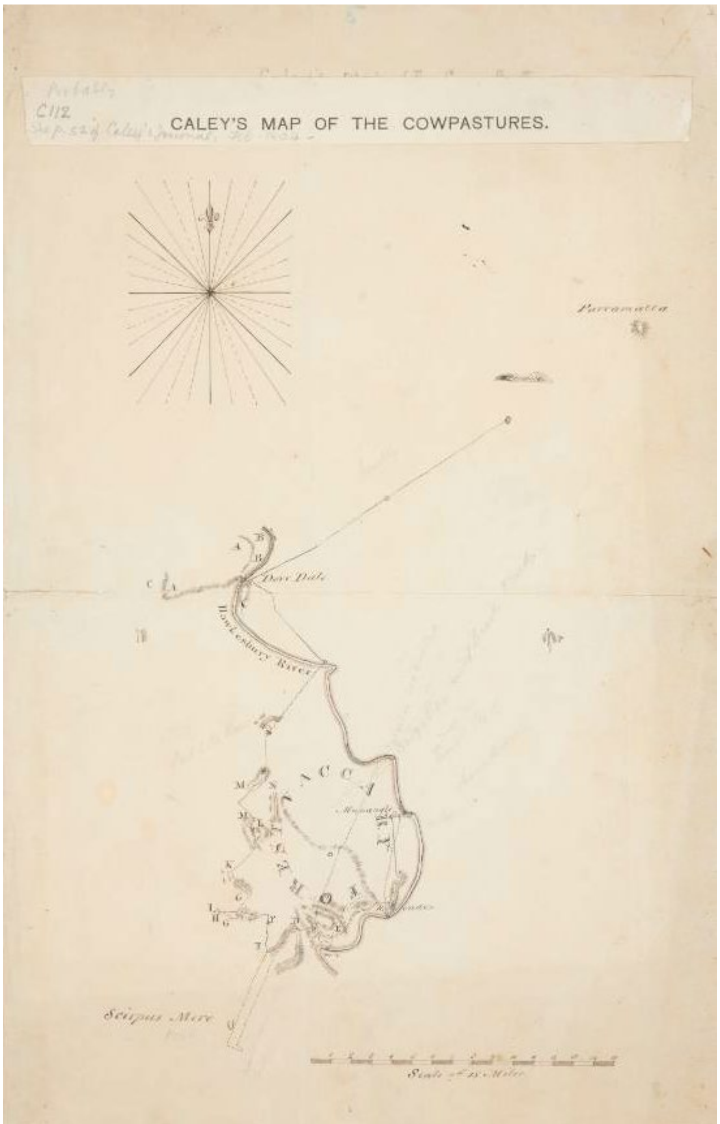
[10] Even at the time of Patricia Vorst's (1974) study, Lake Gandangarra and Lake Werri Berri were considered to be the same lake. In current times, however, they have clearly been separated except during three major rain events when water in Lake Gandangarra has spilled over and flowed to Lake Werri Berri. The earliest Parish maps depict all five lakes being connected as the 'Big Lagoon'. This could possibly be a case of early artistic licence, although the 1886 Railway Guide of NSW suggested that during times of flood the lakes *formed one long body of water extending for a distance of about five miles* (Potter 1886).

[11] Lieutenant William Dawes was later to go on to have postings to Sierra Leone and later the Caribbean and is reported to have died in Antigua in 1836. See Phyllis Mander-Jones, 'Dawes, William (1762–1836)', Australian Dictionary of Biography, National Centre of Biography, Australian National University, published first in hardcopy 1966, accessed online 28 July 2020.

> wagon tracks, and then proceeded from Stonequarry Creek in a south-westerly direction. After five or six miles travelling he came upon a lagoon, around which a dense thicket and some beautiful plants were found growing. This place, which he named Scirpus Mere, is the largest of the Picton Lakes, at the head of Blue Gum Creek - a tributary of the Nattai River. Searching in the vicinity and going a few miles further south, Caley did not find Barrallier's depot or his tracks, and returned to Stonequarry Creek, camping at a place called Mundogra by the natives and described as being "a low flat piece of ground without any trees growing upon it, its green verdure had a pleasant appearance in a country where all was forest"; it was also known as the Long Meadow. From this site Caley took a direct route to the Camden Ford, passing over the Razorback en route and seeing a number of the wild cattle. He returned from thence to Parramatta, having been out nine days.

Cayley produced a map of the journey (see Figure 2.5), including a notation for his '*Scirpus Mere*'. *Scirpus* is a Latin word meaning rush or bulrush; and *Mere* an English term for an expanse of standing water (such as a lake or pool). This is considered a very apt description for Thirlmere Lakes given the ring of grey rush (*Lepironia articulata*) that grows around the circumferences of the lakes (see Figure 2.4).

Figure 2.4 Grey rush (*Lepironia articulata*) surrounding Lake Gandangarra
Photo: M Krogh



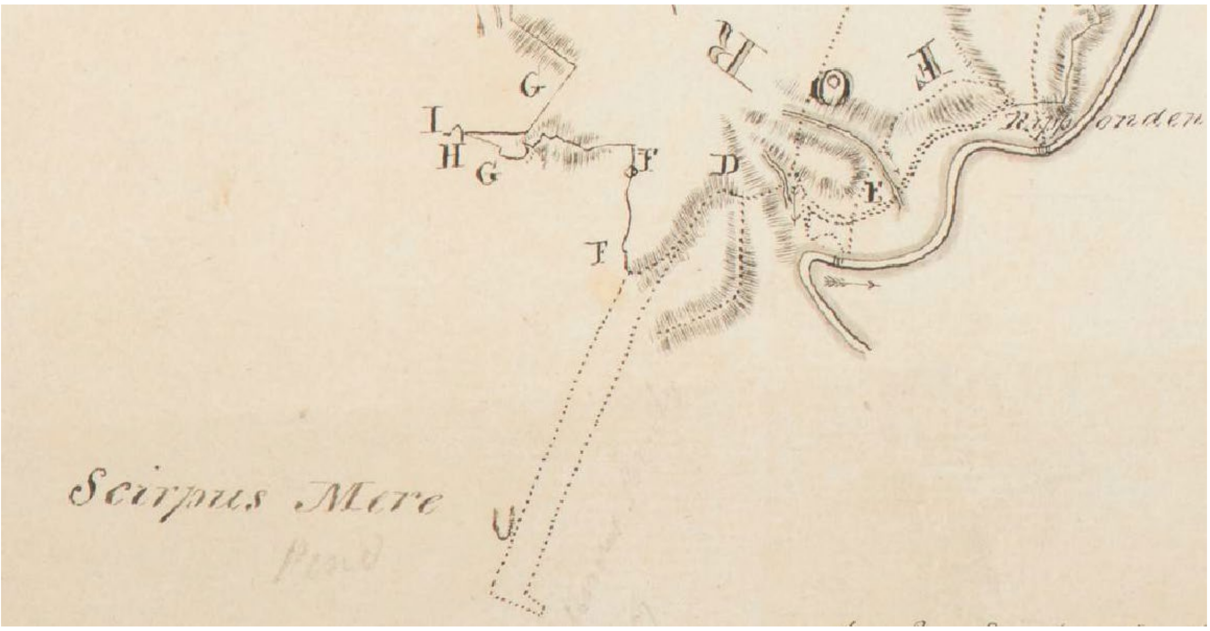


Figure 2.5 George Caley's map, with Thirlmere Lakes (*Scirpus Mere*) area magnified below
Source: Caley 1804, used under Creative Commons Attribution 4.0 International Licence

2.3 Early colonial settlement

Settlement in the vicinity of Thirlmere lakes was initially slow due to NSW Colonial Government restrictions on access west of the Nepean River[12]. Prohibitions on access were not lifted until 1823 and even then, restrictions still applied with only temporary occupation of the area allowed (Jervis 1941). The first major land grant[13] in the vicinity (2000 acres), surveyed in September 1821, was given to Major Antill and was located on the northern side of Stonequarry Creek (named Jarvisfield).

By the mid-1830s, settlers had established themselves on the better soil towards Cedar Creek and Lakesland where they grew hay, corn and vegetables as well as keeping bees, cows and poultry (Chalk 2007). Interestingly, in December 1836, a land grant was made to a William Dawes, described as being *in the District of Picton at the Lagoons* (Jervis 1941). It is possible that this William Dawes was a prominent merchant in the colony and later board member of the bank. This grant (50 acres) appears on the early Parish of Couridjah maps (see Figure 2.6) and is likely to be the land portion later owned by the Racklyeft family bordering on Lake Nerrigorang (a portion of which is now included within Thirlmere Lakes National Park).

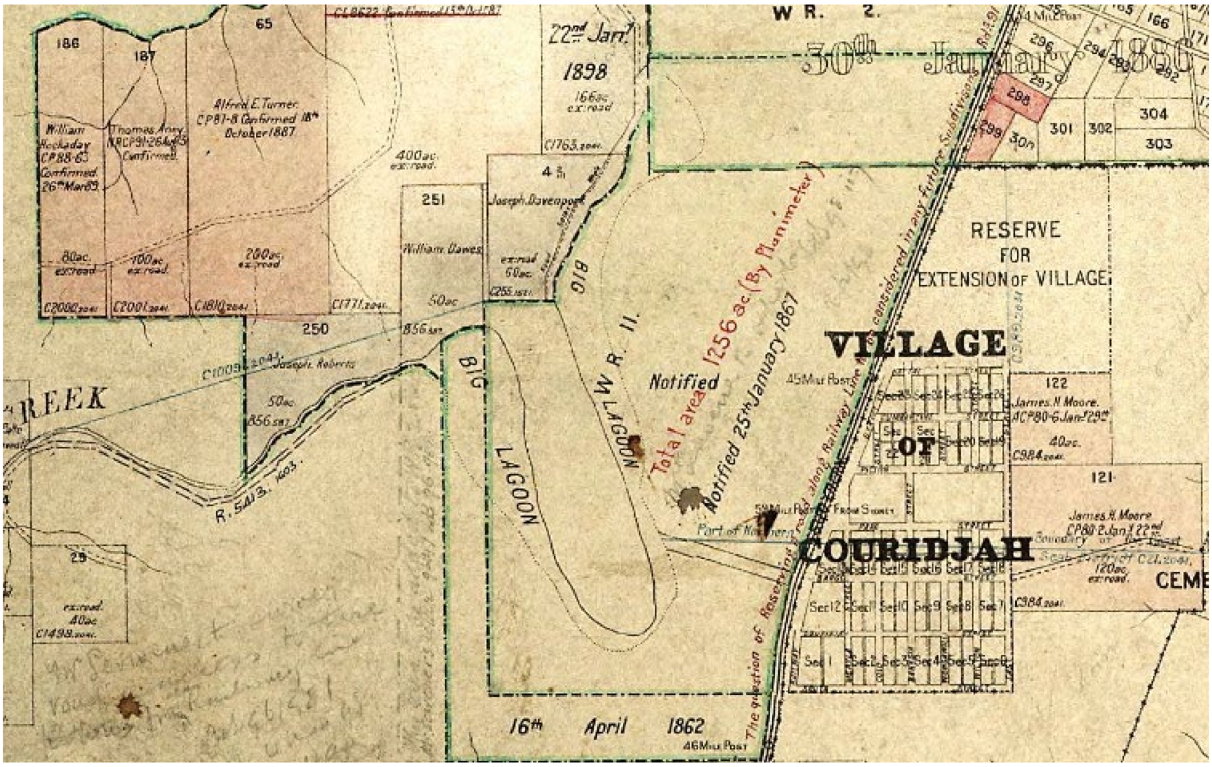


Figure 2.6 Section of the 1894 Parish of Couridjah map

In 1819 Governor Lachlan Macquarie had ordered the construction of a road from Picton[14] through to the Goulburn Plains, which later became known as the Great South Road. This brought about a major shift in the district's focus of settlement in the 1830s to 1850s. In 1837, surveyor William R Govett (cited in Jervis 1941) referred to the district as:

[12] Largely to protect the wild cattle herds of the Cowpastures – see Campbell (1928) and Else Mitchell (1939b).

[13] Grants were also made at this time to JTB De Arrietta (2000 acres) and A Douglas (800 acres). In 1822 further land grants were made to Charles Louis Rumker (Stargard; 1000 acres), George Harper (Abbotsford; 400 acres), Henry Dangar (700 acres; not actually taken up by Dangar) and Rev. William Cowper (600 acres) – see Jervis (1941) and Steele (1907).

[14] Picton was known as Stonequarry at that time.

> The South Road after crossing the Razor Back descends into the settlement of Stone Quarry Creek. There are two or three very good farms in this neighborhood on either side of the road and the scenery is sequestred [sic] and pleasing. Rich, grassy valleys, enclosed by picturesque wooded ridges, which shoot out and terminate in sharp and narrow tongues, open out into wide flats which are partially cultivated. A magistrate is stationed here and a court held, once or twice every week, and there are huts and cottages scattered about, the habitations of settlers holding small farms, of veteran soldiers holding small farms, of veteran soldiers, constables and workmen, and it may be hereafter, that this place may become the seat of a very respectable inland town….

By the 1840s the area supported a large number of firewood cutters who would take their loads by bullock wagon or horse team to Sydney (Chalk 2007). Steps to establish a village at Stonequarry Creek were also taken early in 1840, although the area for a government town, just south of Stonequarry Creek, had first been set aside in November 1821. The opening up of land sales to settlers around Lower Picton (initially called *Private Town* and located on Major Anthill's grant; north of Stonequarry Creek) and Upper Picton (initially called *Government Town* and next to Harper's grant; south of Stonequarry Creek) also led to an increase in population for the area (Jervis 1941; Steele 1907). Picton at that time was, however, still small and the census figures for the village in 1851 gave the population as 142 (Jervis 1941). As Picton subsequently grew, the two areas eventually merged into the township of Picton as it is known today.

2.4 Further expansion

The next major phase of development occurred with the building of the southern railway. A survey from Sydney to Goulburn had been prepared by Thomas Woore and adopted at a meeting in January 1848 (Bayley 1974). Early maps showed a different route to that eventually adopted and passing through Picton. Plans and surveys for the extension of the Great Southern Railway were to commence at Picton, cross Stonequarry Creek and intersect the southern road south of Lower Picton. Thence it would pass through Redbank Range by a short tunnel to the west of the Government Village of Redbank, ascending to the tableland between Redbank and Myrtle Creek on the east and the lagoons and Cedar Creek on the west (Bayley 1974). It would then follow the range dividing Bargo River and tributaries from those of the Nattai River and the chain of lagoons[15] to a point 14 miles from Picton where the line was to pass through a short tunnel through the Saddleback Ridge in the Bargo Brush (Bayley 1974).

Thirlmere, like many towns, has a strong link with the coming of the Great Southern Railway in 1863 to 1867, when a large temporary tent city grew up to house the railway workers. Thirlmere was originally known as Redbank with the name Thirlmere taken from the well-known lake in Cumberland, England (Steele 1907). The extension of the southern railway to Mittagong in 1867 had another direct connection to Thirlmere Lakes, since a pumping station was established near Lake Couridjah to supply water from the lakes to the steam engines that used the southern railway to Mittagong. The stone pumphouse that contained the pumps to supply the water remains as a legacy of those times and an important historical feature for Thirlmere Lakes National Park (Figure 2.7).

A station was initially opened at the commencement of the line under the name *Picton Lagoons Tank*[16]. The name was later changed to Couridjah and the station serviced the Tahmoor/Bargo area (Pells & Pells 2017; Chalk 2007). In 1919 the Thirlmere section of the Main Southern Railway was deviated to a less steep alignment with easier grades and the original line then became known as the Picton Loop Line (Bayley 1974). Today, the Picton loop line still provides a link to the main railway line, which enables heritage steam trains to

[15] Thirlmere Lakes

[16] An even earlier reference was given to this area as *Jones' Hut*.

operate beyond the local area. Over 100 rolling stock items, associated with the history of the railways in New South Wales, can still be seen at the NSW Rail Museum at Thirlmere.

Figure 2.7 Stone cottage that once housed the pumping station near Lake Couridjah
Photo: M Krogh

At one time there was a proposal that Picton and its extensive railway depot would also obtain a water supply from Thirlmere Lakes. Sufficient water pipes were accumulated to extend a water line from Thirlmere Lakes along the railway track to Picton; however, a water supply was subsequently constructed that brought water from a small reservoir on the Bargo River instead (Bargo or Picton Weir). It was thought at the time that Thirlmere Lakes would not be a reliable enough source of supply as it had been reported they were nearly dry in the 1902 drought and then again in the drought of 1928 (NPWS 1997; Pells & Pells 2017).

In the early 1910s the famous bushwalker and conservationist Myles Dunphy was catching the train to Couridjah and using trails past Thirlmere Lakes and down Blue Gum Creek to the Nattai Valley (Pells & Pells 2017). The Government also surveyed a line for a light railway down Blue Gum Creek, through the lower Nattai and along the Burragorang valley up to Yerranderie. Whilst the road eventually made its way past Thirlmere Lakes, down Blue Gum Creek and then out to Yerranderie, the light railway was never built. By the 1920s growth had slowed and the area was being surveyed by government as a site for the future Picton Lakes consumptive[17] village (Chalk 2007). The Picton Lakes Village for tuberculosis sufferers was subsequently established at Couridjah in 1925 (Pells & Pells 2017). Water for the village was supplied from Lake Couridjah.

[17] Consumption is an old term for tuberculosis (TB), an infectious disease usually caused by the bacterium *Mycobacterium tuberculosis.* Colonel JH Goodlet had already started a Home for Consumptives in the area in 1877, building Goodlet House in 1886 (Steele 1907). The Queen Victoria Homes for Consumptives took over Goodlet House in 1897 (Chalk 2007).

Pells and Pells (2017) cite interviews with Mr Ron Silm whose father started Cedar Creek Orchards (about 4 kilometres north-east of Thirlmere Lakes). According to Mr Silm (Pells and Pells 2017):

> He arrived in the area in 1937 and remembers visiting the pumphouse at the swimming lake after that time. When they stopped pumping water for the steam trains they continued pumping for some years for Picton Lakes Village in Couridjah which was a Dept of Health enterprise I think connected with the Sanitarium at QV Hospital.
>
> When water was too low in the swimming lake for pumping they dug a deep channel to connect with the boating lake; it was so deep evidently 2 boys were drowned in this channel.
>
> He remembers times when the lakes were dry sometime in the 40s and 50s. During some of the dry times in the 1980s[18] Ron obtained a permit to pump out of the N extension to the swimming lake, which is currently full of reeds, across the watershed into the Cedar Creek catchment which then flowed down to his orchard beside Cedar Creek.
>
> He remembers 3 separate times they were pumping each time continuing for several weeks with the pumps running 24 hrs a day at 1000 gallons per minute. He believed it had minimal impact on the levels in the lakes.

Dr Philip Pells had a further interview with Mr Silm on 13 May 2012 to clarify details of the pumping he did from the lakes. He stated that he had pumped from Lake Gandangarra and the water flowed down Cedar Creek, and many others along the creek helped themselves to the flow, which took 10 days to reach his property. He had pumped against a head of about 20 foot through a six inch pipe to reach Dry Lake. He and his wife were uncertain as to the date, but it was sometime after they married in 1956 but certainly before the 1980s (Pells & Pells 2017).

The population of the Picton–Thirlmere–Buxton–Tahmoor–Bargo area increased significantly in the post-World War II years and then increased further with the opening of coal mines in the 1960s and 1970s.

During the mid to late 1950s, the aquatic plants around the lake margins and the channels between the lakes were cleared and poisoned to improve conditions for powerboating and water skiing. The Thirlmere Lakes Motor Boat Club was founded in 1958 and a launching ramp installed in 1960 by club members (Horsfall 1984; Horsfall et al. 1988). The boat club was approved by Wollondilly Shire Council who allowed it to control the lakes on Sundays and public holidays. The club held annual events on Lake Werri Berri, including the 1972 NSW Barefoot Ski Championship (Horsfall 1984; Horsfall et al. 1988). When the state park was redesignated as a national park in 1974, water skiing continued to be permitted on the lakes. In 1984, Horsfall reviewed the environmental impacts of powerboats on Thirlmere Lakes finding that it did not appear to be causing a major environmental impact but was polluting the lakes to a limited degree. Between 1979 and 1995, powerboating continued to be permitted in Thirlmere Lakes National Park on the basis that it be restricted to Lake Werri Berri and limited to a maximum of 30 operators' licences, 20 of which were issued to members of a local powerboat club (NPWS 1997). As part of the 1997 Plan of Management though it was recognised that powerboating on such a small, environmentally important lake (Lake Werri Berri) inside a national park was unacceptable for environmental, social and legal reasons. This led to a prohibition of water skiing and powerboating in Thirlmere Lakes National Park.

In more recent times, the lakes have experienced declines in water levels that are of significant concern to the local community (see Section 1.1 above; DECCW 2010; Riley et al. 2012; CSE 2013; OEH 2016). These concerns have recently been amplified by the proposed major extension to Tahmoor Colliery (*Tahmoor South* proposal) which has recently been approved by government.

[18] In his original discussion with David Hunt, Ron said that this pumping occurred in the 1950s. However, in a subsequent interview with Philip Pells, he and his wife suggested this occurred in the 1980s (Pells & Pells 2017).

3. Coal mining near Thirlmere Lakes

3.1 Background

Coal has been a long sought after commodity since the very early days of colonial New South Wales. Over the first 100 years of settlement, numerous coal deposits were discovered and developed. Coal exploration operations at the Tahmoor Mine were commenced by the NSW Government during the 1960s. This was then followed by the granting of exploration titles to private companies. The Tahmoor and Bargo areas were initially secured by separate entities and developed as independent mines (AECOM 2018). Both the Tahmoor and Bargo mines were granted planning and environmental approvals to commence coal mining operations in the mid to late 1970s. In the past, Tahmoor colliery was variously owned by Novacoal Australia Pty Ltd; Austral Coal Limited; Centennial Coal Pty Ltd; and Glencore Coal Pty Ltd. Tahmoor Coal, trading as Tahmoor Coking Coal Operations (TCCO), is currently a subsidiary within the SIMEC Mining Division (SIMEC) of the GFG Alliance (GFG).

3.2 Tahmoor Colliery

The first commercial coal was produced at Tahmoor Mine in 1979 within the Existing Tahmoor Mining Area, which consisted of the Tahmoor North and Tahmoor Central mining areas (refer to Figure 3.1; AECOM 2018). The Tahmoor Mine initially operated using bord and pillar mining methods. These early methods were replaced by longwall mining in 1987 when a gas extraction facility and longwall mining unit were commissioned and installed (AECOM 2018). Since that time Tahmoor Colliery has been owned by a number of different entities, summarised in Table 3.1 (from AECOM 2018).

Table 3.1 Tahmoor Mine Ownership

Source: AECOM 2018

Tahmoor Mine ownership history	Parent company and/or controlling entity	Date commenced
Clutha Development Pty Ltd	N/A	April 1974
BP Coal Development Pty Ltd	N/A	December 1985
Novacoal Australia Pty Ltd	Novacoal Australia Pty Ltd was a business within Kembla Coal and Coke Pty Ltd (a subsidiary of CRA Ltd)	December 1989
Tahmoor Coal Pty Ltd	Austral Coal Ltd	February 1997
Tahmoor Coal Pty Ltd	Centennial Coal Pty Ltd	July 2005
Tahmoor Coal Pty Ltd	Glencore Coal Pty Ltd	November 2007
Tahmoor Coal Pty Ltd	SIMEC (Australia) Mining Pty Ltd. Tahmoor Coal trades as TCCO within the SIMEC Mining Division of the GFG Alliance Group	April 2018

Coal is currently mined from the Bulli seam, producing mostly hard coking coal for steel production. Tahmoor Mine also produces a small amount of thermal coal that is used for power generation. Current operations at the Tahmoor Mine are undertaken within the Tahmoor North mining area with Longwalls (LWs) W1 & W2 approved and an extraction plan currently being considered by Government for LWs W3 & W4 (Figure A1.1, Appendix A).

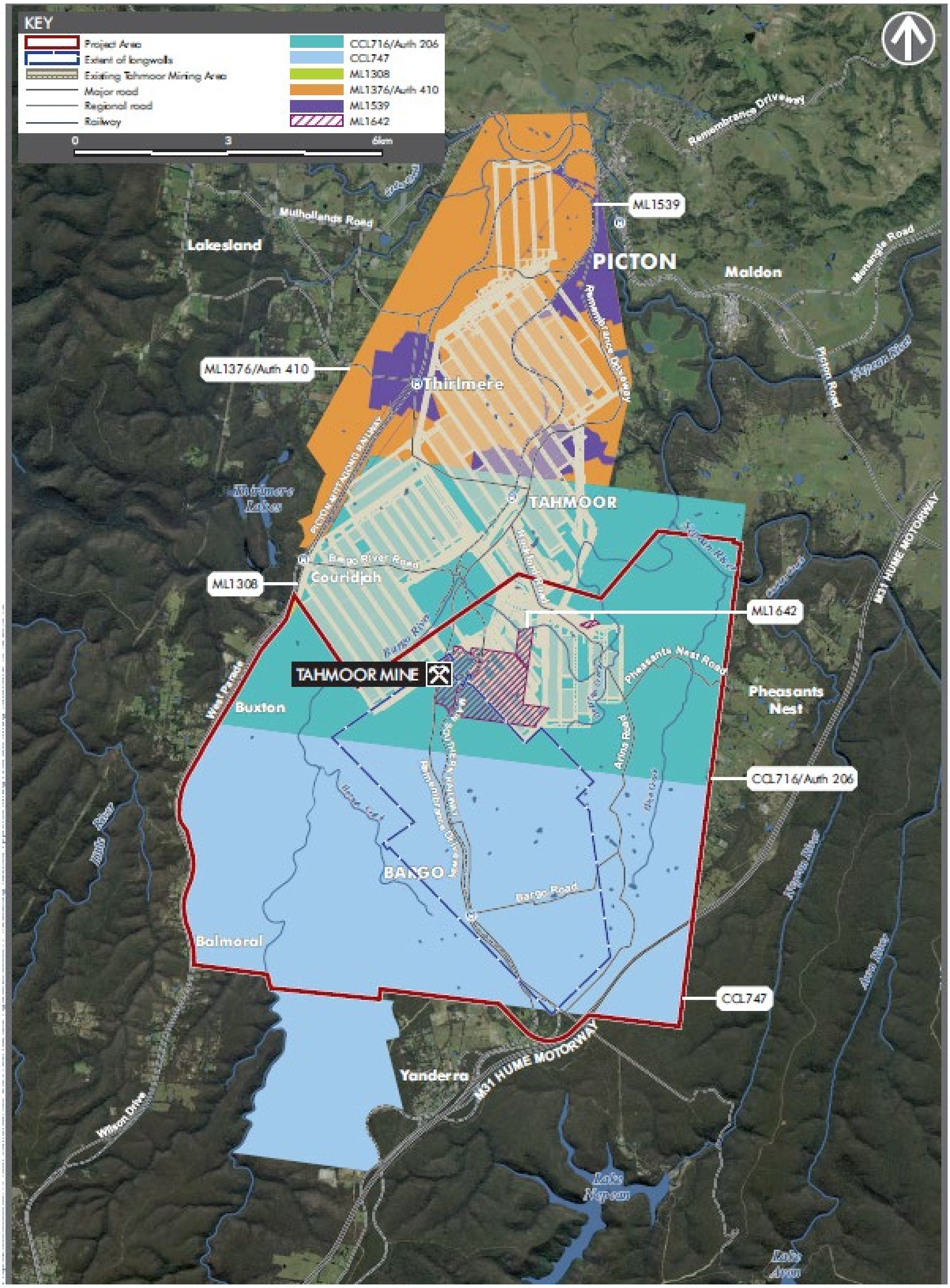


Figure 3.1 **Mining areas at Tahmoor Colliery: Tahmoor North (orange); Tahmoor Central (cyan) and Tahmoor South (light blue)**

Source: AECOM 2018

3.3 Bargo Mine

The NSW Government commenced scout drilling of the coal resource within the area surrounding Bargo in 1965 and subsequently allocated the Bargo coal area to J&A Brown and Abermain Seaham Collieries Pty Ltd via EL275, granted on 23 March 1970 (AECOM 2018). A joint venture was formed between J&A Brown and Abermain Seaham Collieries Pty Ltd and Peko-Wallsend in May 1970 (the Bargo Joint Venture) to conduct a drilling program to investigate the coal resource. The Bargo Joint Venture formed Bargo Collieries Pty Ltd on 11 January 1972, which was subsequently expanded on 21 July 1975, with the inclusion of BHP Limited (AECOM 2018).

The Bargo Joint Venture commenced shaft construction at the Bargo Mine in May 1979, followed by trial mining and in-seam work in January 1981 (AECOM 2018). Although physically commenced, the Bargo Mine development did not progress to commercial production due to economic conditions at the time. Following several feasibility studies undertaken by the Bargo Joint Venture partners, Bargo Collieries Pty Ltd was sold to Tahmoor Coal Pty Ltd in May 1999 (AECOM 2018).

Tahmoor Coal recently sought development consent for the continuation of mining at Tahmoor Mine, extending underground operations and associated infrastructure south, within the approved Bargo area. The proposed development sought to extend the life of underground mining at Tahmoor Mine for an additional 13 years, until approximately 2035. An Environmental Impact Statement (EIS) for the Tahmoor South proposal was submitted in 2019 and revised in 2020 (IPC 2019; IPC 2021). Approval for the Tahmoor South Extension was given by the Independent Planning Commission (IPC) on 23 April 2021 (IPC 2021).

3.4 Longwall mining in the vicinity of Thirlmere Lakes

Early bord and pillar operations at Tahmoor Colliery in the 1970s produced low levels of surface subsidence and therefore relatively low levels of surface impacts. These early methods were replaced by longwall mining methods in 1987 (AECOM 2018). Longwall mining involves removing a panel of coal by working a face of up to 300 metres in width (or sometimes greater) and up to 2 kilometres long (or sometimes longer; see Krogh 2007). Longwall panels are usually laid side by side with coal pillars, referred to as ‘chain pillars’, separating the adjacent panels. Chain pillars generally vary in width from 20–50 metres wide (Holla & Barclay 2000). The roof of the working face is temporarily held up by supports that are repositioned as the mine face advances. The roof immediately above the coal seam then collapses into the void (the ‘goaf’) and a collapse zone is formed above the extracted area. This zone is highly fractured and permeable and normally extends above the seam to a height of five times the extracted seam thickness (ACARP 2002). Above the collapse zone is a fractured zone where the permeability is increased to a lesser extent than in the collapse zone. The fractured zone extends to a height above the seam of approximately 20 times the seam thickness, though in weaker strata this can be as high as 30 times the seam thickness (ACARP 2002). Above this level, the surface strata will crack as a result of bending strains, with the cracks varying in size according to the level of strain, thickness of the overlying rock stratum and frequency of natural joints or planes of weakness in the strata (Holla & Barclay 2000; see Figure 3.2).

Numerous recent publications have dealt with the environmental and social impacts of subsidence, upsidence and valley closure, particularly the effects it has on streams, swamps, and cliffs and steep slopes (Krogh 2007, 2012, 2017; NSW Department of Planning 2008; Commonwealth of Australia 2014a,b,c; NSW Department of Planning & Environment 2015; PAC 2010; IESC 2019; IEPMC 2019a,b[19]).

[19] The NSW Government recently adopted all 50 of the recommendations of the Independent Expert Panel for Mining in the Catchment (IEPMC, 2019a,b) and is creating a taskforce and detailed action plan to oversee future mining in the catchment (see also ABC 2020a; SMH 2020a).

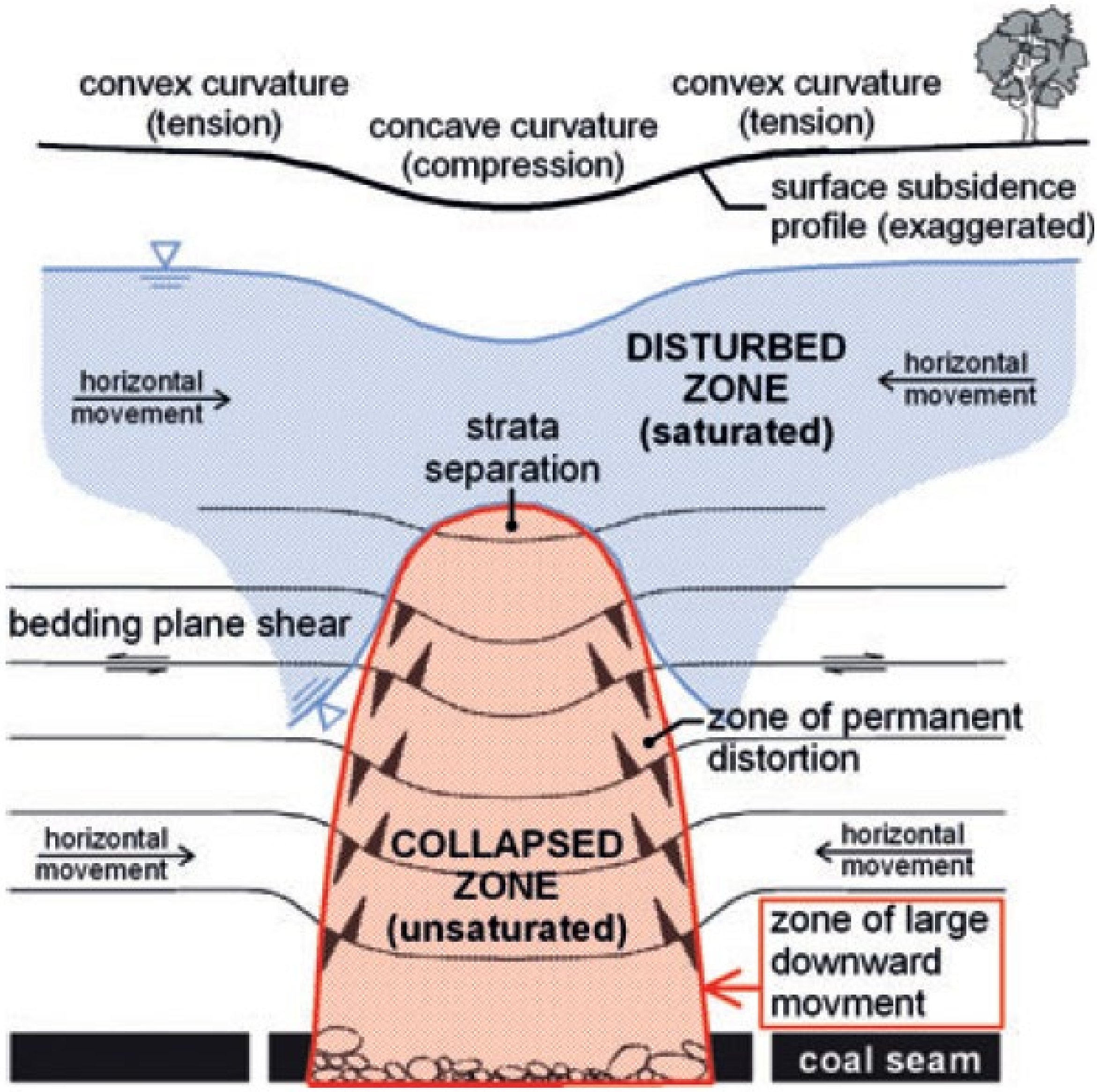


Figure 3.2 **Conceptual ground deformation model associated with Tammetta's technique for predicting the height of complete groundwater drainage**

Source: Tammetta (2013)

The first longwall panel at Tahmoor Colliery was extracted between March and July 1987 with a longwall width of ~180 metres. A summary of the subsequent progression of longwall mining at Tahmoor Colliery is included in Table A.1 (Appendix A) and the longwall layout is illustrated below (Figure 3.3). Relatively limited information on subsidence related impacts or monitoring was available for the earlier longwalls, but improved subsidence monitoring, assessment and reporting have been associated with LW 22 (commenced in 2004) and onwards. LWs 14–21 came the closest to Thirlmere Lakes (~600 metres away at its closest point). Longwall mining in the Tahmoor North area (LWs W1 & W2) is currently occurring approximately 1.5 kilometres to the north-east of the lakes. LW W1 extraction commenced on 17 November 2019 and was completed on 6 November 2020. LW W2 extraction commenced on 7 December 2020 (SIMEC 2021).

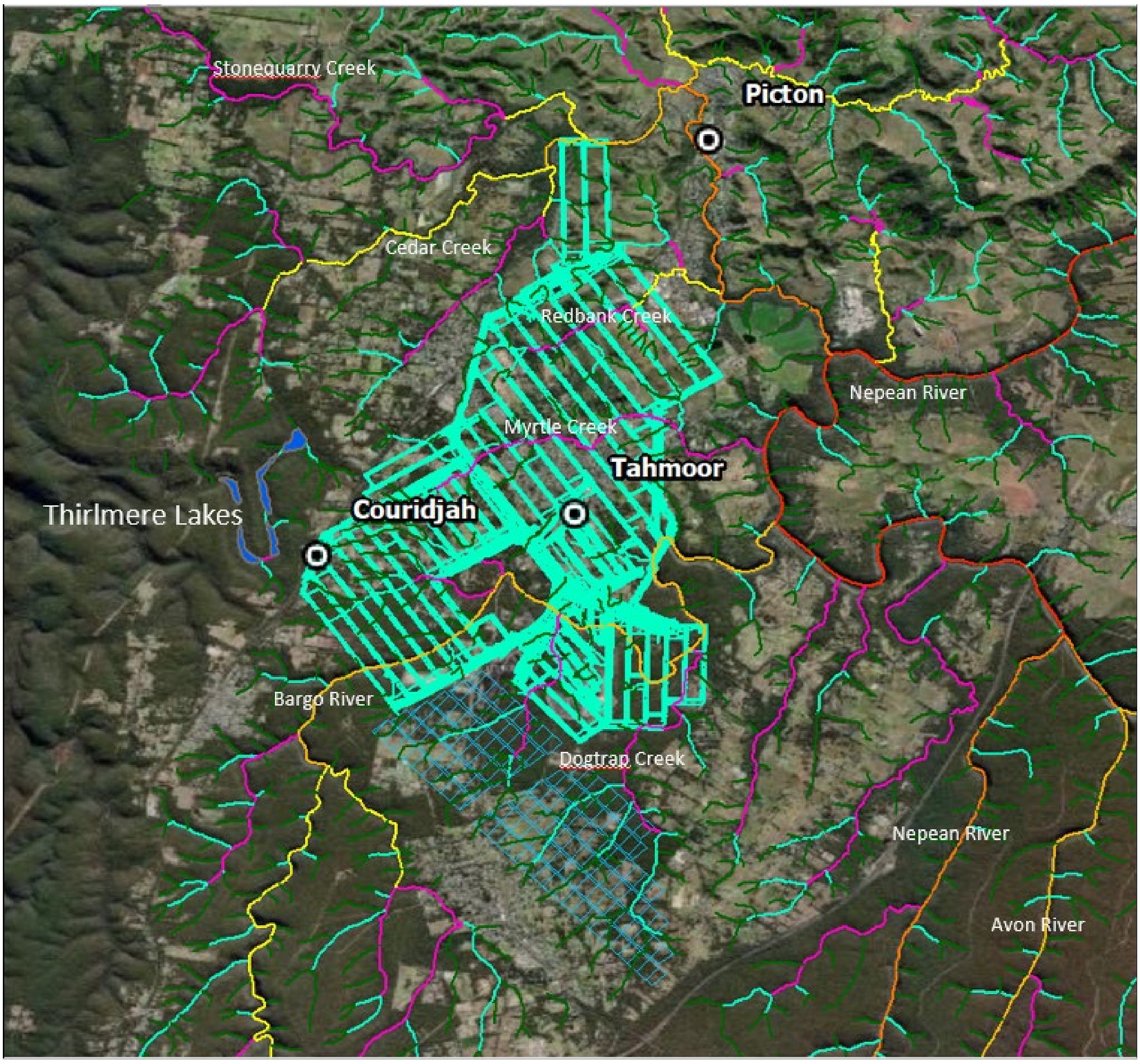


Figure 3.3 Longwall mining layout for Tahmoor Colliery relative to Thirlmere Lakes

3.5 Longwall mining impacts to rivers and streams near Thirlmere Lakes

Bargo River

The first series of longwalls to mine directly beneath the Bargo River commenced in 1991 at Tahmoor Colliery with LWs 8–13. Very little monitoring of the river occurred during this time, although extensive protective works were undertaken at the Rockford Road Bridge (MSEC 2006). During the mining of LWs 14–19 the Bargo River experienced significant impacts with surface flow ceasing in some places and water being diverted underground. MSEC (MSEC157 2006) provided a discussion of these impacts, including a figure (reproduced below; Figure 3.4) identifying the location of fractures in the bed of the Bargo River above the longwalls.

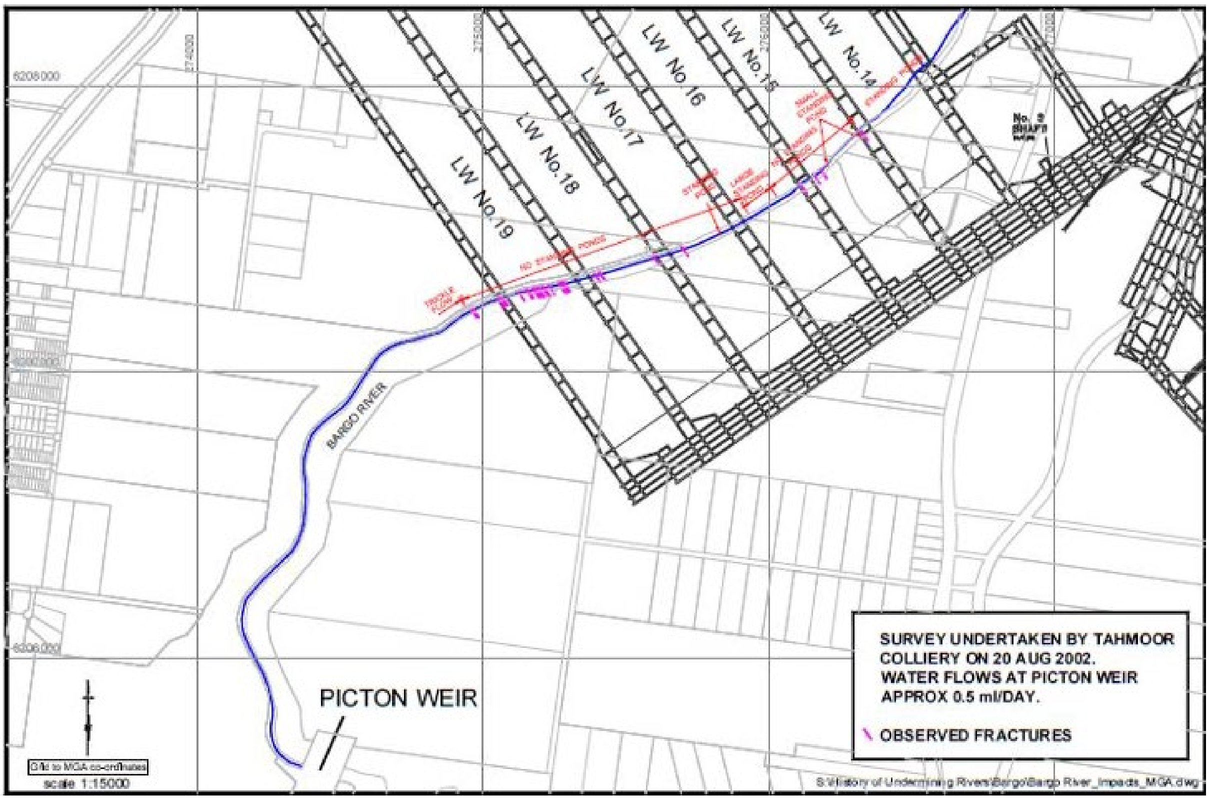


Figure 3.4 Fracturing in the Bargo River as a result of mining
Source: MSEC 2006

Geoterra (2006) described the loss of flow in the Bargo River over Panels 14–19 in January 2002, as LW 19 was being extracted. However, dedicated flow monitoring did not commence until after the loss was reported. Flow loss assessments in this section of the Bargo River were also affected by discharges from Tahmoor Colliery via Teatree Gully (see Section 3.7). Geoterra (2007) stated that:

> Due to Colliery discharges, river flow downstream of Teatree Hollow is currently continuous, except where natural sub-surface diversions occur through jointed / cross bedded or stratigraphically discontinuous rockbars. If the Colliery discharge did not occur, the river would potentially consist of disconnected pools after periods of extended dry weather.

It is noted that no remediation appears to have taken place for the identified subsidence related impacts to the Bargo River.

Redbank Creek and Myrtle Creek

More recently, extraction of LWs 22–32 has caused further damage, especially to Myrtle and Redbank creeks; with Redbank Creek experiencing drainage and significant water diversion over almost 3 kilometres of its length[20].

Myrtle Creek is a 3rd order stream under the Strahler categorisation scheme[21] (Strahler 1952), with the 3rd order section of Myrtle Creek commencing above earlier Tahmoor Colliery longwalls (LW5) and then flowing in a sinuous easterly direction above LWs 22–28, until it eventually joins the Nepean River downstream of the Bargo River confluence. The best

[20] See specific details for stream impacts in Geoterra's end of panel reports for LW22 to LW32.

[21] The NSW Government recognises 3rd order streams and above as likely to display valuable fish habitat, and hence could support viable fish populations (Bringing Back the Fish Project final report (PDF 1.3MB).

summary of impacts to Myrtle Creek is provided in the Geoterra (2014a) End of Panel Report for LW27 (see Figure 3.5). At this time Myrtle Creek had been undermined by LWs 3, 4, 5, 20, 22, 23B, 24B, 25, 26 and 27. Early cracking had been observed in Myrtle Creek over Panels 22 and 23B; however, the effect on stream flow, water quality, ponding or flow reversal had not been directly measured within the Panel 22, 23A and 23B 20 millimetre subsidence zone (Geoterra 2011). Areas of cracking were also recorded above LW25 and Myrtle Creek appears to have experienced fracturing and pool drainage for almost its full distance above LW26 and LW27; with fracturing and reduced pool levels/flows also occurring above LW28 (see Geoterra 2014a). Tahmoor Coal Pty Ltd (Tahmoor Colliery) was subsequently required to prepare a Corrective Management Action Plan (CMAP) to address exceedances of impact assessment criteria for Myrtle Creek (Glencore 2017; NSW Resources Regulator 2020).

Redbank Creek is a 3rd order stream under the Strahler categorisation scheme above LW26–31 and becomes a 4th order stream above LW31 when it is joined by the 3rd order tributary 2. Redbank Creek drains into Stonequarry Creek east of LW32. Redbank has been directly undermined by LWs 25–32 (see Figure 3.7). The department inspected Redbank Creek above the longwalls prior to and after extraction of LW 31 (24/2/17 and 28/3/18 respectively). On the first visit there were extensive lengths of Redbank Creek that contained no water at all as a result of previous longwall impacts (see also reported impacts, pool drainage and water loss in Geoterra 2011, 2013, 2014b & 2017). Where water was present it was usually heavily iron stained. Some of these impacts are illustrated in Figure 3.7. Subsidence associated with LW 31 caused further fracturing and drainage, including the pool behind the Redbank Creek weir, leading to the loss of significant areas of aquatic habitat (Figure 3.8; Geoterra 2019; MSEC 2019). Further impacts to pool levels and water quality in Redbank Creek occurred with the mining of LW 32 (MSEC 2020; Geoterra 2020). Tahmoor Coal Pty Ltd (Tahmoor Colliery) was subsequently required to prepare a CMAP to address exceedances of impact assessment criteria for Redbank Creek (SIMEC 2018; NSW Resources Regulator 2020). Impacts to Redbank Creek subsequently featured in the media (ABC 2018; SMH 2020b).

Overall, Geoterra (2015) identified ~22 pools in Myrtle Creek where there was either cracking with no flow and dry pools or pools where levels and flow were reduced (see Figure 3.4). Geoterra (2019) identified ~75 pools in Redbank Creek where there was either cracking with no flow and dry pools or pools where levels and flow were reduced (see Figure 3.6). While Tahmoor Coal has now produced CMAPs for Myrtle and Redbank creeks (Glencore 2017 – CMAP Myrtle Creek; SIMEC 2019 – CMAP Redbank Creek), rehabilitation activity is as yet only in its infancy and it is currently unclear whether these areas can be successfully remediated or how similar the remediated areas will be to their pre-mining state. It is also unclear how many of the impacted pools will be targeted for remediation and how ‘successful’ remediation will be defined.

Further stream impacts (to Cedar Creek and Matthews Creek) have been associated with the mining of LWs W1 & W2 (see SLR 2021).

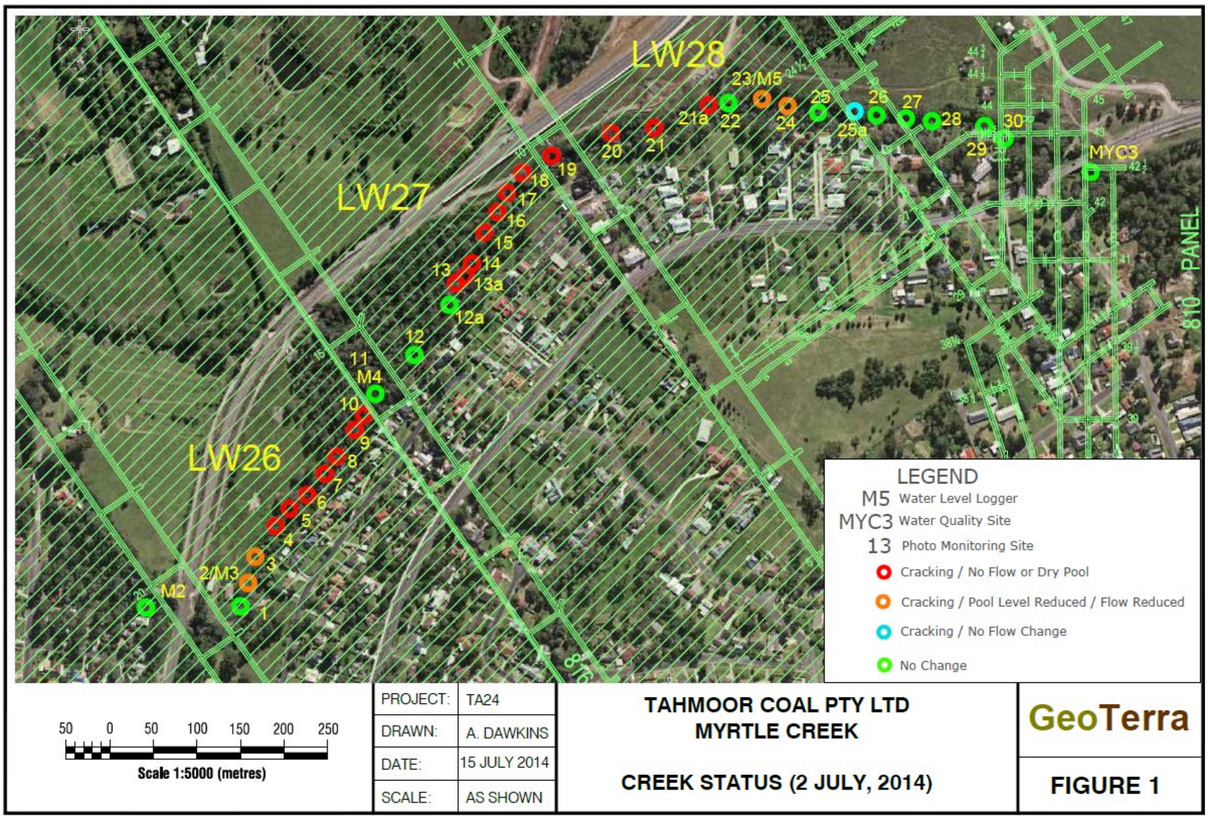


Figure 3.5 **Fracturing and diversion of flows/loss of pool water in Myrtle Creek**
Source: Geoterra 2015

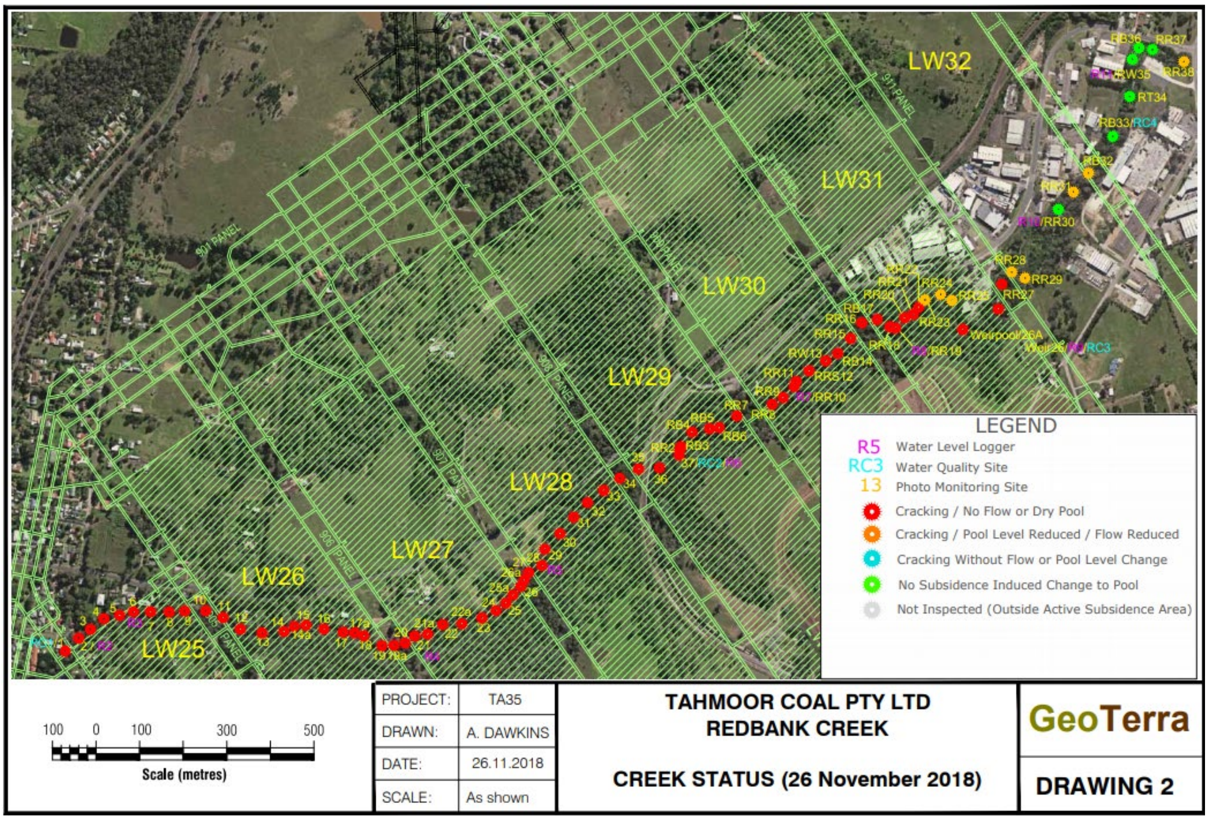


Figure 3.6 **Fracturing and diversion of flows/loss of pool water in Redbank Creek**
Source: Geoterra 2019

Figure 3.7 Pool drainage and iron stained water in Redbank Creek prior to LW31
Photos: M Krogh

Figure 3.8 Redbank Creek weir pool looking downstream (left) and looking upstream at the weir wall (right). Prior to LW31 impacts above (photos taken 24/2/17); after LW31 impact below (photos taken 28/3/18)
Photos: M Krogh

3.6 Groundwater impacts at Tahmoor Colliery

The major geological units that characterise the area around the Tahmoor Mine are the Sydney Basin Triassic and Permian rock units, with the Hawkesbury Sandstone being the primary aquifer. These aquifers fall within the *Sydney Basin Nepean Sandstone Groundwater Source* and have been classified as being 'Highly Productive' by the NSW Government based on considerations of bore yield and groundwater quality (HydroSimulations 2019).

Beneath the Hawkesbury Sandstone, the Bulgo Sandstone is also a significant aquifer; however, it is typically found to be of lower groundwater yield than the shallower systems. The Bulgo Sandstone is included in the Narrabeen Group, which is the thick sedimentary sequence that separates the near surface Hawkesbury Sandstone from the deeper Illawarra Coal Measures.

Very little baseline information is available for groundwater levels in the Picton–Tahmoor–Thirlmere area prior to mining. Whilst many registered bores have an identified standing water level recorded when they were originally drilled, very few of these have had levels measured subsequently, let alone consistently over time. According to Geoterra (2020), regular manual and data logger-based standing water level monitoring of open standpipe piezometers and private bores was initiated in June 2004[22]. This is almost a decade after LWs 17–19 came in closest proximity to Thirlmere Lakes (mid 1990s). Additional piezometers were progressively installed at later times and locations (summarised in Geoterra 2020).

HydroSimulations (2019) provided a summary of past impacts to groundwater in the Tahmoor Colliery LW W1 & W2 Extraction Plan, stating:

> Bores overlying the longwall panels (P1–P3, and P7) show mining related drawdown in the range of approximately 6 to 10 m. Recovery at the bores positioned within the centre of a longwall panel (P1 and P2) typically took 10 years. For bore P7, positioned at the southern end of LW 25, recovery was moderately faster, occurring in around 6–7 years.
>
> For bores overlying roadways or development headings (P4 and P8) the drawdown response was minimal. Bore P4 remained responsive to rainfall, however, it experienced several small drawdown events in the range of 1 m. Recovery following these events generally occurred within 6 months.
>
> Effects of mining on bores located outside of the mine footprint are difficult to assess as monitoring was discontinued at bores P5 and P6. For the available data, water levels at bore P5 appeared to remain responsive to rainfall with no observable mining related drawdown. Data from P6 does not show response to either climate or mining. It is believed that groundwater levels at this last site are influenced by the nearby Nepean Fault.
>
> Bore P9 is the most recent of the four existing monitoring locations with data having been recorded since October 2017. The open standpipe bore is screened at three depths from 28 m, 40 m and 68 m, all within the Hawkesbury Sandstone. This bore is located on the northern bank of Redbank Creek and overlies the roadway between Longwall 31 and Longwall 32, where extraction commenced in November 2018. Data has not been collected at the two shallowest monitoring locations, V1 and V2, since May 2018. However, data continues to be collected from the deepest screen, V3.
>
> An investigation of shallow groundwater in boreholes (including P9) around Redbank Creek was conducted by SCT in late 2018 (SCT 2018b). This report identified increases in hydraulic conductivity at bore P9 in the presence of subsidence-induced 'surface cracking'. This indicates the water drains from shallowest horizons and recharges a slightly deeper horizon.

[22] After the commencement of LW22.

More recently, trigger level notifications have been identified for LW W1 (SIMEC 2020). During the April 2020 to November 2020 reporting period, a number of groundwater intakes in open standpipe piezometers recorded reduction of water level elevations below the baseline range: for piezometer P12 (intake P12C) and P13 (intake P13C), as well as the two deepest intakes at P16 (intakes P16B and P16C; SIMEC 2020). Piezometers P12 & P13 are located near Stonequarry Creek at the northern end of LWs W1 & W2. Piezometer P16 is located near Matthews Creek west of LW W1.

It is interesting to note that whilst mining of LWs 29–32 appeared to have had a relatively small impact on water levels in the Hawkesbury and Bulgo Sandstone at TNC36 (see Geoterra 2019), recent mining of LW W1 (approximately 500 metres from TNC36; SLR 2021) has now led to significant changes to aquifer levels in TNC36 (see Figure 3.9, Figure 3.10 and Figure 3.11, and SLR 2021). SLR (2021) stated that:

> Approximately 60 m of depressurisation is apparent in the lower Bulgo Sandstone (piezometer BGSS-412.5m) for the period from February 2016 to August 2019, with the rate of drawdown increasing in 2020. After February 2020, declines were observed in water levels in all monitored horizons and these are considered to be primarily a result of LW W1 extraction, with:
>
> - 80 m or more drawdown in BGSS-214m
> - almost 50 m in BGSS-169m, 24 m in the lower Hawkesbury Sandstone (HBSS-97m), and
> - approximately 9 m in the mid-Hawkesbury Sandstone (HBSS-65m).

Longer-term monitoring is required to fully understand these responses, whether they persist and whether the aquifers drain/depressurise[23] further (or recover).

3.7 Discharges at Tahmoor Colliery

Tahmoor Colliery currently discharges to Teatree Hollow, a tributary of the Bargo River under environment protection licence (EPL) 1389. The quality of the discharge is however poor[24] and represents a significant point source of pollution to the Bargo River. The impacts these discharges have on the environment has previously been described by Cardno (2010), Niche (2018), Morrison et al. (2019), Belmer and Wright (2019) and Fleming et al. (2021). Media articles also reported on the discharge (ABC 2020; Wollondilly Advertiser 2020; EPA 2020).

Under the terms of the recent approval for the Tahmoor South proposal, it is noted that prior to commencement of second workings Tahmoor Coal must commission the water treatment plant required under Special Condition E1.1 of EPL1389. Surface discharges must comply with all relevant provisions of the *Protection of the Environment Operations Act 1997*, including any discharge limits (both volume and quality) set for the development in any EPL.

In terms of the volumes of the discharge, EPL1389 currently specifies a maximum discharge (outside wet weather events) of 15.5 megalitres/day. Figure 3.12 illustrates the daily discharges from Tahmoor Colliery between 1995 and 30 June 2020 (data supplied by Tahmoor Colliery). On an annual basis, total flows have ranged between approximately 0.5 gigalitres/year (mid 1990s) to almost 2 gigalitres/year more recently (Figure 3.12; Table 3.2). Over the period 1995 to 30 June 2020 this amounted to a total mine water discharge of approximately 36 gigalitres[25]. Whilst a small proportion of this mine water is likely to contain potable or recycled water used underground, the majority is likely to be sourced from aquifers above and adjacent to the mining domain. Unfortunately there has been no assessment of the cumulative impact of such losses on the groundwater aquifers of the region[26].

---

[23] Note that drainage and depressurisation are entirely different physical processes and can occur over different spatial and temporal scales.

[24] It is also likely to be toxic to sensitive aquatic species (e.g. see Cardno 2010).

[25] Equivalent to approximately 26,000 Olympic swimming pools. This estimate does not include days where there were no data provided or the gauge was identified as not functioning.

[26] Especially in terms of aquifer volume and recharge characteristics.

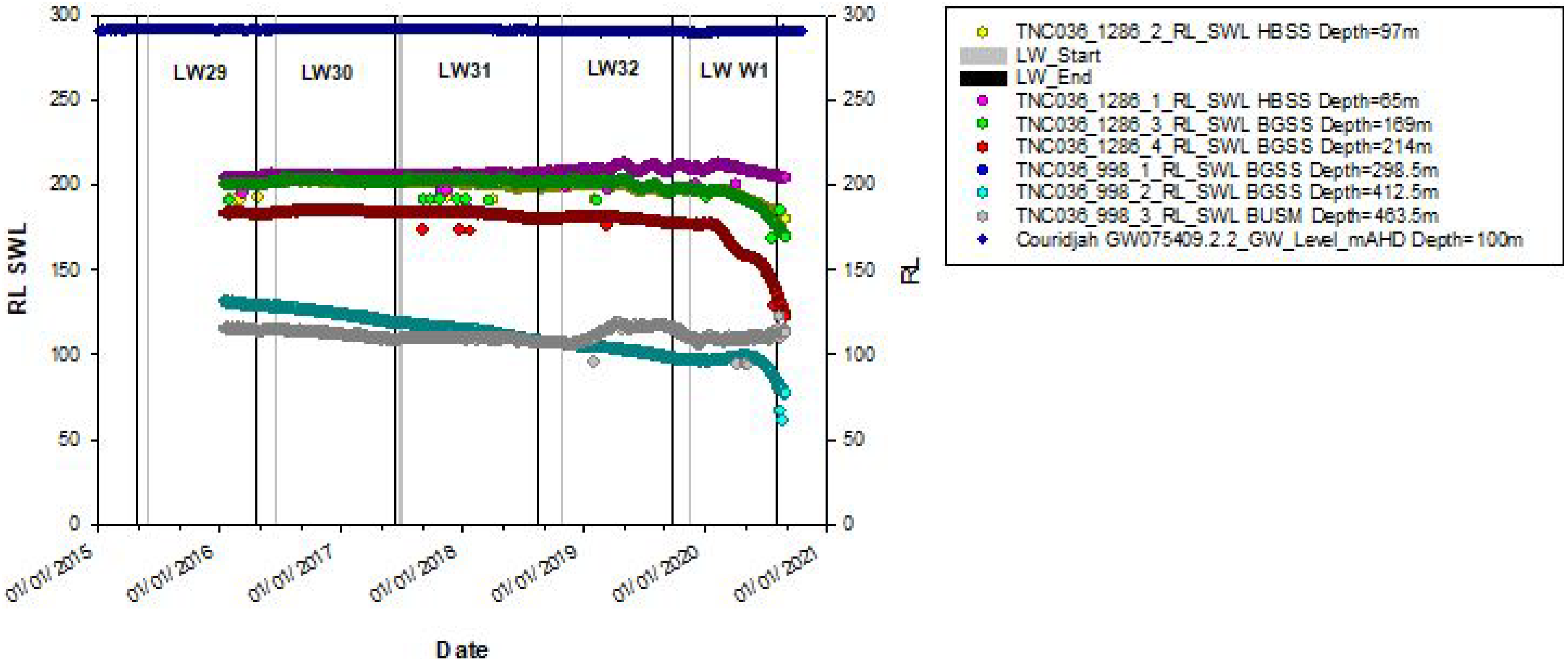


Figure 3.9 **Groundwater levels in TNC36**[27]

Data sourced from Tahmoor Colliery.

[27] Groundwater pressures at TNC36 have recently been re-assessed and this resulted in the removal of the transducer records at 298 and 463 metres (Groundwater Exploration Services [GES] 2020) – see SLR (2021).

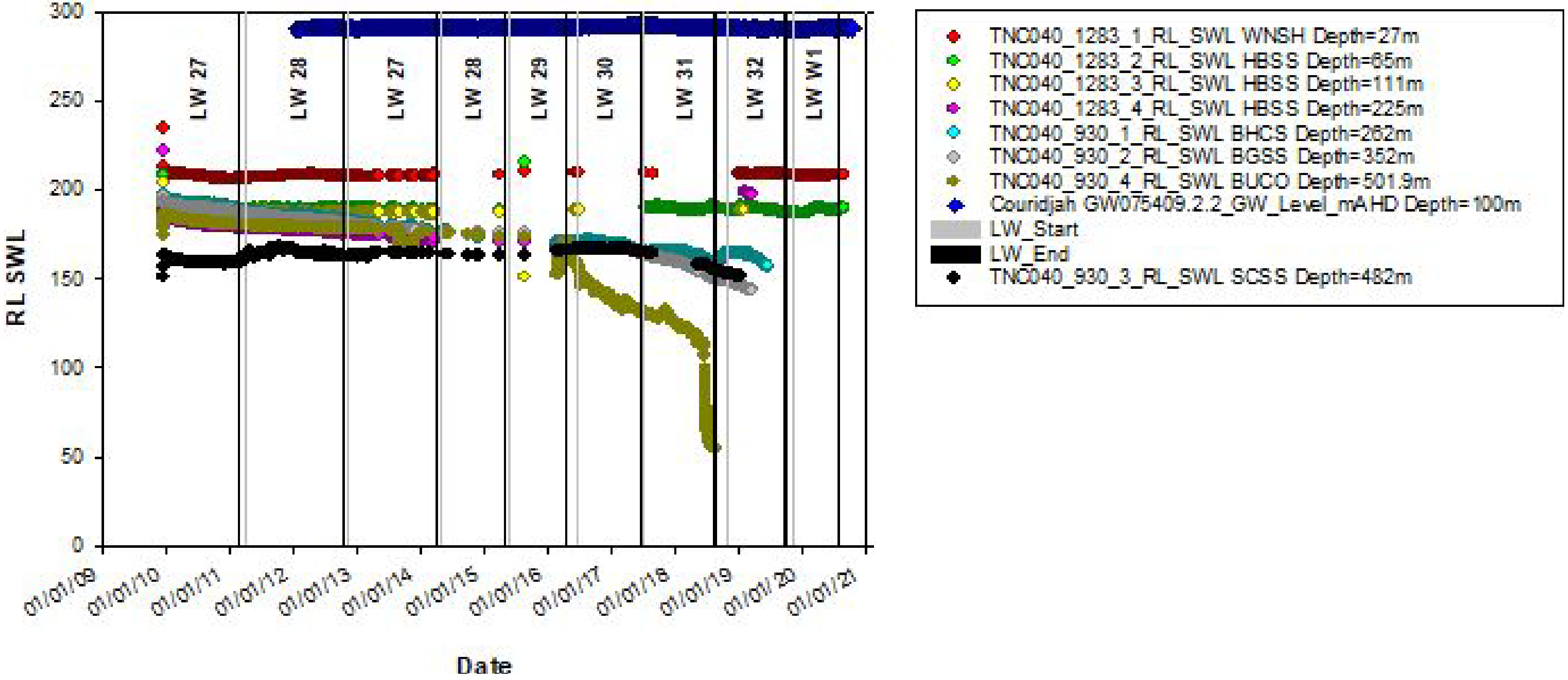


Figure 3.10 Groundwater levels in TNC40

Data sourced from Tahmoor Colliery.

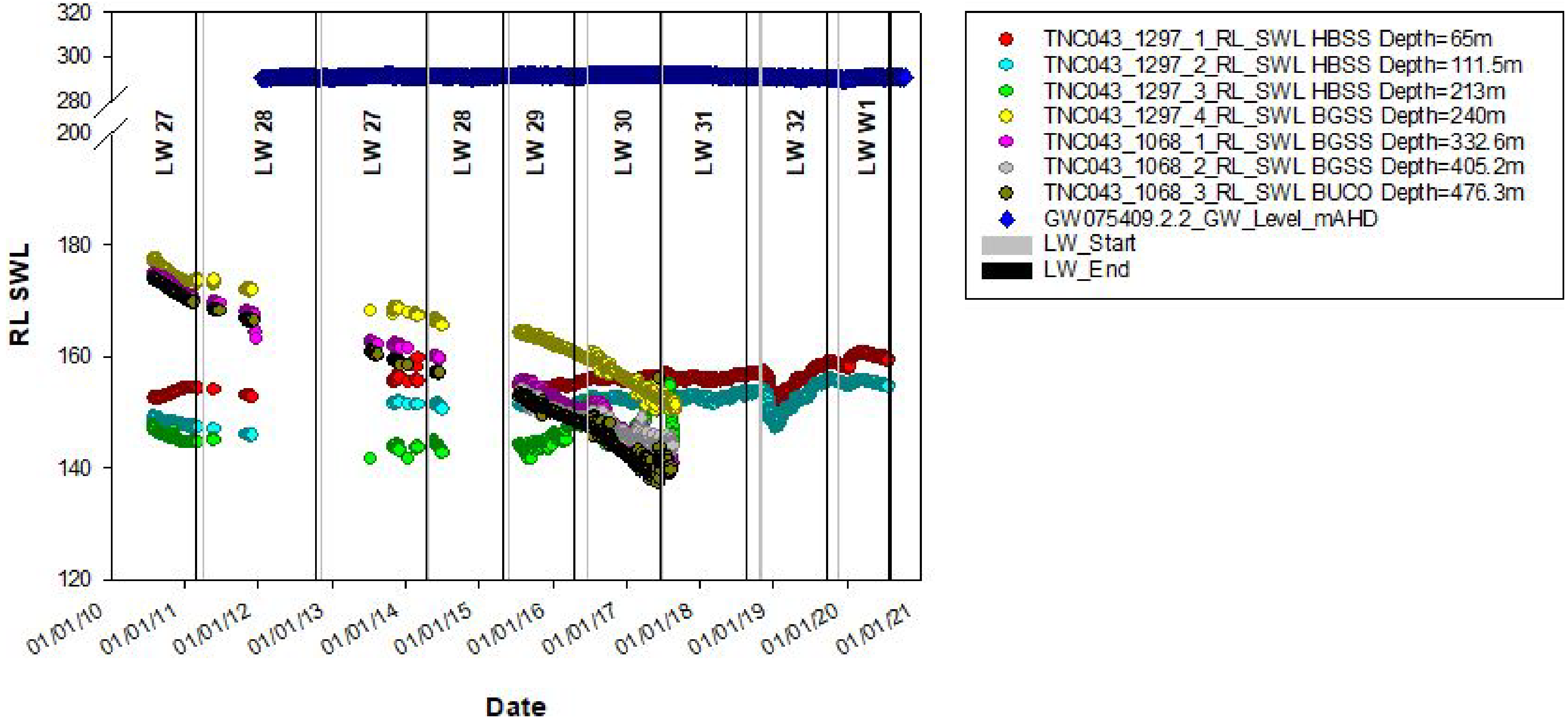
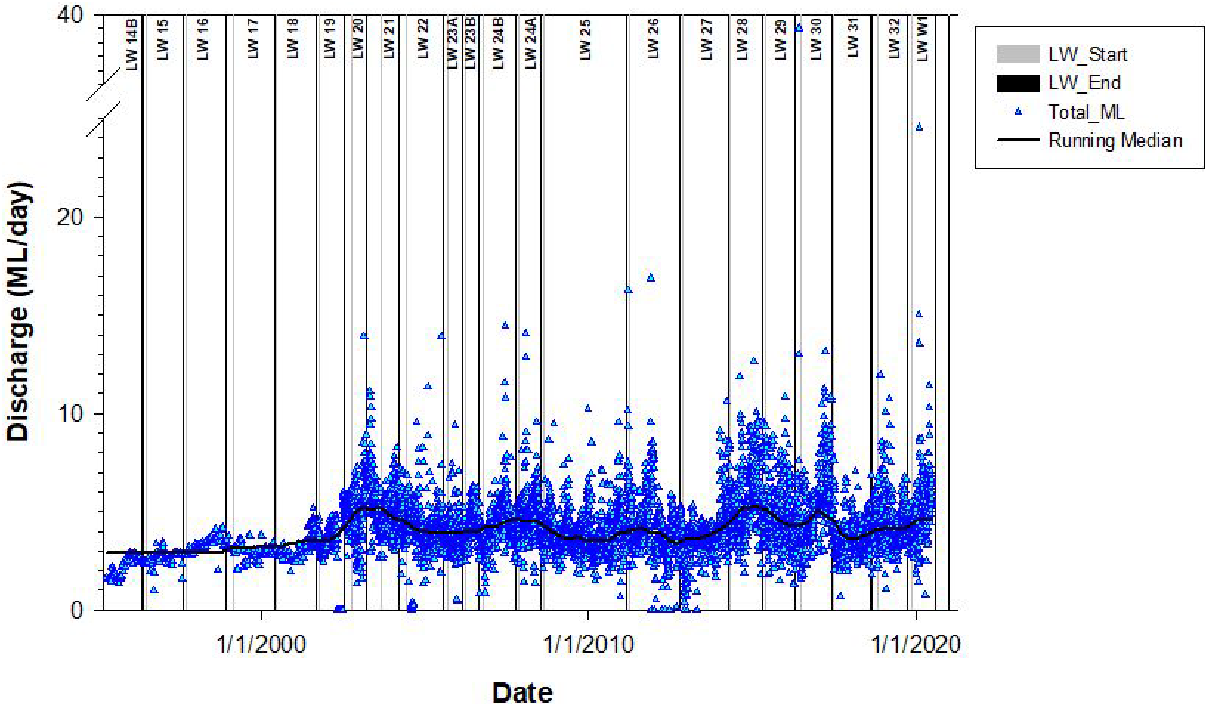


Figure 3.11 Groundwater levels in TNC43

Data sourced from Tahmoor Colliery.



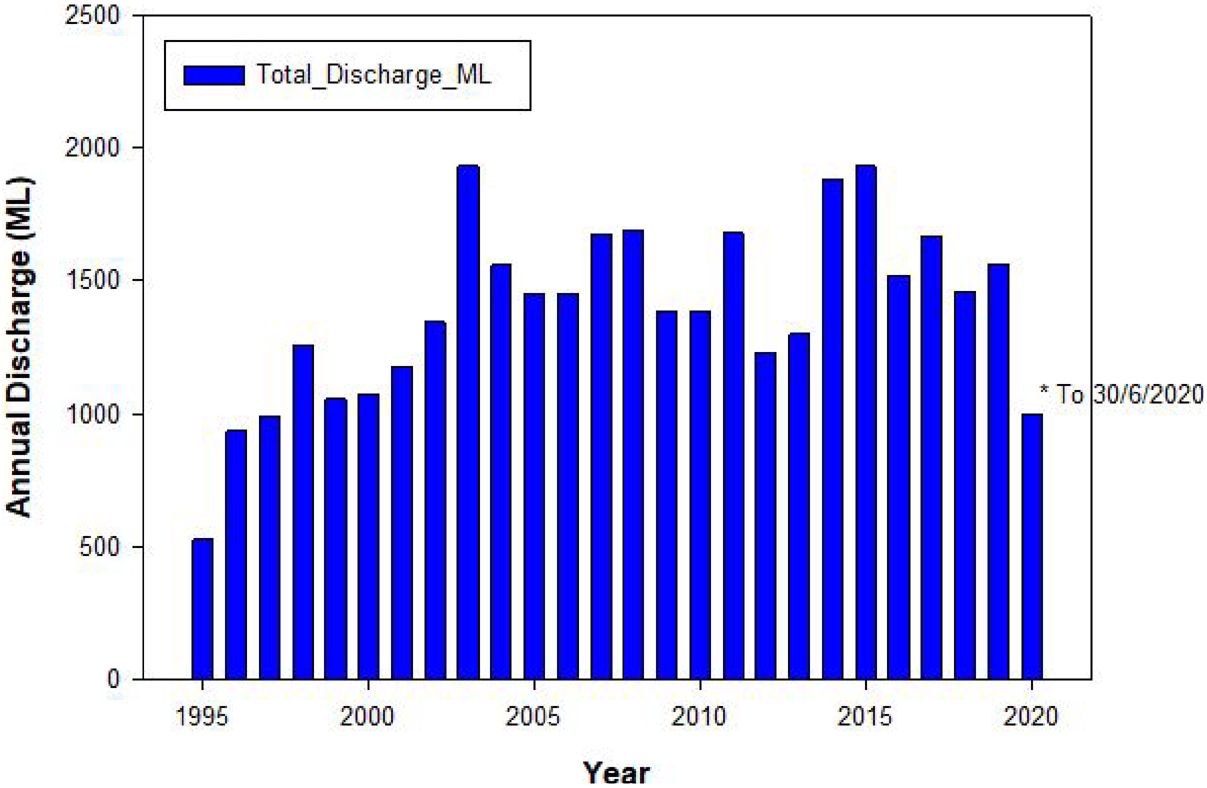


Figure 3.12 Tahmoor Colliery discharge data 1995 to 30 June 2020; weekly/daily time series (above) and annual volume (below)

Data supplied by Tahmoor Colliery.

Table 3.2 Tahmoor Coal LDP1 annual discharge volumes[28]
Data supplied by Tahmoor Colliery.

Year	Total discharge (megalitres)	Year	Total discharge (megalitres)
1995	525.5	2008	1690
1996	934.7	2009	1382.9
1997	991.3	2010	1386.2
1998	1261.1	2011	1679.2
1999	1052.4	2012	1228.5
2000	1070.8	2013	1300.4
2001	1173.4	2014	1884.4
2002	1344.2	2015	1932.6
2003	1931.7	2016	1519.8
2004	1561.4	2017	1670.3
2005	1454.2	2018	1459.9
2006	1454	2019	1562.7
2007	1678.4	2020	998.5

3.8 Discussion

It is obvious that longwall mining has had a substantial impact on streams near Thirlmere Lakes, particularly where the streams have been directly undermined. It is currently unclear whether these areas can be successfully remediated or how similar to their pre-mining state the remediated areas will be once remediation is deemed complete. Impacts to areas that receive no remediation are likely to remain in perpetuity and therefore these areas are unlikely to support the aquatic habitat and connected flow that once existed in those areas.

Groundwater responses to longwall mining are complex and assessments have often been compromised by poor experimental design (e.g. lack of a baseline), poor quality and reliability of data, and a lack of consistency in measurement. Rarely has the ‘natural’ variation in groundwater levels been characterised, monitored and compared to impacted bores. The Thirlmere Lakes Inquiry (Riley et al. 2012) noted that:

> There are recorded instances in the Thirlmere region of private bores in the Hawkesbury Sandstone aquifers experiencing catastrophic decline in groundwater level and going dry or experiencing a reduction in yield when longwall mining passed near or under them. There are also instances of private bores not being affected and of affected wells recovering following mining and of water rising in some wells.

These conclusions are supported by published accounts in the USA that have identified increases in overburden transmissivity, declines in groundwater levels, increases in water level fluctuations, and decreases in spring flow (e.g. Booth 2006; DEP 2005; Cifelli & Rauch 1986; Schmid & Kunz 2000; see Krogh 2007). While groundwater levels recovered in some areas in the USA post-mining, there have been a number of areas where no recovery has occurred (Booth 2006).

Loss of bore water has been reported over Tahmoor Colliery longwalls. Geoterra (2007) reported that:

> Complaints were received prior to extraction of Panels 22, 23A and 23B in regard to private bores at least 175m north of Panel 21. Two bores were redrilled, one property received temporary trucked in water and another complaint was dismissed as it was assessed that mining did not affect the bore’s performance as it was outside the probably area of subsidence effects.

[28] The figure provided for 2020 is to 30 June 2020.

Pells and Pells (2011, 2017) also discussed bore water losses on the basis of interviews with landowners. Riley et al. (2012) summarised much of this information, stating:

> During 2003, two bore owners, a poultry farmer and market gardener were identified by the mine as having a low risk of reduction in bore supply due to their proximity to Longwall 21. A subsidence management plan was prepared and, as part of this, both properties were connected to mains supply. One poultry farmer, who reported water loss in his bore drilled to 61 m in 1980, had a new bore drilled to a depth of ~120 m (Centennial Coal 2005). The new bore had such a high iron content that the farmer's misting system in the poultry shed suffered clogging problems.
>
> Pells and Pells (2011, 2012) undertook a hydrocensus in September and October 2011 and subsequently in 2012. They reported four bore owners with decline in water level or loss of yield when mining occurred beneath or within 1 kilometre: GW049796, GW042537, GW011200 and GW037860. All bores were 60–120 metres deep, pumped from one or more aquifers in the Hawkesbury Sandstone and with yields of <3 litres/second. Of the four monitoring bores, bore GW042357 is located closest to the lakes, and is approximately 0.6 kilometres east of Lake Couridjah. Pells and Pells report other bore owners who stated they were not affected by mining, although one landowner had only purchased the property after it had been undermined.
>
> The committee also interviewed a number of private bore owners who reported a decline in water level or loss of yield when mining occurred beneath or nearby (see Chapter 5). Three of these bores were located between the Loop Line and Thirlmere Lakes and all penetrated one or more aquifers within the Hawkesbury Sandstone. One private bore owner (GW047416) reported a catastrophic decline in water level in a single day, when the mining was closest to the Loop Line (probably Longwall LW21; September 2003 to March 2004; at a distance of ~1.2 km). This bore is located 0.6 km directly east of Lake Gandangarra.

The last bore impacted by mining at Tahmoor Colliery was stated to be at the Pescud property[29] (GW109010), which was reported to Tahmoor Coal in December 2015 (Geoterra 2020).

Due to the lack of consistent long-term groundwater monitoring in appropriate areas in the Tahmoor–Thirlmere–Picton area, it is still largely unknown how far and how fast the observed groundwater depressurisation over the longwall panels propagates to the west of the Tahmoor mining domain (i.e. towards Thirlmere Lakes). Whilst mining of LW 29–32 (~1.5 kilometres south of TNC36) appeared to have had a relatively small impact on water levels in the Hawkesbury and Bulgo Sandstone at TNC36, recent mining of LW W1 (approximately 500 metres east of TNC36) has now led to significant changes to aquifer levels in TNC36. Groundwater modelling for the Tahmoor South proposal predicted drawdowns in the Hawkesbury Sandstone (i.e. beneath the Thirlmere Lakes/Blue Gum Creek alluvium), peaking between 1–5 metres with maximum drawdown at the lakes due to Tahmoor South predicted to occur in 2070–2100 (i.e. 50–70 years in the future[30]; HydroSimulations 2018, 2020). Such time lags in response to mining-induced groundwater depressurisation may mean that the full consequences of aquifer depressurisation as a result of earlier mining in the Tahmoor Mining domain are yet to occur. Continued monitoring of surface water and groundwater at Thirlmere Lakes and groundwater bores closer to the mine is needed to understand how groundwater aquifers behave in the future.

Discharges from Tahmoor Colliery under EPL 1389 are currently averaging ~3–4 megalitres/day (1–2 gigalitres/year). Over the period 1995 to 30 June 2020, discharges from Tahmoor Colliery amounted to a total volume of approximately 36 gigalitres. Whilst a proportion of this mine water volume is likely to have contained potable or recycled water used in underground operations, the majority is likely to be sourced from aquifers above and adjacent to the mining footprint. The cumulative impact of such losses on the groundwater aquifers of the region has received inadequate attention in previous mining assessments.

[29] Above LW26.
[30] Well after the Tahmoor South's proposed mine life.

4. Geology

4.1 Background

The conceptual geological model for the lakes environment involves a late Cretaceous to early Tertiary alluvium (clayey quartz sand) overlying Triassic Hawkesbury Sandstone (quartz sandstone having a clay matrix and sideritic cement) – see Figure 4.1 and Figure 4.2. The deposition of the Hawkesbury Sandstone occurred after the uplift of the Lachlan Fold Belt tilted the Sydney Basin. The uplift event led to the deposition of the deltaic sand (i.e. Hawkesbury Sandstone), which is believed to be derived from the Upper Devonian quartzites of the Lachlan Fold Belt (Herbert 1980). The deposition of the Hawkesbury Sandstone is alluvial in origin and formed from a high energy, braided stream system in a deltaic/alluvial environment. Shale lenses found within the main Hawkesbury Sandstone are believed to be from abandoned channels within the rapidly shifting braided channel environment.

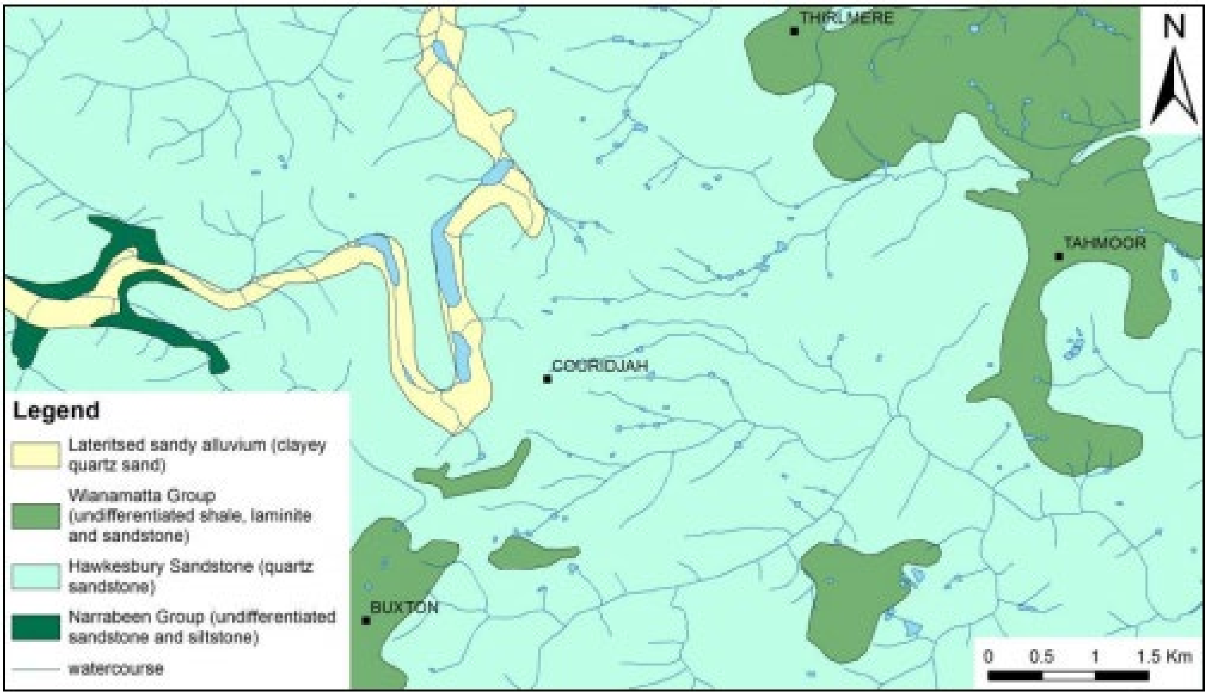


Figure 4.1 Geology of the Thirlmere Lakes region (modified from Stroud et al. 1985)
Source: OEH 2016

Beneath the Hawkesbury Sandstone the geology continues to be representative of the regional southern Sydney Basin sequence: Permo-Triassic Narrabeen Group (shale, shaly sandstone, quartz-lithic sandstone and clay siltstone) overlying Permian Illawarra Coal Measures (lithic sandstone, shale, siltstone, claystone, coal seams and carbonaceous shale), and then at depth the Permian Shoalhaven Group (lithic sandstone and micaceous siltstone). Within the sedimentary sequence several low permeability layers are considered to act as aquitards, the most important of which was considered to be the Bald Hill Claystone[31].

[31] But see recent discussions of the aquitard properties of Bald Hill Claystone in the TLRP4 report (McMillan et al. 2021).

Hawkesbury Sandstone			Up to 120
Narrabeen Group		Newport Formation	10
		Garie Formation	3
		Bald Hill Claystone	12
		Bulgo Sandstone	95
		Stanwell Park Claystone	20
		Scarborough Sandstone	30
		Wombarra Shale	25
		Coalcliff Sandstone	15
Illawarra Coal Measures		BULLI COAL	1.5
	Eckersley Formation	Unnamed Member	10
		Balgownie Coal Member	1
		Lawrence Sandstone Member	9
		Cape Horn Coal Member	0.3
		Unnamed Member	1
		Hargrave Coal Member	0.1
		Unnamed Member	3
		WONGAWILLI COAL	9.4
		KEMBLA SANDSTONE	14
	Allan's Creek Formation	American Creek Coal Member	3
		Unnamed Member	27
		APPIN FORMATION	
		TONGARRA COAL – Upper Split	2
		TONGARRA COAL – Lower Split	0.5
	Wilton Formation	Unnamed Member	15
		Woonona Coal Member	4
		Unnamed Members	26
		ERINS VALE FORMATION	
		PHEASANTS NEST FORMATION	
		Figtree Coal Member	0.5
		Unnamed Member	20
		Unanderra Coal Member	2
		Unnamed Member	>84

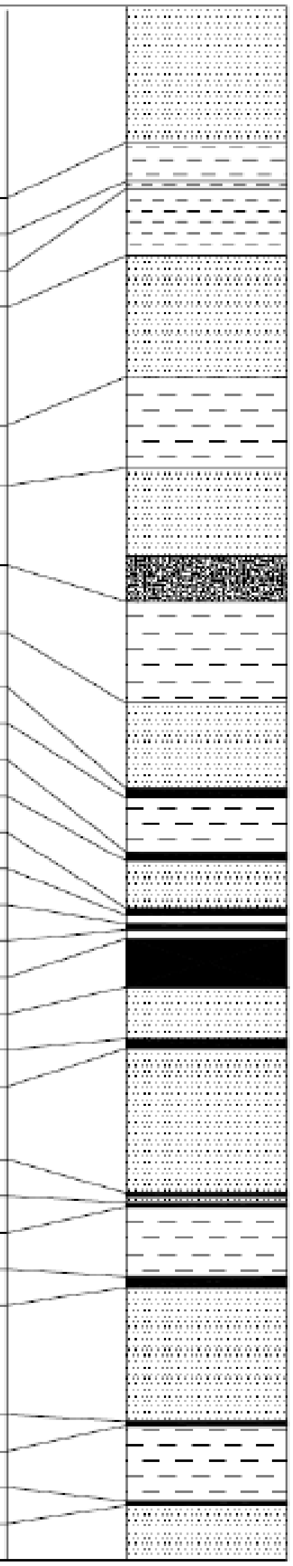


Figure 4.2 Stratigraphic section of the Southern Coalfield below the Wianamatta Group and Mittagong Formation, showing thickness of each unit

Source: Fig.4, p.21, NSW Dept of Planning (2008); © State of New South Wales through the Department of Planning

A knowledge of the geology and stratigraphy around and underneath Thirlmere Lakes is fundamental to understanding subsurface hydrology, including groundwater catchment boundaries, flow pathways (particularly the direction and slope) and surface water interactions with the underlying groundwater systems. Previously there were very few boreholes within 1 kilometre of Thirlmere Lakes that provided detailed information suitable for the analysis of geological stratigraphy for the lakes themselves.

A knowledge of the geological structures (faults and dyke intrusion zones) near and underneath Thirlmere Lakes is also fundamental to understanding groundwater flow pathways within the underlying strata. Geological structures and bedrock fracturing in the vicinity of the lakes can provide conduits for fracture flow through otherwise low permeability strata or formation boundaries.

In addition, the mineralogy of the underlying rocks has the ability to significantly affect the permeability, porosity and storativity of a hard rock aquifer. Groundwater flow at shallow depths (up to approximately 200 metres below ground surface) is suggested to be dominated by flow through fractures, while at greater depths groundwater flow is controlled mainly by the porosity of the rock matrix (Commonwealth of Australia 2014). The Bald Hill Claystone was previously considered to be a significant low permeability formation separating Hawkesbury Sandstone from the deeper groundwater systems. The matrix permeability of the Bald Hill Claystone was suggested to be significantly lower when compared to hydraulic conductivities measured for sandstone formations. However, field packer test results indicate that the hydraulic conductivity of the Bald Hill Claystone can be quite similar to other strata (Reid 1996; Pells & Pells 2011) and research associated with the *Thirlmere Lakes Research Program* is now challenging previous theories regarding the nature and aquitard properties of the Bald Hill Claystone.

To address the geological knowledge gaps for Thirlmere Lakes, geological studies were undertaken by UNSW and collaborators via a research agreement (TLRP4) with UNSW. The original research leader was Dr Wendy Timms (UNSW), but project leadership was later passed to Dr Martin Andersen (UNSW) when Dr Timms moved to Deakin University.

The aims of the *Geological mapping and geophysical surveys of the Thirlmere Lakes area* research project (TLRP4) were to undertake:

- field mapping of the geology of sediments and rock masses, including structures (joints, fractures, faults and dykes)
- geophysical surveys of sediments and, where possible, rock masses near structures, and
- 3D geological modelling and sections with historic bore data and geological information.

The project used a range of geological and geophysical techniques to investigate the subsurface stratigraphy and geology of Thirlmere Lakes. The key research findings of the *Thirlmere Lakes Research Program Geology* theme (TLRP4) are contained in McMillan et al. (2021).

4.2 *Geology* theme – key research findings

Geological faulting has occurred in and near the Thirlmere Lakes National Park. These faults have manifested as fault propagation folds (FPFs, or monoclines) at the surface, which have strongly influenced the development of the lakes and the sources of sediments available to the lake system. Only two structures, the Eastern and Western FPFs, were identified that had demonstrable displacement and which could be classified as faults. Several other lineaments exist within the region that could not be given a more distinct classification with the available evidence. These lineaments may be either volcanic intrusions or small displacement faults, fault propagation folds, fault propagated joint swarms (see Och et al. (2009)) or transfer features. Inferred and field confirmed geological structures are illustrated in Figure 4.3.

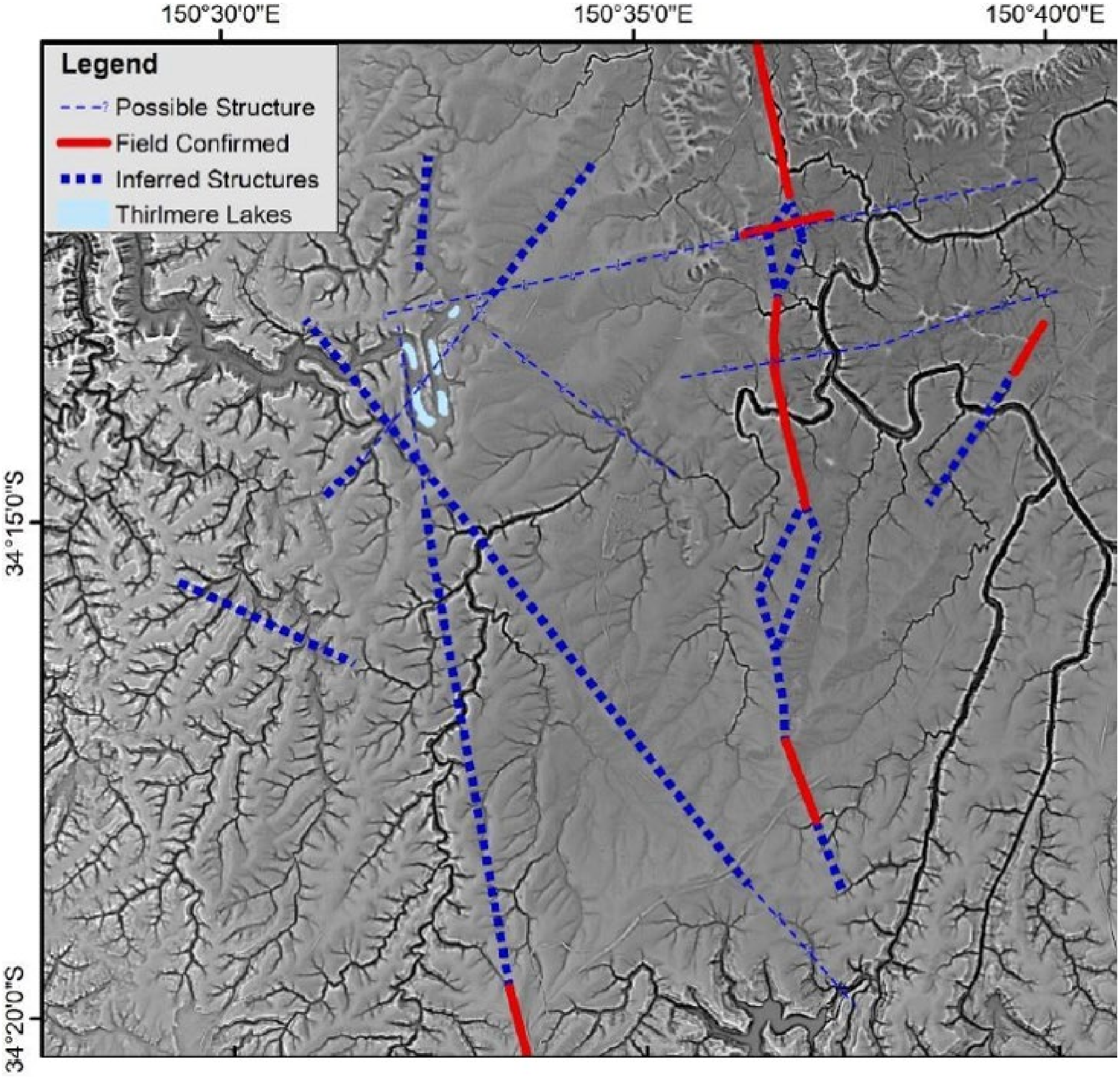


Figure 4.3 **Interpreted geological structures near Thirlmere Lakes**
Source: McMillan et al. 2021

The identified fracture patterns surrounding the FPFs effectively provide a much wider fault damage zone (100s rather than 10s of metres) when compared to traditional fault geometries. These wider zones created within the Hawkesbury Sandstone increase the probability of them being intersected by groundwater infrastructure such as water supply bores (e.g. for agriculture). Additionally, processes such as longwall mining would require a larger set back distance (i.e. wider buffer zone) to avoid the fault generated damage zone intersecting with the angle of draw that defines that area of ground movement above a longwall panel. In the case of Thirlmere Lakes, the Eastern FPF and the completed Tahmoor longwall panels, such a distance exists, and the identified FPFs were considered unlikely to have been directly affected by the mining.

It was hypothesised that the identified fracture patterns for the FPF zones, the Eastern and Western FPF fracture networks, are interconnected at the point of intersection between these two structures. It was therefore considered possible that any groundwater impacts experienced by the Western FPF could be transmitted along the Eastern FPF from the point of intersection between these two structures. As such, any significant groundwater abstraction along strike of the Eastern or Western FPFs (e.g. directly or indirectly related to mine dewatering or production bores) may influence the groundwater in the Hawkesbury Sandstone under the lake system through these highly transmissive, naturally produced fracture networks.

The application of geophysical surveys (ERT, EM34 and GPR) was used to describe the general stratigraphy of the lakes system:

- The upper ~15 metres across all surveyed lakes and sills is represented by unconsolidated alluvial/colluvial sediments.
- The upper 2–3 metres of the sills are typically unsaturated sand, which generally overlay clay.
- Across the lakes, the upper 4–5 metre horizon comprised saturated clay.
- In the areas to the north and east of the lakes system along the Boundary and Slades Road, the shallow dipping layers were observed to a depth of 5–6 metres with a very gentle dip gradient to the south-west and north-east, typical of the Hawkesbury Sandstone constraining sediment depths.

For further details see McMillan et al. 2021.

5. Geomorphology

5.1 Background

A number of hypotheses exist concerning the geomorphology and evolution of Thirlmere Lakes. An account of the hypotheses prior to 1974 was presented in Vorst (1974). The most widely accepted hypothesis was that the lakes were formed in an abandoned Tertiary-age valley of a westward flowing stream whose headwaters were truncated. This truncation was proposed to have occurred with the tectonic activity that gave rise to the faults and monoclines to the south and east. The current estimate of the age of the valley is estimated to be 15 million years, based on the age of the Lapstone Monocline, following the work of Bishop et al. (1982) and Pickett and Bishop (1992). More recently, the Independent Committee presented an alternative hypothesis that the Thirlmere Lakes valley is a structurally-controlled headwater reach of Blue Gum Creek, where the Hawkesbury Sandstone has not been breached by incision and hence still controls the geometry of the catchment in both cross section and planform. The position of the lakes within the surrounding landscape is illustrated in Figure 5.1.

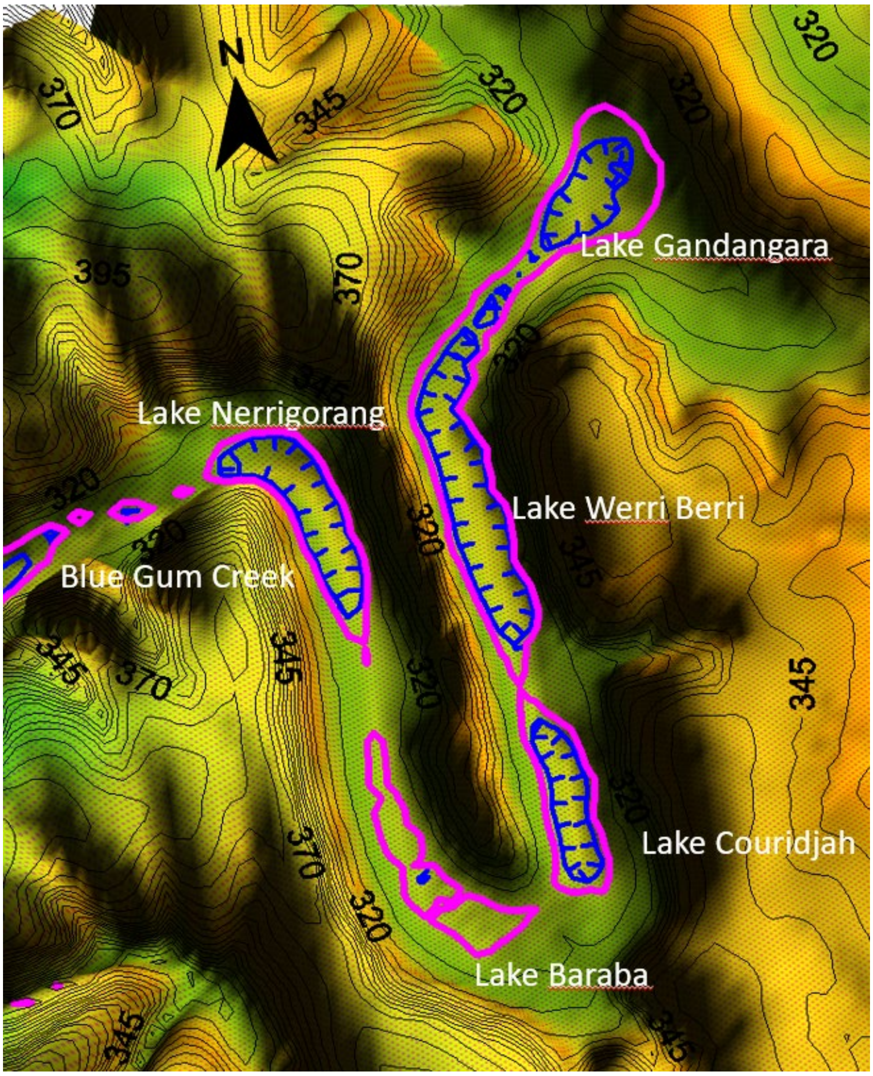


Figure 5.1 Position of the lakes within the surrounding landscape

Contours based on the digital elevation model developed for the surface water balance study. Pink contour line is 305 metres Australian Heigh Datum (AHD); blue hashed area is lake area inside the 303 metres AHD contour.

Vorst (1974) found that the bedrock cliffs on either side of the valley reclined at angles between 45° and 70° from the vertical. However, interference with the sound waves because of the narrowness of the valley during her seismic survey prevented the bedrock base from being defined; its depth was suggested to be somewhere beyond 50–60 metres. Identifying the bedrock base of the valley is fundamental to understanding the geomorphology of Thirlmere Lakes. It is also fundamental for understanding sediment (soil and peat) volumes. The nature and extent of the sediments has implications for the storage and movement of groundwater, which plays a role in helping maintain the surface water in storage.

To try to address geomorphological knowledge gaps for Thirlmere Lakes, geomorphological, sedimentological, chronostratigraphic, geochemical and palaeoecological studies were undertaken by UoW and collaborators via a research agreement (TLRP1). The research leader was Associate Professor Tim Cohen.

The aims of the *Thirlmere Lakes: the geomorphology, sub-surface characteristics and long-term perspectives on lake-filling and drying* research project (TLRP1) were to:

- identify the long-term frequency of ‘dry and wet phases’ of Thirlmere lakes
- determine the subsurface characteristics of the valley fill in the lakes, and
- characterise the nature of underlying bedrock morphology under the lakes.

The project used a range of geological, geo/biochemical, geophysical and palaeoecological techniques to investigate the subsurface stratigraphy and sedimentology of Thirlmere Lakes (Cohen et al. 2020). This involved 357 metres of coring/drilling with over 40 cores from the lakes and deep drilling on the lake margins and on the alluvial sills adjacent to the lakes. A robust geochronological framework was developed based on 41 optically stimulated luminescence (OSL) samples and 33 radiocarbon samples.

As a result of the TLRP studies, further detailed work on sediment cores, more accurate lake elevations and a better understanding of bedrock depths are now available (Cohen et al. 2020, Chen et al. 2020 and Anibas et al. 2021). A comparison between what was known about lake elevations and sedimentology available at the time of the Thirlmere Lakes Inquiry (Figure 5.2) and what is known now (Figure 5.3) is illustrated below. The key findings of TLRP1 are contained in Cohen et al. 2020.

5.2 *Geomorphology* theme – key research findings

Deep drilling at Thirlmere lakes was undertaken at three locations as part of TLRP1 and in each hole there were varying amounts of unconsolidated sediment and also varying thicknesses of what appears to be weathered rock. In some locations, such as the thalweg of the valley at Blue Gum Creek, unconsolidated material (potentially Pleistocene alluvium) occurs all the way to refusal where clean unweathered rock was encountered. In other locations there were 2–7 metres of what could be tentatively interpreted as in-situ weathered Hawkesbury Sandstone underlying Pleistocene alluvium; however, currently we cannot readily differentiate in-situ weathered rock (e.g. saprolite) from weathered Pleistocene alluvium. The refractive seismic surveys show seismic velocities of 200–400 metres/second representing the upper part of the Pleistocene fill and 1625 metres/second to 2700 metres/second in the lower part of the sequence. In some cases the upper velocities represent unweathered rock and in other instances velocities of ~2000 metres/second represents either weathered Hawkesbury Sandstone or compacted Quaternary alluvium.

The main findings of the deep drilling (also utilising existing deep boreholes) and the seismic lines can be summarised as follows:

- The depth of unconsolidated material is greatest at the Lake Nerrigorang end of the Thirlmere Lakes and is in the order of 30–40 metres (268–282 metres AHD).
- At the Dry Lake/Lake Gandangarra sill the depth of fill is ~15 metres (295 metres AHD; see Figure 5.4 and Figure 5.5).

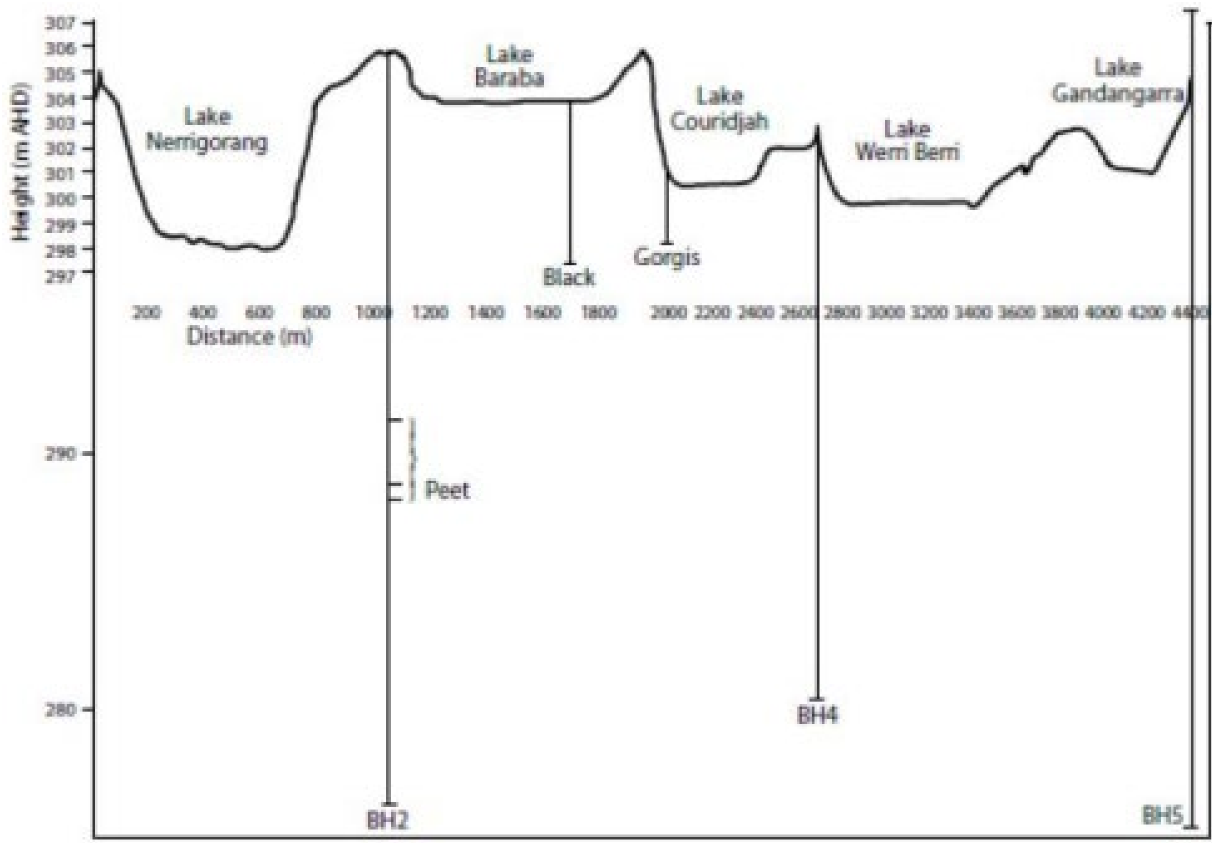


Figure 5.2 **Location and depth of cores studying sedimentology prior to the *Thirlmere Lakes Research Program***
Source: Thirlmere Lakes Inquiry – Riley et al. (2012)

Both these techniques suggest a net western gradient in the underlying bedrock; presumably representing past river gradients of the valley prior to uplift and prior to the formation of the lakes. The age of the fill valley within the Thirlmere lakes is at least 300,000 years but this represents an age determination at only one-third to half the depth of the alluvium so is a minimum age only. An interpretation of sediment and bedrock depths for the valley is illustrated in Figure 5.4 and Figure 5.5.

The Thirlmere Lakes have become separate lakes via alluvial fan aggradation that has formed sandy or organic sills separating the five lakes. Both lake floors and sills have been aggrading through time but the existing chronology would suggest the lakes have become distinct and separate waterbodies since the last interglacial (e.g. since 125,000 years ago).

The sediments within Thirlmere Lakes have been classified into five lithostratigraphic members (LMs) that share similar characteristic sedimentological, geomechanical and hydraulic properties. These members are:

- Sand (LM1)
- Sandy clay/Clayey sand (LM2)
- Silty clay (LM3)
- Organic silty clay (LM4)
- Peat (LM5).

These LMs combine in different thicknesses and combinations to produce three dominant lithostratigraphic formations (LFs) that reflect the depositional location:

- Lithostratigraphic formation 1 (LF1, hillslope sediments)
- Lithostratigraphic formation 2 (LF2, alluvial fan sediments)
- Lithostratigraphic formation 3 (LF3, lake sediments).

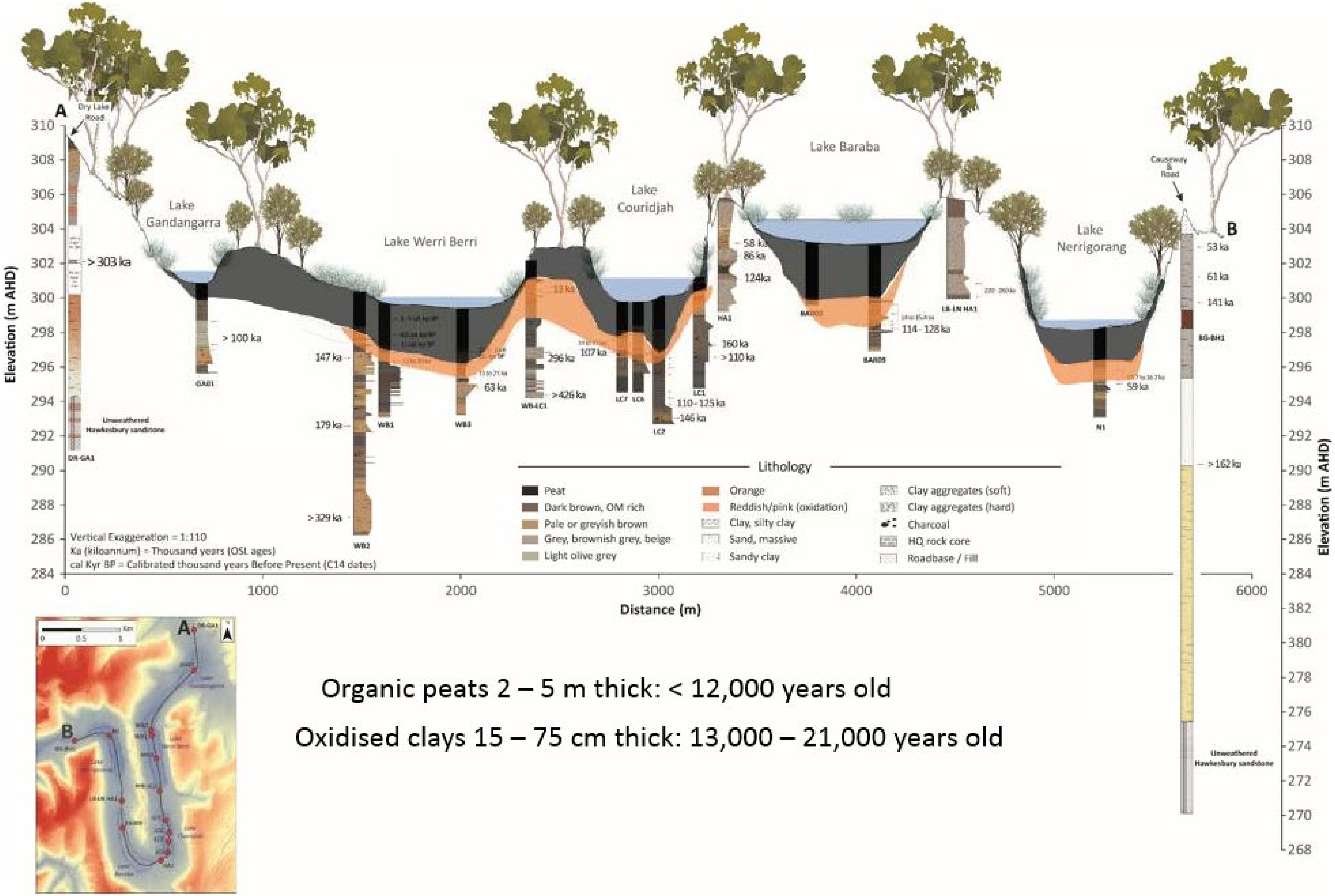


Figure 5.3 **Location and sedimentology as a result of the *Thirlmere Lakes Research Program***
Source: Tim Cohen UoW

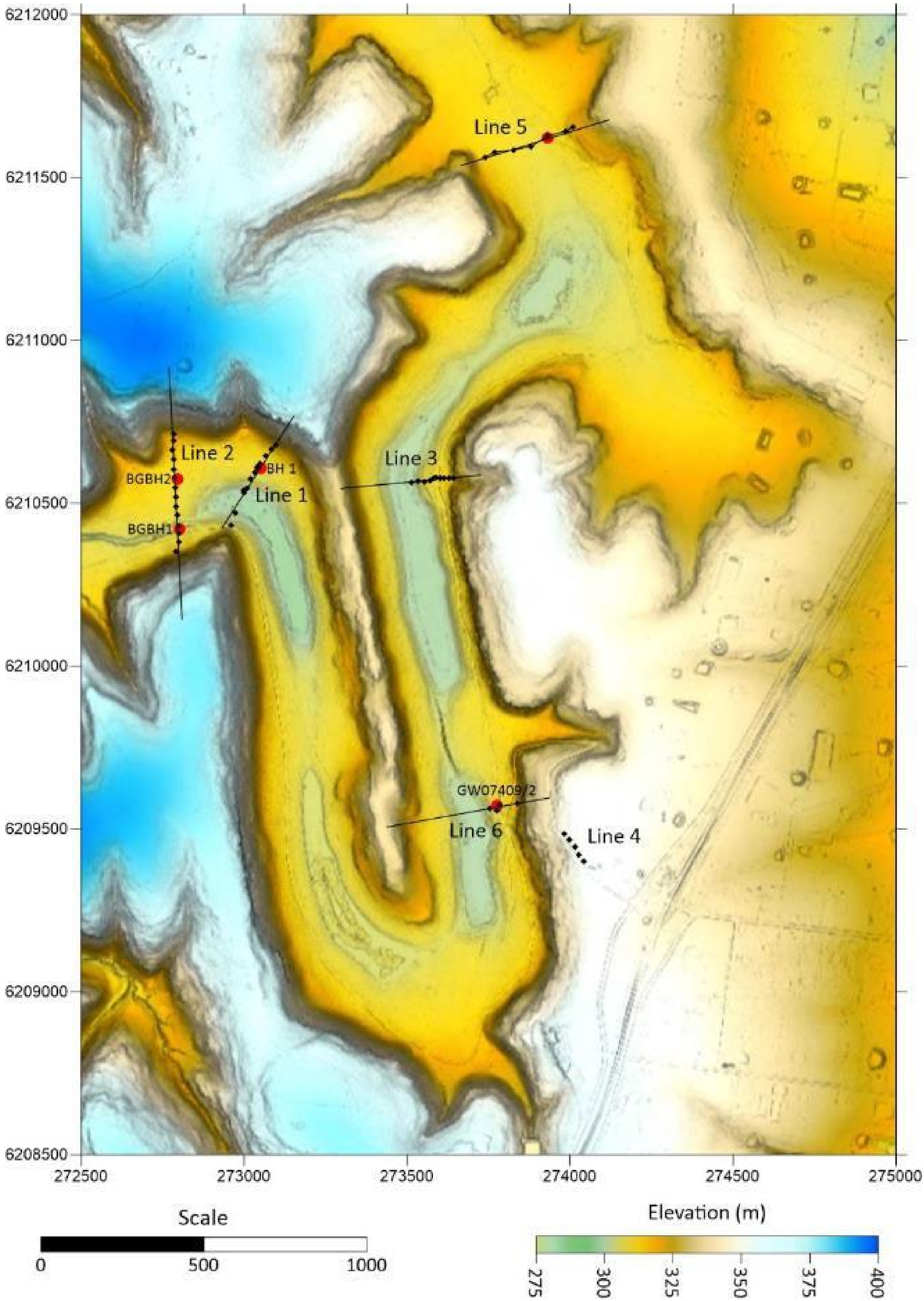


Figure 5.4 **Location of seismic lines and boreholes used to calibrate depth of sediment and bedrock**

Source: Cohen et al. 2020

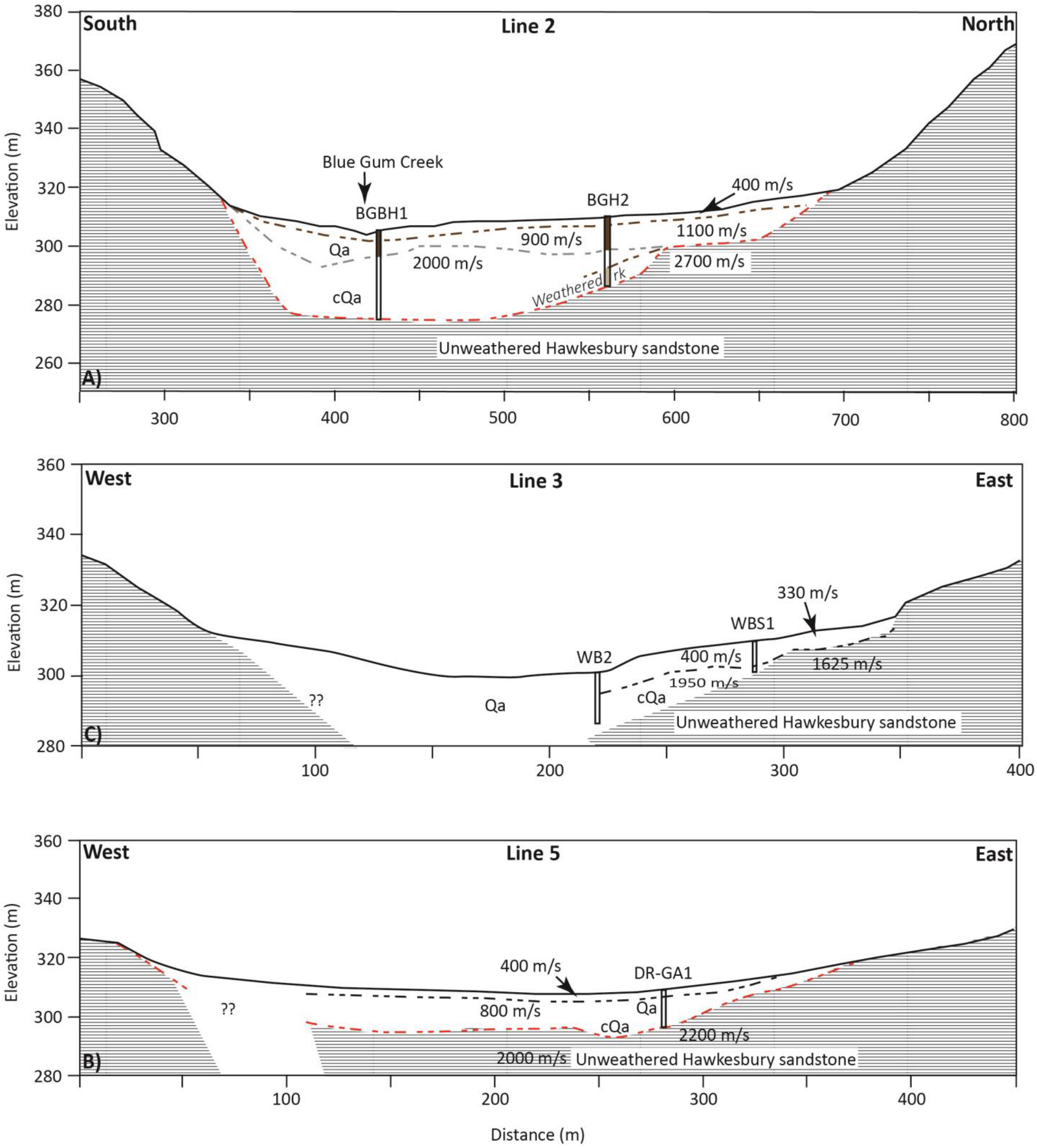


Figure 5.5 **Depth of sediments and bedrock in the Thirlmere Lakes valley. Seismic and interpreted bedrock valley morphology Lines 2, 3 and 5. Qa represents Quaternary alluvium and cQa represents compacted and weathered Quaternary alluvium**

Source: Cohen et al. 2020

The lake sediments (LF3) are comprised of an upper peat sequence that has started to accumulate over the last 12,000 years. These organic-rich sediments represent the modern Thirlmere Lakes and this unit varies in thickness from up to 5 metres in Lake Baraba to an average of ~2–3 metres in the other lakes. This LM has very low bulk density (0.174 ± 0.103 grams/cubic centimetre) and very high moisture content (83 ± 9%) and total organic carbon (TOC) contents of up to 40%.

This Holocene peat unit grades into a distinct oxidised silty clay that underlies all lakes. This unit represents a distinctive marker horizon in the LF3 lake sediment formation but also varies in thickness across and within any given lake. This unit has been dated in two lakes (Couridjah and Werri Berri) to be 21,000 to 12,000 years (the last glacial maximum [LGM] and the deglacial) and represents a massive hydrological change where Thirlmere Lakes dried and the lake sediments were sub-aerially exposed. This unit signifies *catastrophic drying* at Thirlmere Lakes and it also currently acts as a local aquitard based on the obvious saturated zone of sediment immediately overlying it.

The oxidised silty clay unconformably overlies older lake sediments that are 50,000 to 100,000 years in age. This would suggest that the process responsible for the deposition of the oxidised silty clay layer has eroded some of the underlying lake sediments (possibly through aeolian erosion). The underlying LF3 lake sediments are comprised of organic silty clays that are weakly bedded but which contain palaeoecological information (pollen and diatoms) that are suggestive of permanent waterbodies at Thirlmere Lakes during the last interglacial 125,000 years ago (Marine Isotope Stage [MIS] 5e). Indeed, the stratigraphic relationships show that the underlying organic silty clays were deposited when at least three of the lakes were joined as one waterbody. The LF3 sediments are also characterised by episodic sandy lenses that have been deposited from the hillslopes into the centre of the lakes suggesting significant past erosion events. Such events are most likely linked to past fire as charcoal concentration is often, but not always, high in these deposits. The LF3 sediments also show that the MIS 5e organic silty clays are decomposed variants of what is seen in the Holocene peats. There is a repetition of the organic and less organic facies at Thirlmere Lakes and the chronology would support up to three interglacial cycles of lake (discontinuous) sedimentation.

For further details see Cohen et al. 2020.

6. Climate and surface water balances

6.1 Background

The average annual rainfall of the nearest long-term rainfall gauge at Picton is ~820 millimetres. Rose and Martin (2007) report it as being received in two relatively wet periods from January to March and in June each year (i.e. a bimodal distribution is apparent). The median rainfall for each month is generally greater than 25 millimetres with considerable variation in rainfall from year-to-year. After long dry spells the Thirlmere Lakes can dry out with known low level stages occurring in 1902, 1929 and 1940 (Rose & Martin 2007; Pells & Pells 2011; Riley et al. 2012) and more recently during the last two decades. It was noted by Riley et al. (2012) that the community used the term ‘dry’ even when there was some water in the bed of the lakes. When referring to the historic and oral records of lake levels, it was considered more correct to say the lakes were ‘substantially dry’, meaning a large section of the lakebed was exposed and cracked due to desiccation (Riley et al. 2012). Riley et al. (2012) provided a detailed analysis of rainfall patterns in the area during the course of the Thirlmere Lakes Inquiry.

6.2 Long-term climate records for NSW over the last 100 years

Rainfall in Australia is highly variable, both temporally and spatially, and to a greater degree than in many other countries and continents (Nicholls et al. 1997). This strong interannual variability is related to a variety of climate modes of variability, including the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and the Southern Annular Mode (SAM) (King et al. 2014). In attempting to address the question of *Where has the water in Thirlmere Lakes gone*?*,* it is equally important to address the question of *Has there been less water getting in*?.

Analysis of Australian long-term rainfall records has demonstrated three abrupt shifts in mean rainfall over the period 1890–1989 (in 1890–95, 1945–50 and 1967–72), where rainfall appears to have ‘step-like’ changes compared to rainfall records at other times (Vivès & Jones 2005). Deacon (1953), Kraus (1954) and Gentilli (1971) all noted a wetter period in the late 19th to early 20th century, and then a drier period in the first half of the 20th century. Pittock (1975) analysed 20th century rainfall records, examining the influence of the high pressure belt and the Southern Oscillation Index on interannual rainfall patterns, locating a significant rainfall increase in the late 1940s.

From late 1996 to mid-2010, much of southern Australia experienced a prolonged period of dry conditions, known as the Millennium Drought (BoM 2015). The drought conditions were particularly severe in the more densely populated south-east and south-west. The following years, 2010 and 2011, were dominated by La Niña conditions and heavy rainfall for most areas except the far south-west. The rainfall was particularly heavy during summer with large areas experiencing record or near record rainfall. This rainfall was sufficient to give Australia its wettest two year period on record (2010–2011) and set many records at individual locations, and effectively ended the extremely dry hydrological conditions that were a signature of the Millennium Drought (BoM 2015).

Long-term climate data can be sourced from the Queensland Government SILO website. This site provides interpolated daily climate data back to about 1897, either at individual rain gauges (e.g. Picton Post Office ‘infilled’ and ‘interpolated’ where there are missing records) or ‘interpolated’ data at 0.05 degree increments of latitude and longitude. An illustration of the last 100 years of rainfall is provided in Figure 6.1. Overlaid on this are significant drought periods (as defined by the Bureau of Meteorology).

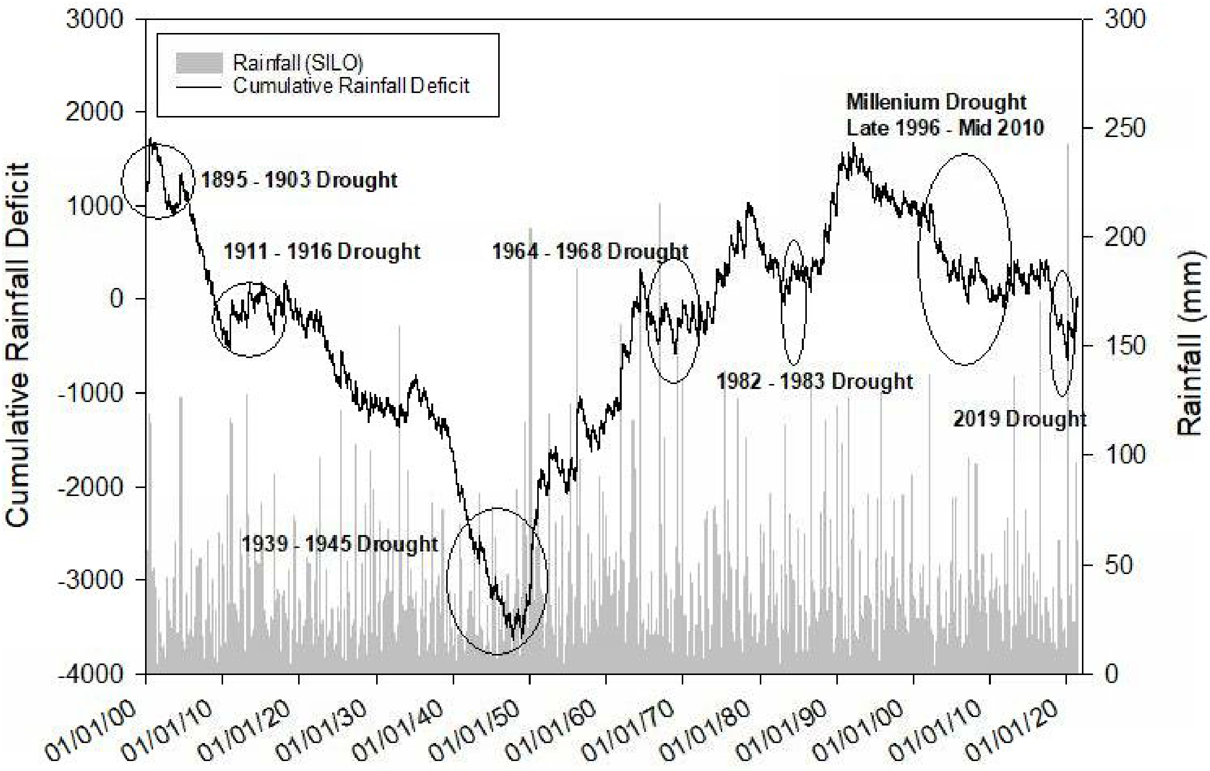


Figure 6.1 **Long-term climate record and cumulative rainfall deficit for Thirlmere Lakes rainfall (taken from SILO interpolation for –34.20°S, 150.55°E, close to Thirlmere Lakes)**

The cumulative rainfall deficit or departure is a concept used to characterise rainfall trends. It is calculated by determining the mean of the rainfall for the period in question, subtracting the mean from each data point to determine the departure from the mean, and accumulating the resulting departures (Weber & Stewart 2004; McCallum et al. 2009). Where the trend line increases upwards for long periods of time, this identifies periods of generally above average rainfall. Conversely, strong declines in the cumulative rainfall deficit or departure trend line are indicative of periods of below average rainfall, which if they persist long enough, often end up being declared droughts. Although of shorter duration, the recent 2019 drought was particularly significant, having the lowest annual rainfall (251.5 millimetres) on record in New South Wales and the highest mean temperature[32].

6.3 Recent climate

In response to the Thirlmere Lakes Inquiry, a new monitoring network was established at Thirlmere Lakes to provide near real-time information on the water levels in each of the five lakes in Thirlmere Lakes National Park, as well as the installation of a local weather station[33]. A service level agreement for the provision of hydrometric information services was agreed between the department and DPE Water (subsequently transferred to WaterNSW). This service level agreement expired on 30 June 2021. Monitoring data has been made available on the WaterNSW website (Real-time water data) in accordance with the service level agreement. Figure 6.2 illustrates the variation in lake levels over the period of the *Thirlmere Lakes Research Program* studies.

[32] Climate change and variability: Tracker: Australian timeseries graphs (bom.gov.au) [accessed 15/7/2021].

[33] Two tipping bucket rain gauges were installed to monitor rainfall immediately adjacent to the lakes (at Lake Nerrigorang and near Lake Gandangarra).

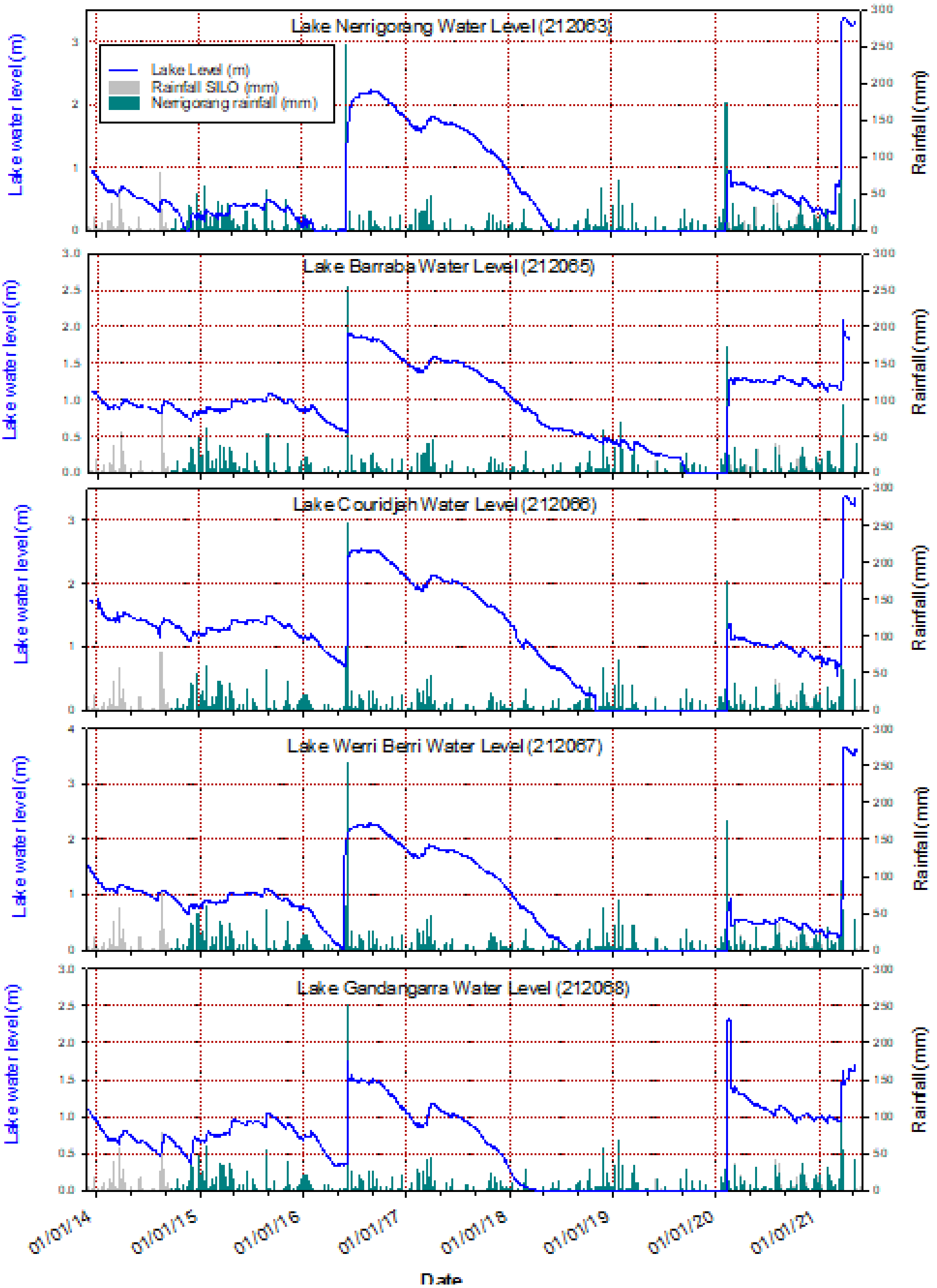


Figure 6.2 Thirlmere Lake levels over the course of the monitoring program

Three major rain events, the June 2016 east coast low and the February 2020 and March 2021 rainfall events, had the greatest effects on lake levels over the period of these records (see Figure 6.2, and Figure 6.3, Figure 6.4 and Figure 6.5). The June 2016 east coast low rain event saw approximately 315 millimetres of rain fall over two days (4–5 June). Lake levels rose by over 1 metre in each of the lakes (Figure 6.3). Nearby Stonequarry Creek rose to ~8.75 metres[34] causing extensive flooding in Picton.

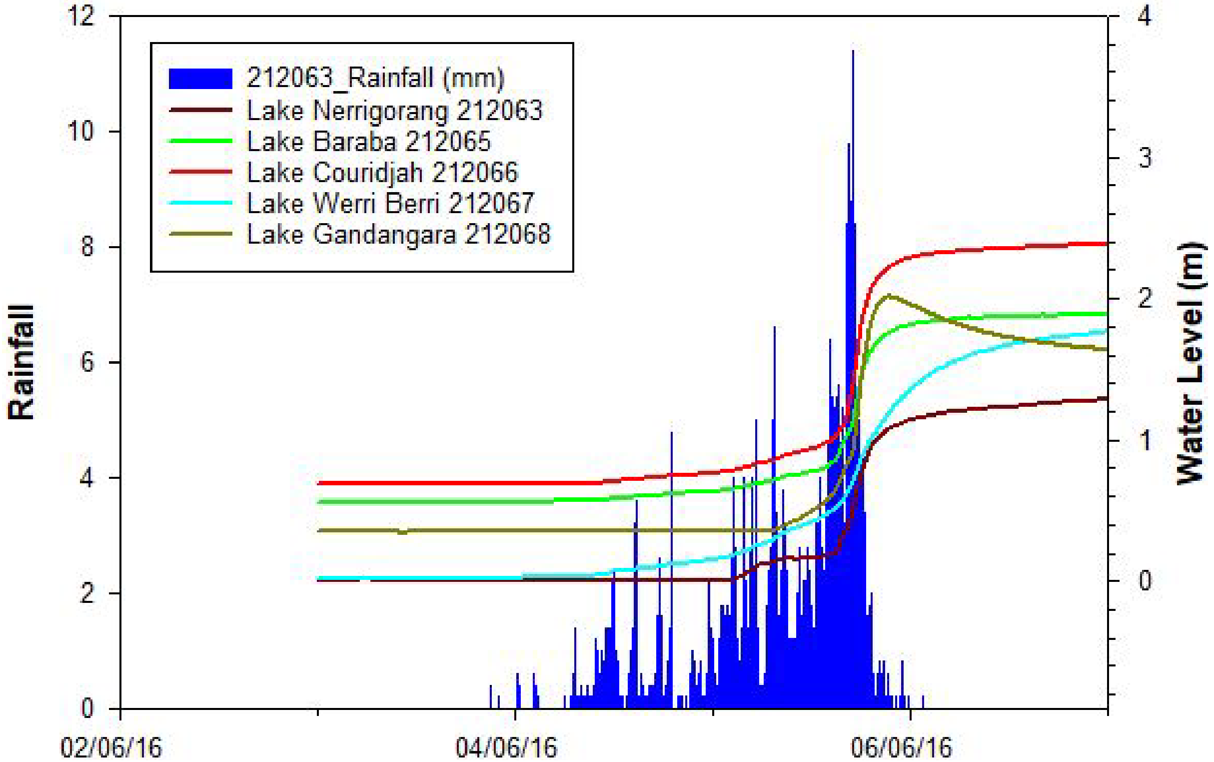


Figure 6.3 Thirlmere Lake levels over the course of the 2016 major rain event
Data presented are at 15-minute increments.

During the February 2020 rain event, approximately 303 millimetres of rain fell between 7 and 10 February (Figure 6.4). This rain event was described as *a trough with embedded low-pressure circulations.* Lake levels rose by between 0.5 and 1 metre in each of the lakes, and Stonequarry Creek rose to ~6.3 metres.

During the March 2021 rain event approximately 288 millimetres of rain fell between 18 and 23 March (Figure 6.5). The March 2021 rain event was described as *a blocking high-pressure system in the Tasman Sea combining with a low-pressure system off north-west Australia feeding a large volume of moist tropical air into the east*. This event led to rises in Lake Couridjah and Lake Nerrigorang levels to over 3 metres with Lake Werri Berri reaching almost 4 metres. More subdued responses were seen in Lake Gandangarra and Lake Baraba. Stonequarry Creek rose to ~4.9 metres.

The rise and subsequent decline in the Lake Gandangarra and Lake Baraba 15-minute hydrographs (Figure 6.5) most likely illustrates lake levels reaching the sill between the lakes, thereby establishing connectivity between the lakes (e.g. Lake Gandangarra and Lake Werri Berri became connected lakes during the June 2016 and March 2021 events[35]). Water levels continued to rise after these events as illustrated for the March 2021 event at the Lake Gandangarra – Lake Werri Berri sill (Figure 6.6).

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[34] At the WaterNSW gauge on Stonequarry Creek (Station 212053).

[35] Some water was observed to flow from Lake Gandangarra to Lake Werri Berri during the February 2020 event as well, but not of the same magnitude as the other events, nor for very long.

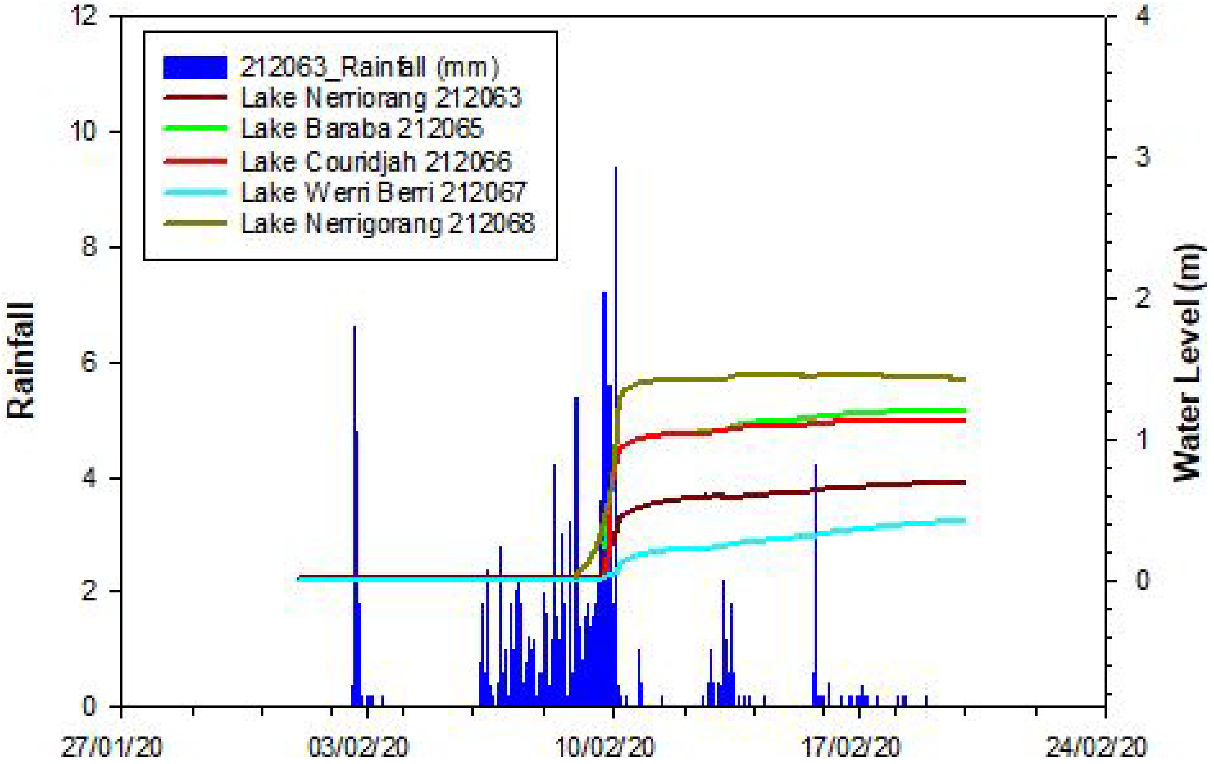


Figure 6.4 **Thirlmere Lake levels over the course of 2020 major rain event**
Data presented are at 15-minute increments.

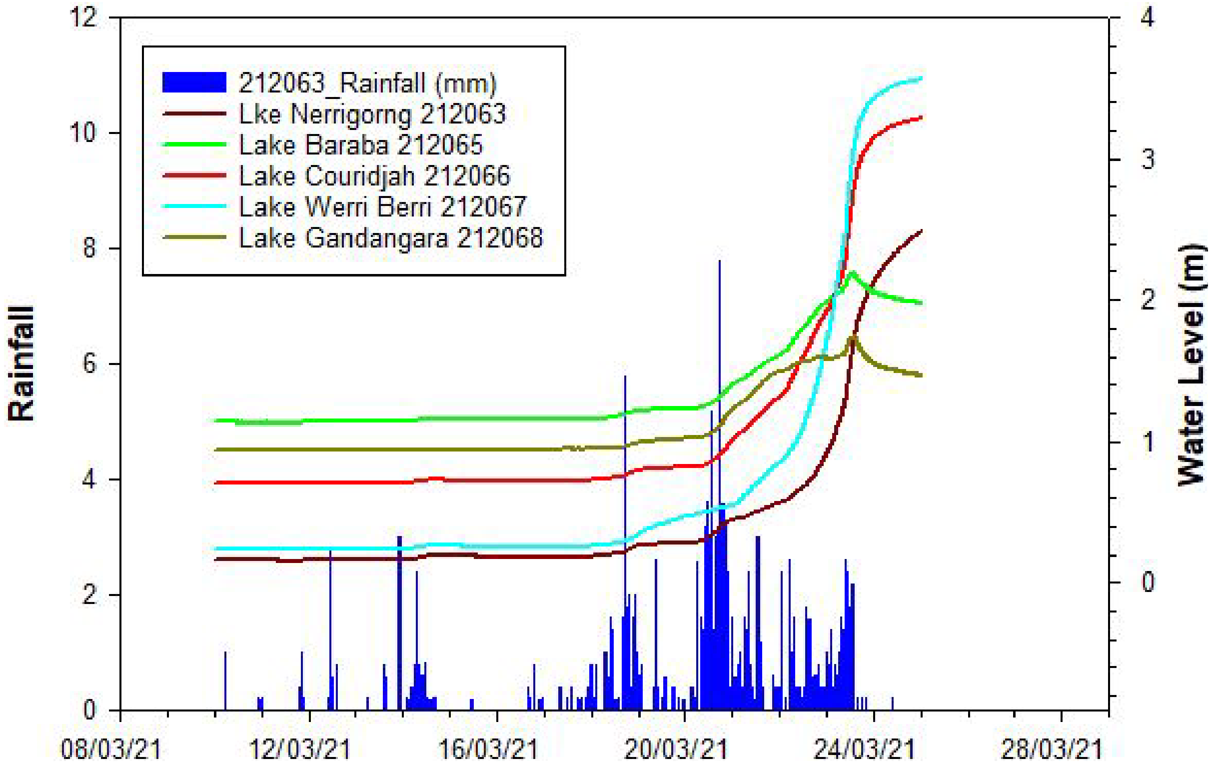


Figure 6.5 **Thirlmere Lake levels over the course of the 2021 major rain event**
Data presented are at 15-minute increments.

Figure 6.6 Sill between Lake Gandangarra and Lake Werri Berri water levels after the March 2021 rain event

Photos: M Krogh

The importance of antecedent conditions prior to these events was most clearly illustrated in the February 2020 event where the lakes had become dry at the surface due to the intense dry period experienced during 2019 through to early 2020. Water levels had also declined in the underlying peat. It appears that during this rain event, the peat water store needed to be filled first before surface water reappeared in the lakes (Figure 6.7).

6.4 Water balance modelling

A water balance model attempts to account for how water is delivered, stored, moves through and exits an ecological system. The model imposes a constraint by the need to account for all water entering, leaving and being stored in a catchment. This adaptation of the principle of conservation of mass helps constrain the potential for error in a water balance (Boughton 2005).

Whilst the primary water input to Thirlmere Lakes and their surrounding catchments is rainfall precipitation, the lakes can also receive water via runoff, infiltration and interflow processes from their catchment. *Surface runoff* (also known as overland flow) is the flow of water that occurs when excess stormwater (or other sources) flows over the ground surface. This might occur because soil is saturated to full capacity, because rain arrives more quickly than soil can absorb it, or because impervious areas send their runoff to surrounding soil that cannot absorb all of it. Surface runoff is a major component of the water cycle.

Infiltration is the process by which water on the ground surface enters the soil. *Interflow* is the lateral movement of water in the unsaturated zone, or vadose zone, that first returns to the surface or enters a stream prior to becoming groundwater. Interflow occurs when water infiltrates into the subsurface, hydraulic conductivity decreases with depth, and lateral flow proceeds downslope. As water accumulates in the subsurface, saturation may occur, and interflow may exfiltrate as return flows, becoming overland flow (Ward & Trimble 2004). Groundwater can also be a source of water to the lakes.

Figure 6.7 Lake Werri Berri water levels during the February 2020 rain event
Sunday morning 9/2/20 after 139 mm of rain (above left and right); Thursday morning 13/2/20 after a further 182 mm of rain (below left and right). Photos: M Krogh

The major water outputs from the lakes include evapotranspiration and streamflow. *Evapotranspiration* (ET) is the sum of evaporation and plant transpiration from the Earth's land and water surfaces to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception and waterbodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapour through stomata in its leaves. Evapotranspiration is an important part of the water cycle and one of the most difficult quantities to measure. Surface water can also move into groundwater aquifers in the vicinity of the lakes and can also represent a loss from the lakes.

A water balance model attempts to calculate all these inputs and outputs (fluxes) and storages in the system. A preliminary conceptual model for Thirlmere Lakes was illustrated by a schematic water balance based on observations and the experiences of recent lake behaviour (Figure 6.8; from OEH 2016). Whilst the diagram illustrated the interrelationships between contributing factors in the water balance, up until recently not all components were well known or measured, nor could they be accurately quantified.

The *Thirlmere Lakes Research Program Surface Water Balance* theme (TLRP3) developed an integrated water balance budget for the Thirlmere Lakes to help provide a more detailed understanding of their hydrological dynamics. This theme was undertaken by UNSW with Lead Researcher Associate Professor Will Glamore.

The aims of TLRP3 were to:

- establish a water balance budget for Thirlmere Lakes that accurately integrated the surface water dynamics, hydrologic/environmental parameters and relevant groundwater systems using high quality field data

- develop detailed conceptual models for the lakes
- address key water balance knowledge gaps via a comprehensive field sampling campaign
- establish an open access database, and
- create dynamic hydrologic models to simulate the water balance of Thirlmere Lakes.

The conceptual model used in the surface water balance studies is illustrated in Figure 6.9. The key research findings of TLRP3 are contained in Chen et al. 2020.

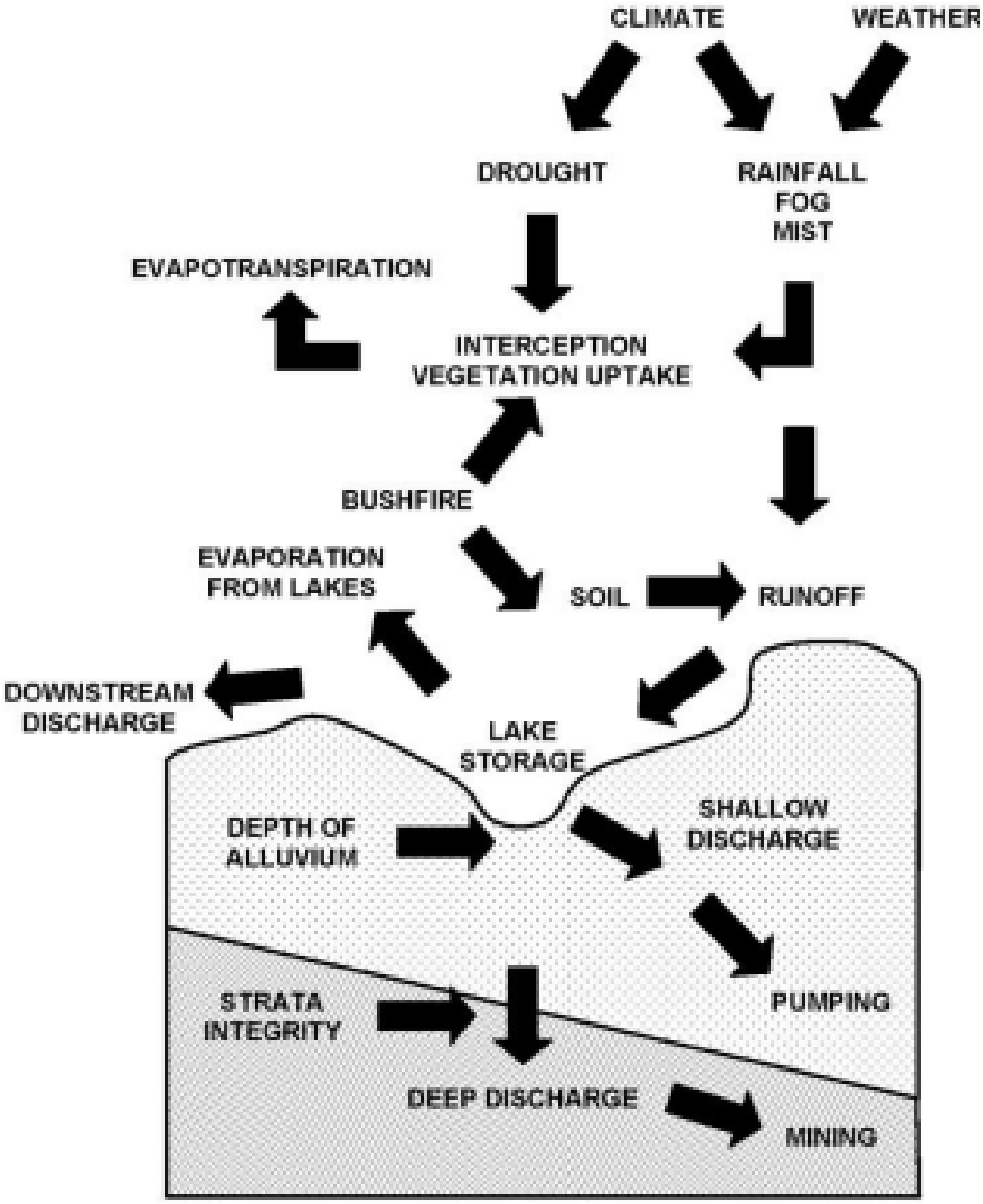


Figure 6.8 Preliminary conceptual model of lake inputs and outputs
Source: OEH 2016

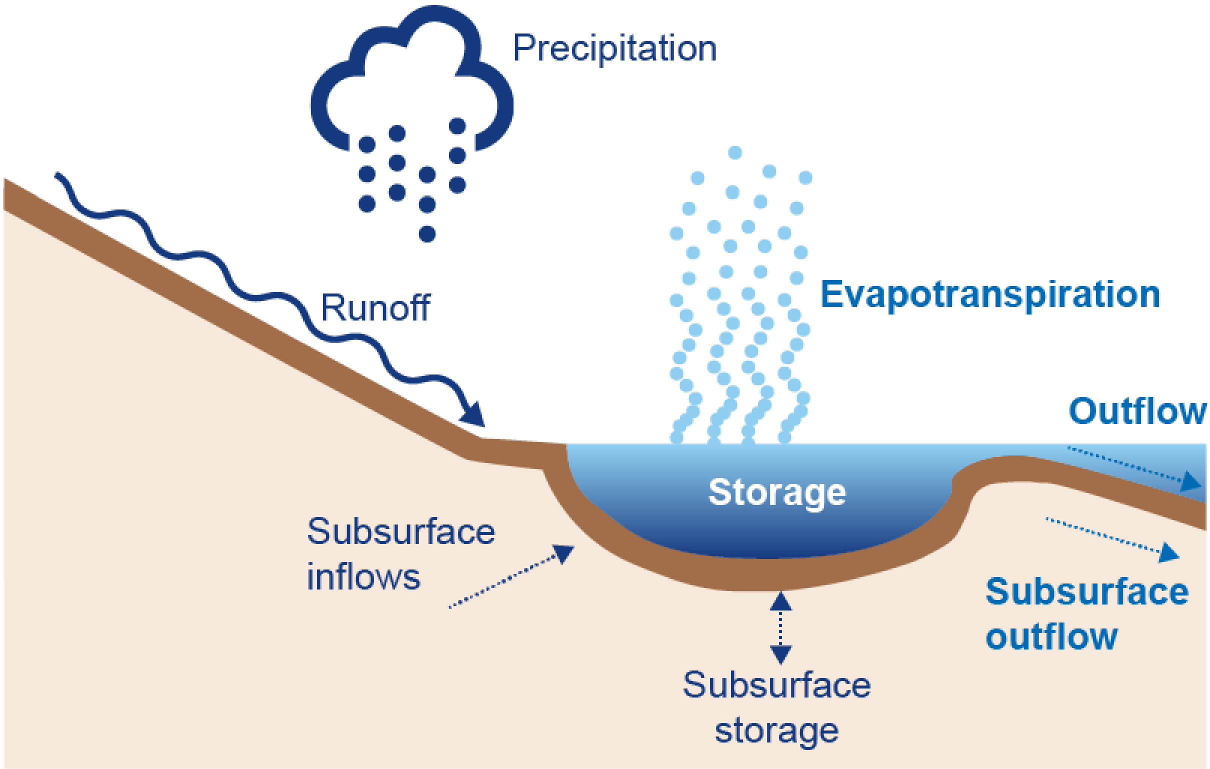


Figure 6.9 **Conceptual water balance model developed for Thirlmere Lakes**
Source: Modified from Chen et al. 2020

6.5 *Surface Water Balance* theme – key research findings

Between 2017 and 2020, hydrologists from UNSW and collaborators undertook detailed field campaigns and analyses investigating the hydrology of Thirlmere Lakes. Field campaigns were designed to collect essential environmental variables for the construction of a water balance for the lakes. Bathymetric surveys were undertaken to calculate the stage–volume relationship and reduce uncertainties in estimating water volumes. Since rainfall and ET are the essential drivers of lake water fluctuations, detailed meteorological and micrometeorological variable monitoring were carried out by staff from the department, WaterNSW, and UNSW. Rainfall data was directly measured onsite and ET calculations adopted a combination of the Penman–Monteith, eddy covariance, and surface renewal methods. The meteorological inputs were obtained from locally deployed, highly accurate instruments.

To extend the data record beyond the 2017–2020 period, remotely sensed water level data based on satellite images was obtained. Lake water levels were obtained from these images using an improved technique for delineating water areas. The longer-term (30+ years) water level data also improved the understanding of how the lakes respond during wetting and drying at higher lake stages.

Collaborative partnerships with the other research teams, including the department, ANSTO and UoW, assisted in improving the water balance formulation. This included water chemistry data and geology/geomorphology data. Based on an improved understanding of the field conditions, a conceptual water balance model was formulated and reviewed by the research teams and community stakeholders. A numerical water balance model was developed for Thirlmere Lakes National Park based on the conceptual model approach. The model was calibrated based on lake water levels during the study period, satellite imagery analysis and historical imagery. To further reduce the potential uncertainties in the water balance results, an isotopic model was coupled with the water balance model. An integrated approach that incorporated the physical water level data, remotely sensed water level data and water chemistry data was used to calibrate the coupled water balance model.

The coupled water balance model effectively reproduced the water levels at Thirlmere Lakes National Park. Multi-decadal lake volumes were subsequently obtained from the calibrated and validated water balance model. This enabled a detailed investigation of the local and regional processes that influence the Thirlmere Lakes water balance.

The study found that the lakes are a climate-sensitive wetland, primarily driven by rainfall and evaporation. The results suggest that the recent drought between 2018 and 2019 is not unprecedented and that the severe drought period of the 1940s also caused the lakes to dry out. The analysis revealed that the dominant factors leading to droughts may be different for each drought.

The field and modelling results suggest that the recent water level declines are primarily associated with climate variability versus the nearby longwall mining. However, this conclusion does not preclude the influence of the ongoing longwall mining and bore extraction in the future, and ongoing monitoring was recommended.

The three main conclusions for the study were:

1. The lakes are controlled by the climate

Thirlmere Lakes are highly sensitive to the climate, especially rainfall and evaporation. When evaporation is greater than rainfall, the lakes lose water and may eventually dry out. There is no evidence that the lake water levels have been influenced by pressure changes in the deep groundwater system (or nearby longwall mining).

2. The recent drought is not unprecedented

The study has found evidence that the lake waterbodies have previously dried out, including during the World War II Drought and in other historic periods (e.g. the Millennium Drought). In recent times, these dry periods have been short-lived and eventually the lakes refill.

3. A vulnerable ecosystem

The lake water levels and volumes are reliant on catchment rainfall. This is because:

- the lakes are near the top of the catchment and have limited inflows from surrounding catchments
- the lakes have a small catchment compared to the lake size
- there is a limited connection to deep groundwater, and
- stream inflows and groundwater are less important relative to rainfall and surface runoff from the catchment.

For further details see Chen et al. 2020.

6.6 Uncertainty in the surface water balance for Thirlmere Lakes

Conceptual catchment models are common tools in calculating the runoff dynamics and the water balance for a given area or region. The model parameters are usually calibrated to obtain a good fit between observed and simulated outputs. Since computer models are not a perfect representation of reality, the model results have an inherent level of uncertainty (Engeland et al. 2005). For the water balance model developed for Thirlmere Lakes, individual lake models were set to spill when the water level reached the sill level for each lake surveyed during the project. As a result, it cannot reproduce very high water levels at the lakes (e.g. Lake Werri Berri when water levels were as high as the stone steps). Across the five lakes, the water balance model explained 83–98% of the variation in lake levels.

This is the variance explained by a linear regression of how well the changes in lake volumes were predicted by rainfall and runoff volume and evapotranspiration volumes over the period January 2014 – September 2020. During this period, lake levels remained below the individual sills of the lakes, except for short periods during the June 2016 and February 2020 rain events. Other uncertainties can also affect the model, including *input uncertainty* and *parameter uncertainty* and these are discussed below.

Input uncertainty

The major drivers of variations in water levels for Thirlmere Lakes are rainfall and evapotranspiration. An estimate of rainfall uncertainty was made by comparing the rainfall data recorded at the site with the SILO interpolated rainfall estimates over the same period. The differences between the two provide an estimate of the impacts of the spatial interpolation as well as potential errors in the rain gauge measurements (e.g. due to undercatch or blockage). It was found that there was on average a 5% difference between the two products. A similar analysis was repeated for the evapotranspiration estimates with a difference of 10%. This is most likely due to the localised impacts of wind speed used to estimate site evapotranspiration.

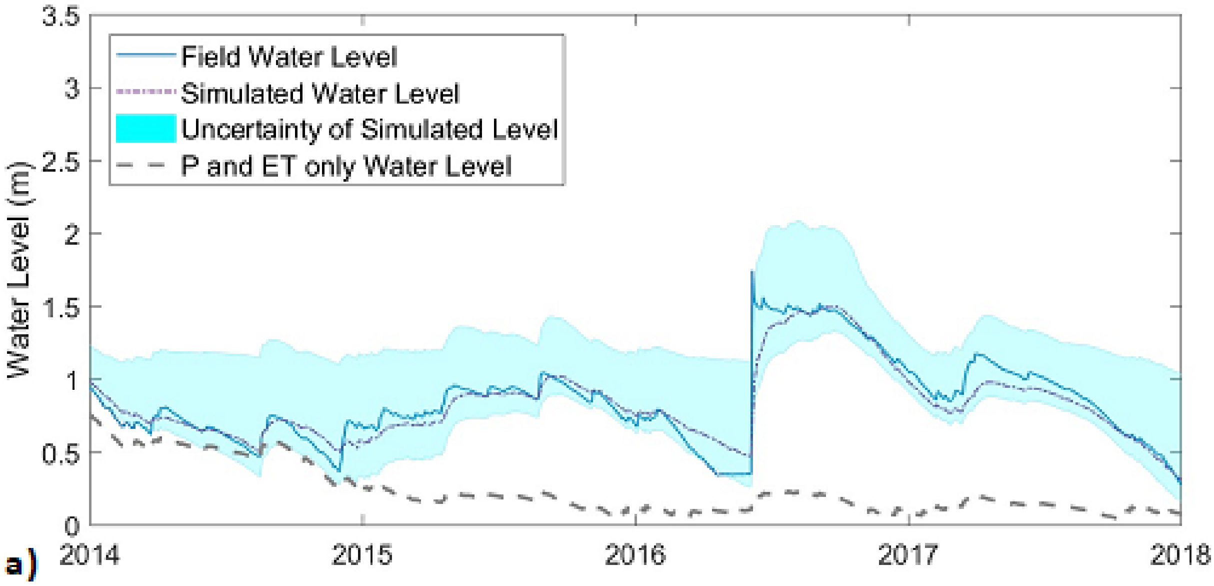
The remotely sensed data used to validate the model has considerable uncertainty, which is likely non-stationary in time, due to the different Landsat satellite missions over the period and the uncertainty in the algorithm to calculate the water extent of the lakes, which for example, had an average error of 25% for Lake Gandagarra. Although large, this error was an improvement on previous algorithms, which had average errors of 50–150%.

Parameter uncertainty

Within the water balance model, parametric uncertainty results from the lake infiltration and bank storage parameters. Lake infiltration was estimated during drying periods to reduce the uncertainty in the estimates. Remotely sensed data were also used to assist with the infiltration calibration. There were limited field data to calibrate the bank storage parameter. Hence, for the purposes of understanding parametric uncertainty in the water balance model, both the infiltration and storage parameters were varied by up to 10%.

There is also parameter uncertainty in the GR4J model that was used to estimate the catchment runoff into each lake. This uncertainty is a function of transferring the GR4J model parameters from the Stonequarry catchment to the Thirlmere Lakes catchments, as well as inherent uncertainty in the GR4J model calibration at Stonequarry catchment. This uncertainty was not quantified as it was assumed to be minor compared to the water balance model parametric uncertainty.

Figure 6.10 compares the input and parametric uncertainty in the water balance model (light blue shading) with the uncertainty in the remotely sensed estimates of lake water levels. Both shaded areas represent the 95% confidence limits obtained from Monte Carlo sampling of the uncertainty bounds described above, with uniform distributions assumed for each of the sampled ranges.



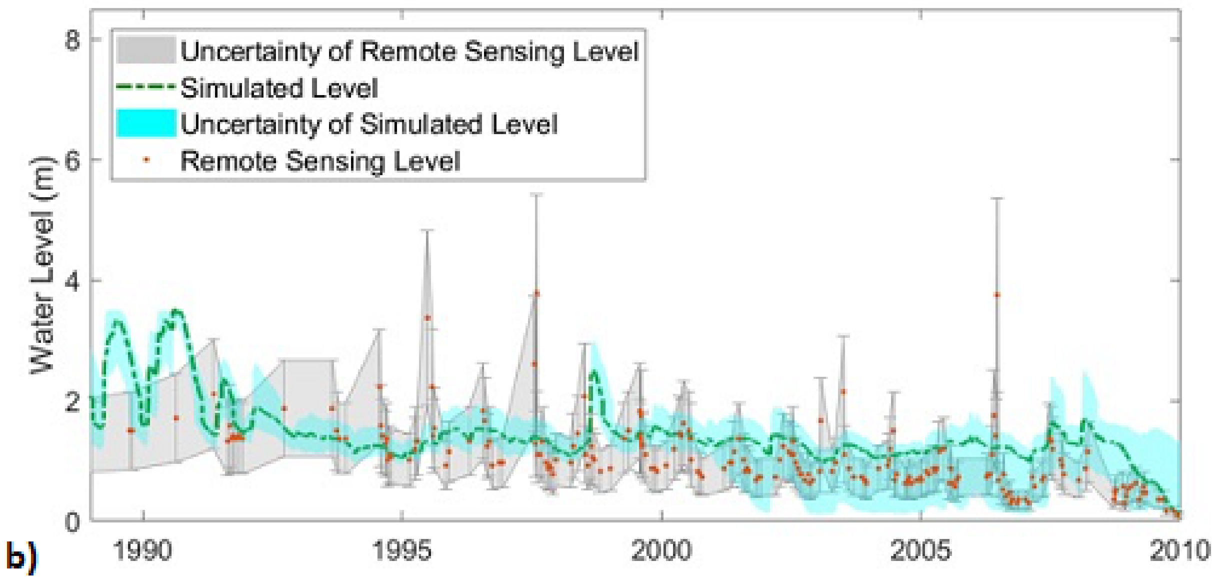


Figure 6.10 Confidence limits (95%) on the water balance model estimates of water level for Lake Gandagarra

a) Field and simulated water levels for the period 2014 to 2018. The dashed line shows simplified model results considering precipitation (P) and evapotranspiration (ET) only.
b) Simulated (green dashed line with blue shading) compared to remotely sensed water levels with uncertainty (grey shading). The red dots represent the levels estimated from the remote sensing method (Figure 7 from Chen et al. 2021).

7. Surface water to groundwater connections

7.1 Background

Groundwater is derived from rain that percolates down through the soil or through fractures in rock, filling up the pores between sand grains or the fissures in rocks. Up to half of all rainfall may reach the water table and recharge groundwater systems. About 97% of the world's available freshwater lies underground (Boulton et al. 2003). Geological formations such as those composed of sand, sandstone and limestone that contain usable quantities of groundwater are called aquifers. The aquifer closest to the ground surface is called the shallow, or unconfined, aquifer (its upper surface is the water table) but there are also deeper, confined (sometimes called sub-artesian if the water does not reach the surface) aquifers where the water is confined under pressure between relatively impervious layers (WRC 2003).

Many surface water ecosystems in Australia are reliant on groundwater for baseflows, and exchanges between stream and groundwater along the course of channels (Boulton et al. 2003). In periods of low flow and drought, groundwater can assume greater importance to maintaining base flows in streams and wetlands. This also means that groundwater can have greater influence on water quality during drought conditions. The extraction of groundwater must also be managed as it can result in more saline water entering the aquifer, as well as reduced base flows to waterways.

Exchange of groundwater and surface water occurs in most watersheds and is governed by the difference between water table and surface water elevations (Winter et al. 1998; Healy 2012). If the water table is higher than the stream stage (or lake level), groundwater discharges to the stream/lake and the stream/lake is referred to as a *gaining* stream/lake. In contrast, if the water table is lower than the stream stage (or lake level), the stream/lake discharges to groundwater and the stream/lake is referred to as a *losing* stream/lake. The Inquiry report suggested there was no regional groundwater flow and that flow drains away from the lakes because the lakes are positioned on a topographical high (Riley et al. 2012). This hypothesis suggested there was only a local groundwater flow system contributing to water levels in the lakes. A question still remained, however, as to whether the lakes were an area for discharge of the local groundwater system or whether through-flow (inflow from one side, outflow from the other side) was also occurring.

In 2010, the NSW Office of Water (NOW)[36] undertook a groundwater assessment for Thirlmere Lakes (Russell et al. 2010). It subsequently initiated a drilling program to follow up on previous work at Thirlmere Lakes, with bores being drilled near Lake Nerrigorang, Lake Couridjah and Lake Gandangarra (Russell 2012). Since that time, groundwater levels have continued to be measured in the Thirlmere Lakes bores (see Figure 7.1). Towards the end of 2019, the department also installed monitoring equipment in the Tharawal Aboriginal Land Council (TALC) bore on the ridge to the east of Thirlmere Lakes (Figure 7.1). Monitoring of these bores illustrates the sensitivity of shallow (~15 metres below ground level) groundwater levels to significant rainfall events, with the Nerrigorang shallow bore being the most responsive to rainfall, much more so than all the other bores. There was also a clear separation between the shallow bores (~15 metres depth) and the deeper bores (~100 metres depth) in terms of water level. Episodic declines in the TALC bore levels are potentially related to groundwater extraction near to the lakes (with subsequent recovery; presumably when pumping ceased). It is interesting to observe that the Couridjah deep bore levels show a similar (but more muted) response to this suggested groundwater extraction.

[36] Now part of Department of Planning and Environment.

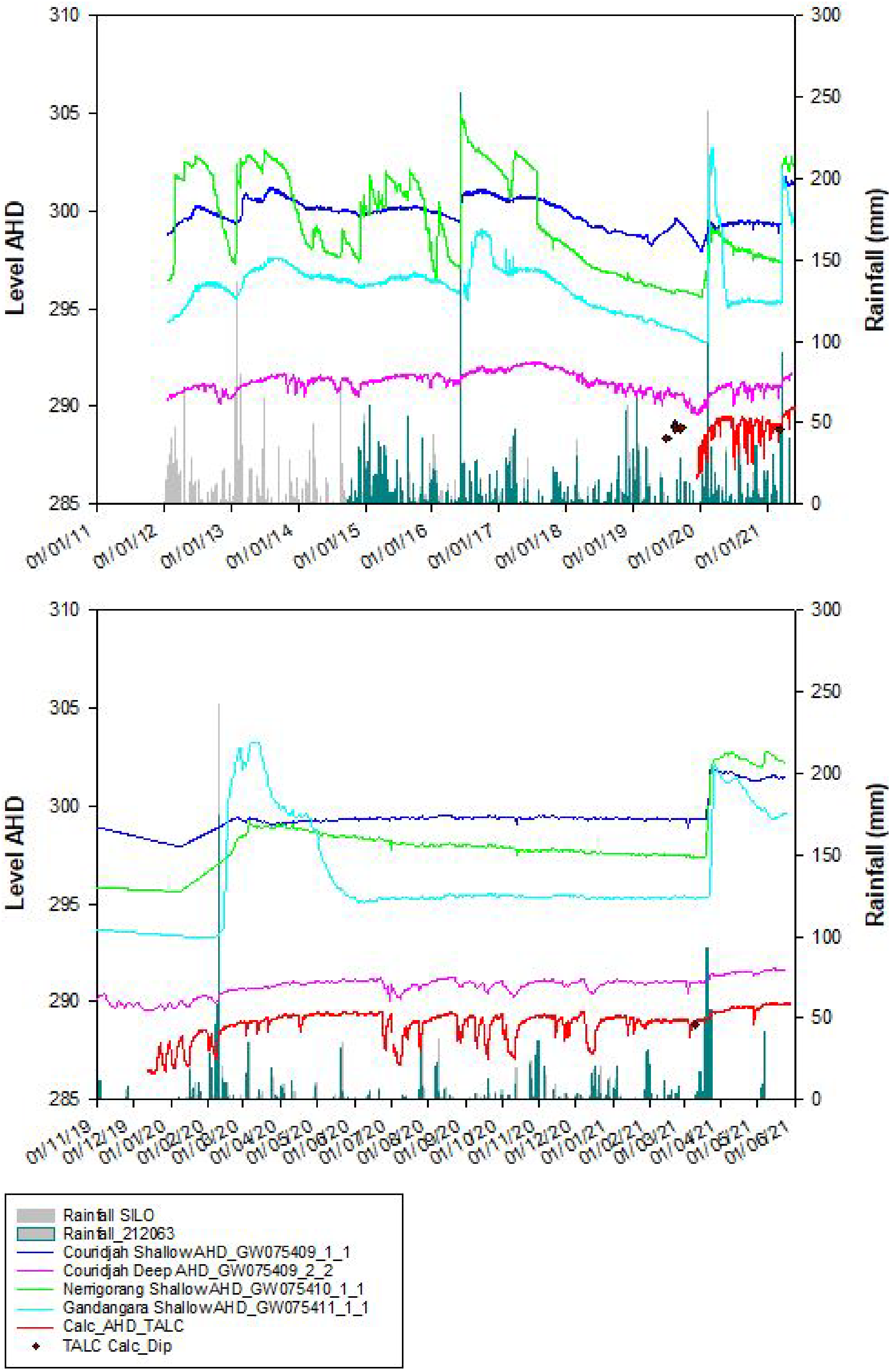


Figure 7.1 Groundwater levels in bores at or near Thirlmere Lakes

Full period of monitoring (above); November 2019 to May 2021 (below). AHD for TALC bore calculated using depth to water level.

Porosity and permeability are two of the primary factors that control the storage and movement of fluids in rocks and sediments. *Porosity* is the ratio of the volume of the void space to the total volume of material and is usually expressed as a percentage (%).The effective porosity lacks a single or straightforward definition; however, it is most commonly considered to represent the porosity of a rock or sediment available to contribute to fluid flow through the rock or sediment. The term *permeability* or *hydraulic conductivity* as defined by Darcy's law (and used in groundwater flow assessment) is a measure of the capacity of a rock to transmit water. The hydraulic conductivity of a rock is a function of hydraulic conductivities of the matrix (the rock material itself) and defects (open joints and separated bedding planes) resulting from stresses applied to the rock. Hydraulic conductivity can be measured in the field or in the laboratory. Field measurements using packer tests refer to the total (matrix and defect) hydraulic conductivity, while the laboratory permeability tests using rock cores measure matrix permeability. *Storativity* or the storage coefficient, is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storativity is a dimensionless quantity, and ranges between zero and the effective porosity of the aquifer.

As part of the *Thirlmere Lakes Research Program*, the *Surface Water to Groundwater Connectivity* theme (TLRP2) addressed the question of surface water – groundwater interactions at Thirlmere Lakes. This theme was undertaken by UNSW with Lead Researcher Associate Professor Martin Andersen. The aims of the *Surface Water – Groundwater Interaction* research project (TLRP2) were to:

- determine the degree of connectivity between surface and groundwater (i.e. whether the lakes are a perched system)
- quantify the spatio-temporal water fluxes between the lakes and the underlying alluvial aquifer
- determine thresholds in lake water levels and groundwater levels that control these interactions
- measure the depth of the alluvial aquifer and determine groundwater confinement, and
- map the stratigraphy of the lakebed/shallow aquifer and quantify their hydrogeological parameters.

The key research findings of TLRP2 are contained in Anibas et al. 2021.

7.2 *Surface Water to Groundwater Connectivity* theme – key research findings

A piezometer network of more than 30 piezometers, with a minimum of four piezometers at each lake, was developed (Figure 7.2). Most were hand-augured and therefore shallow, but the manual approach allowed access to sites that could not have been accessed by a drilling rig and it also allowed a more detailed spatial description of the lithology. As most piezometers were either close to lakes or other piezometers, a high vertical precision was deemed necessary to resolve hydraulic head gradients. A collaboration with Dr Craig Roberts and a team of surveying students at UNSW used state-of-the-art geospatial surveying techniques to establish a dataset of vertical levels all referenced to the same common local physical benchmark as well as the Australian GDA2020 datum. This provided vertical precisions on piezometer and lake elevations of less than +/–10 millimetres. Using this high precision survey, accurate hydraulic head timeseries could be calculated and hence hydraulic gradients – both direction and magnitude – could be established allowing the resolution of surface water to groundwater interactions over time. The overall precision on hydraulic heads, including other sources of errors (dipping and logger precision), is assessed to be about +/–21 millimetres.

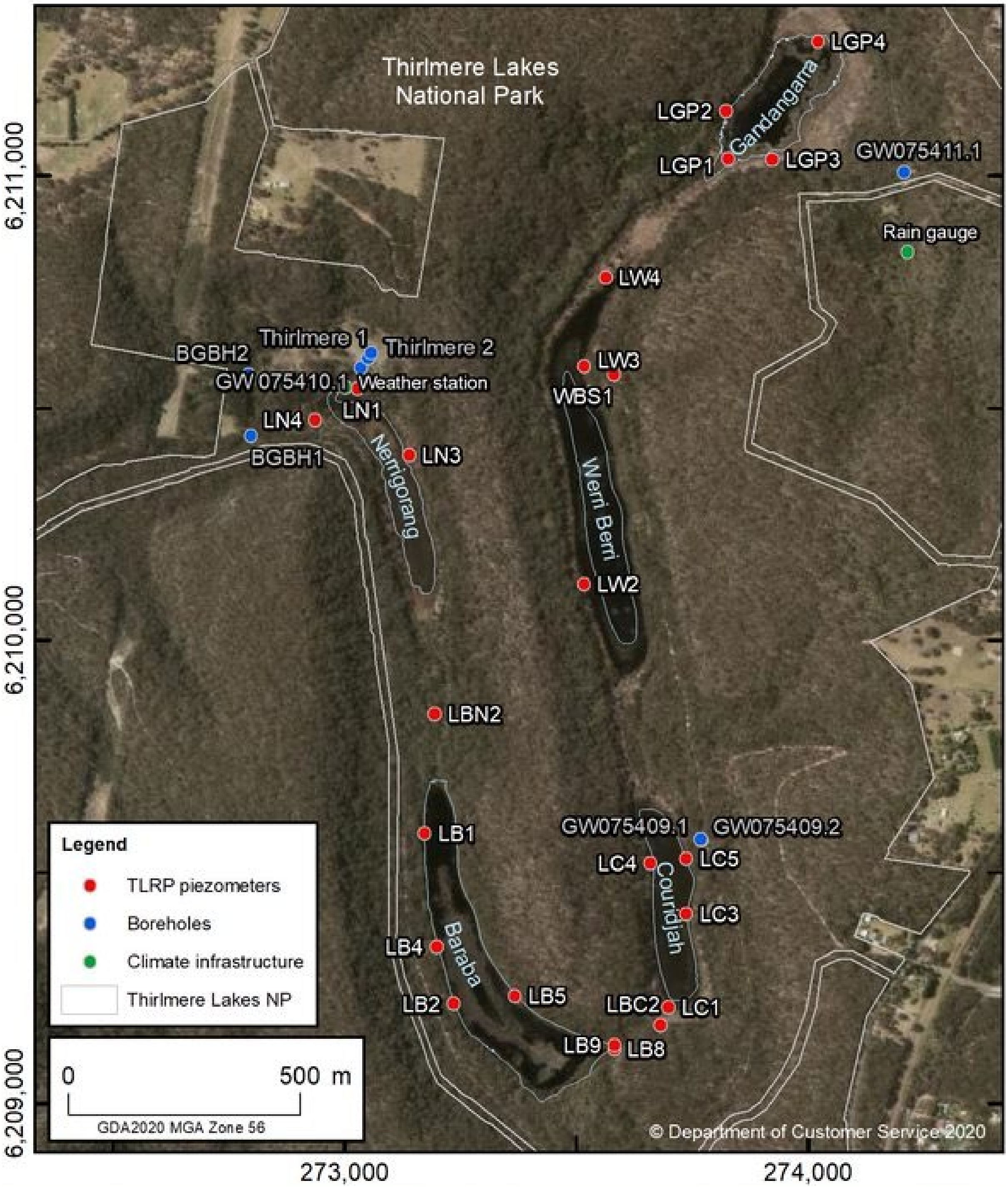


Figure 7.2 **Piezometer network established at Thirlmere Lakes**
Source: Anibas et al. 2021

The study period was divided into a dry and a wet period to interpret the dynamics of the system, with the lowest water levels in December 2019 and highest in March 2020. It was found that vertical downward hydraulic gradients prevailed across the site during both wet and dry conditions. The state of hydraulic connection is difficult to determine and requires further investigation of the lithological properties of both the alluvial groundwater and more regional groundwater system. During the dry period, hydraulic heads in the shallow piezometers (<~4 metres depth below land surface) near the lakes were lower than the lake levels, but generally decreased at similar rates to the lake levels probably due to a combination of downward leakage and lateral transport driven by evapotranspiration. The relative proportion of each process is not known and difficult to determine. During the February 2020 recharge event, the shallow piezometers all responded synchronously with the rising lake levels and most measured hydraulic heads align to the lake levels of their adjacent lake during the wet period. This indicated that for most of the shallow piezometers a hydraulic connection to the lake's surface water does exist despite the heterogeneous shallow lithology across the Thirlmere Lakes and the presence of low-permeable peat and clay layers. However, due to the differences in the responses between each lake and their differing absolute surface water elevation it can be inferred that each lake is individually nested within its own shallow low-permeable sediments.

Deeper piezometers further from the lakes typically had lower water levels during the dry period and showed a delayed response to the February 2020 recharge event, but typically recharged to a higher hydraulic head than the adjacent lake levels. This is interpreted as diffuse recharge through the relatively small catchment rather than via leakage or overflow from the lakes. The hydraulic head in these deeper piezometers then declined faster than the shallower piezometers, likely due to vertical leakage or groundwater flow down the catchment.

Several months after the February 2020 recharge event, groundwater levels were higher around the lowest lying lakes, Lake Nerrigorang and to some extend around Lake Gandangarra, and it is likely these lakes received some groundwater discharge during this period.

The sediment logs reveal a layered lithology with vertical variations in sediment type and composition at sub-meter scales. Close to the lake banks a sediment log typically consists of a peat layer on top of clay followed by a variable combination of sand, silts and clays. Further away from the lakebed the peat layer is absent and replaced by unsaturated mixed sand, clay and silt layers. Typically, a 0.5–1.5 metre thick saturated sand or mixed sand clay layer was encountered 3–5 metres below land surface at most sites. The piezometers established as part of TLRP2 were not deep enough to inform on the depth of the unconsolidated alluvial sediments. Geophysical surveys were done in collaboration with Dr Peter Hatherly and TLRP1 and TLRP4 and these still need to be collated and integrated across investigations. Thus far, our results show that the shallow sediment layers are flat and horizontally extensive. A change in seismic velocity is detected around the depth of the primary saturated layer.

In collaboration with the TLRP4 team, it has been established that the deep Thirlmere 2 and GW075409.2 bores in the Hawkesbury Sandstone and the deeper Thirlmere 1 bore in the Bulgo Sandstones are all showing a confined groundwater response. Confining responses in the shallow piezometers of the unconsolidated sediments have yet to be analysed. A preliminary qualitative analysis has indicated that some piezometers show a transition from an unconfined to a confined response due to increasing hydraulic heads during the February 2020 recharge event.

Direct evidence of groundwater–surface water interactions was investigated using natural heat tracing in the lakebed sediments. The plans to deploy temperature arrays were partly disrupted by the lakes drying up; however, three surveys were conducted, which in combination covered several locations in all five lakes. At five of the temperature array deployment sites across Lake Nerrigorang, Lake Couridjah, Lake Baraba and Lake Gandangarra, fluxes were below the detection limit of +/–10 millimetres per day. This does not mean there was no leakage, but that it is below this threshold and indeterminable using heat tracing. For five sites, mainly on the eastern banks of Lake Couridjah and Werri Berri, downward leakage of between 10 and 81 millimetres per day were detected. At one site on Lake Baraba, an upward flux of about 32 millimetres per day was detected; however, this upward flux could not be verified by hydraulic head gradients at the same location and time. As the heat tracing estimates are point measurements and the lakebed sediments highly heterogeneous, upscaling the results to the entire lake area for each lake would be highly uncertain.

The network of piezometers was hydraulically tested to estimate the hydraulic conductivity of the sediments along their screened intervals. It should be noted that these estimates are strongly biased towards the more permeable sandy layers as these were targeted for the placement of the piezometer screens, and hence the estimates are not representative for the peat and clay layers, which are likely to have hydraulic conductivities several orders of magnitude lower. The hydraulic conductivity of these layers will still need to be assessed before hydrometric methods can be applied to obtain Darcy flux estimates through the lakebeds.

For further details see Anibas et al. 2021.

8. Water chemistry and environmental isotopes

8.1 Background

Hydrogeochemical relationships between surface waters and groundwater can be investigated using a combination of analytes that include water chemistry, natural stable isotopes and radioactive isotopes. The *Thirlmere Lakes Research Program Environmental Isotopes* theme (TLRP5) used environmental isotopes investigations to assess periodic and recent water losses from Thirlmere Lakes. This theme was undertaken by ANSTO with Lead Researcher Dr Dioni Céndon.

The aims of TLRP5 were to:

- characterise and compare dynamic hydrogeochemical and environmental isotope signatures of rainfall, surface flow, lakes and groundwater
- investigate a range of possible water loss pathways and interpret viable connections and net flows that match environmental isotope characteristics within the lakes and groundwater.

The key research findings of TLRP5 are contained in Peterson et al. 2020.

8.2 *Environmental Isotopes* theme – key research findings

One of the general misconceptions about declining water levels in Thirlmere Lakes is that this can only be explained by increased losses. 'Where has all the water gone?' presumes an increase in outputs from the lakes, but misses the complementary question 'Is there less water getting in?' Reduced inputs, including lower rainfall and a declining local water table adjacent to the lakes relative to historical levels, are equally likely to have contributed to recent low lake levels. Anecdotal evidence from landholders where private bores to the east of the lakes were sampled is that the water table in the surrounding landscape has been lowered substantially since the bores' installation.

The Tahmoor South Project mining proposal models show maximum drawdown from cumulative mining effects will exceed 10 metres for many registered bores, with nearby GW102439 predicted at 7.8 metres, GW018568 at 8.3 metres and GW011200 at 9.8 metres (HydroSimulations 2020). Perhaps related to drawdown in this direction, the clearest indication of recent lake losses to shallow groundwater is towards the east at Lake Couridjah in GW075409-1 and LC3 and east of Lake Werri Berri in LW3. In comparison, unevaporated groundwaters were found flowing towards the lakes from the south and/or west. Lake Baraba was the most resilient of the lakes during the drought and appears to have been better supported by relatively unexploited shallow groundwater levels in the less developed landscape to the south and west.

Groundwater input (i.e. discharge to the lakes and/or contributions to underlying sediments) is undoubtedly a critical factor for the lakes system. Even during this exceptionally dry period with lowered water tables, we have direct evidence of nearby discharge into Blue Gum Creek (at BGCk-DP or 'Rusty Springs') and inferred discharge into or flow below Lake Baraba (e.g. mixed LB4 has unevaporated LBN2 and LBC2 at similar levels at each end of the lake). Every lake showed evidence of multiple loss mechanisms including recharge to groundwater.

During the recession of flow following large rain events, groundwater discharge into Blue Gum Creek was indicated by oxidising iron and higher total dissolved solids, low pH and decade old apparent ages from tritium (^{3}H). Persistent groundwater discharge into Lake Baraba is inferred by its steady chemical and isotopic signature. Lake Baraba's resilient lake levels, despite evaporation losses common to all the lakes, suggests a larger reservoir of water than the bathymetry of the lake allows. This may be explained by hidden groundwater discharge into the lake, and/or relatively fast connections to a hidden reservoir in the adjacent upper sediments or its large peat store (Cowley et al. 2020).

Mine waters exhibit starkly different chemistry (Na-HCO_3 type) from the lakes (Na-Cl and/or humic), exhibiting evolved groundwater beyond that typically found in the deep wells around the lakes that are in shallower strata (see Table 8.1). Mine samples also show no hint of evaporated stable water isotopes found in lake signatures. Given the consistent apparent radiocarbon age in GW075409-2 of around 3000 years, movement of water from the lakes towards the mine is also expected to take many years. There is no chemical or isotopic evidence linking groundwater in the mine directly to surface water in the lakes at present. It is unlikely that a measurable signature would arise in the near future due to apparent flow rates to depth.

Table 8.1 Comparison of selected chemical and isotopic analyte measurements

Sodium (Na) and Chloride (Cl) concentrations as micromoles (μM). Tritium (3H) as tritium units (TU) and Carbon-14 (14C) as apparent age. Source: Peterson et al. 2020.

Analyte	Units	Lake Couridjah	GW075409-2	Mine – 810 Panel	Mine – Shaft 3
TDS	mg/L	111	239	2312	413
pH	pH units	5.5	5.6	7.18	6.91
Na	μM	1020	1301	21052	2345
Cl	μM	911	2020	1885	2933
^{14}C	years	0	~3000	740,000	~6000
^{3}H	TU	2.23	0.04	0.09	0.21

A lack of chemical or isotopic signature does not preclude the possibility of indirectly diminished groundwater discharge and/or runoff into to the lakes. Mining and/or agricultural and/or other water abstraction in the region have lowered historical levels of shallow groundwater surrounding the lakes. Lowered groundwater levels could be the result of either direct pumping of water supply bores, or by pumping deeper mine water and increasing downward hydraulic gradients towards underlying strata.

The lakes follow the same head loss rates as most of the underlying groundwater at almost all levels. With lake signatures occurring in many shallower groundwater piezometers, this suggests a steady connection and losses to groundwater. This could be hastened by lowering groundwater heads, which would increase hydraulic gradients and losses proportionally.

Apart from large rainfall events with widespread runoff, the lakes are supported by elevated groundwater tables, including possible discharge at depth into Lake Baraba from the west or the south (there are limited groundwater bores there to test this).

Less frequently Lake Nerrigorang is supported by groundwater discharge and/or surface runoff with a groundwater signature from its north and west, while the upper portion of Blue Gum Creek gets most of its water from surrounding hills, rather than from the lakes. Lake Werri Berri can be fed either by groundwater and/or overflow from either adjacent lake, depending on rainfall intensity and amount.

Lake Baraba, despite being the highest lake, has groundwater inflow and outflow in the order of a few megalitres per month. This might be partly explained by its very large, recently quantified peat stores (Cowley et al. 2020).

Outflow from Lake Baraba is via points unknown or diffuse through its supporting aquitard, but it mixes with adjoining shallow piezometers and contributes to a slightly deeper underlying aquifer that includes LB2, LC3 and possibly GW075409-1. Piezometers with older, more evolved signatures around Lake Couridjah in this level may be within relatively stagnant portions of this aquifer, as water only migrates there over the course of many years.

From the LB2-LC3 level, water may migrate northward along both sides of the U bend towards the lowest pressures on each side. This is in the vicinity of LW4 on the eastern limb and LBN2 to LN3 on the western limb, but only LN3 shows a mixed evaporated signature. The other two, being groundwater dominated, may intercept groundwater flow from the surrounding landscape.

LBC2 sits higher than these and is fed by unevaporated groundwater, probably from the south and/or west. This flows below and mixes with LC1 and below Lake Couridjah. It may also contribute to LB4's mixed signature below Lake Baraba and possibly north to LBN2.

Lake Couridjah sits at an intermediate level, with its losses mostly explained by evapotranspiration. During high levels it may contribute to Lake Werri Berri.

Lake Gandangarra, like Lake Baraba, sits perched above its neighbour(s), but lacked Lake Baraba's groundwater support during most of the study period. Instead, Lake Gandangarra has a larger rainfall catchment than all other lakes and was supported by more runoff after large rain events. Occasionally it overflows into Lake Werri Berri, but is dominated by evaporation between runoff events.

If there is any focused recharge to deep groundwater beneath the lakes, it looks more likely to be somewhere below Lake Nerrigorang, and/or Lake Werri Berri. These have lower percentages explained by evapotranspiration losses and lowered surface water levels. Both have evidence of shallow unevaporated groundwater inputs that are adjacent to and/or mixing with lake water but are insufficient to sustain these two lakes.

Lake Nerrigorang, whether a focal site for groundwater loss or not, retains some peculiar signatures that confirm its separation from other lakes, at least near the surface. Its Cl/Br ratio is low due to elevated Br, its pH was often lower than the other lakes and similar to groundwater in the weathered upper Hawkesbury Sandstone, and it supports vast amounts of the water lily Nymphaea sp. (Kobayashi et al. 2020), not found in other lakes during our sampling. These unique factors indicate it is not simply supplied from its elevated neighbour, Lake Baraba, but receives groundwater and/or runoff supply from the surrounding ridges at times.

For further details see Peterson et al. 2020.

9. Peat sediments and water storage capacity in Lake Baraba

Lake Baraba October 2018. Photo: Kirsten Cowley

9.1 Introduction

Peatlands are recognised globally as significant water storage reservoirs, storing about 10% of all freshwater despite occupying only about 3% of the land surface (Boelter 1964; Price & Schlotzhauer 1999; Rezanezhad et al. 2016). Peatlands both in Australia and globally began forming at the end of the last glacial maximum between 15,000 and 9000 years ago (during the Holocene period), when increases in temperature and moisture increased organic matter deposition within saturated sediments (Young 1986; Gorham & Rochefort 2003; Fryirs et al. 2014; Garneau et al. 2014; Bispo et al. 2016). Anoxic conditions commonly exist within the peat sediments, which slows decomposition and preserves the organic matter. The organic matter in turn assists in the water storage retention of these peatland systems.

The aims of the *Peat Sediments and Water Storage Capacity in Lake Baraba* research project were to:

- investigate the depth of peat in Lake Baraba, and
- calculate peat volumes and water storage capacity in Lake Baraba.

This chapter is revised from the paper:

Cowley KL, Fryirs KA, Cohen TJ, Marx S, Forbes M and Krogh M 2020, Upland peatlands of eastern Australia as important water storage reservoirs, *Proceedings of the Linnean Society of New South Wales*, vol.142, no.1, pp.67–76.

9.2 Peat sediments

Sediment cores recovered from all five of the Thirlmere Lakes contained peat that has accumulated over time at different accumulation rates with different unit depths (see *Chapter 5 Geomorphology* and Cohen et al. 2020). Comparisons between the sediment cores of Lake Baraba and Lake Couridjah indicate that the Lake Baraba Holocene peats have accumulated at double the rate of that of the Lake Couridjah Holocene peats (Cohen et al. 2021).

In contrast to the other lakes, Lake Baraba maintained a higher water level during a significant drought period between 2017 and 2019 (DPIE 2019). It is possible this water level persistence may be partially due to the high water storage capacity of the Lake Baraba peats (Black et al. 2006).

Of the five Thirlmere Lakes, Lake Baraba has the second largest catchment area (82 hectares; Chen et al. 2020) and is at the highest elevation (304 metres AHD). Lakebed area for Lake Baraba was calculated at 72,084 square metres (see Cowley et al. 2020). The sediments of Lake Baraba consist of highly organic, fine-grained peats (mean organic matter content 76%) to a maximum depth of 4.9 metres. Below the peat are yellow/grey/white clays and sands, clayey sands and coarse sands from depths of 0.8–5.6 metres (see Figure 9.1). The maximum peat depth recorded in this study in Lake Baraba was 4.9 metres, with a mean depth of 1.4 metres (Figure 9.2 and Table 9.1).

Figure 9.1 Lake Baraba: dried lakebed (top left); peat cores (top middle & right); deeper clay layers in cores (bottom left, middle, right)

Photos taken 23/01/2020, M Krogh.

Mean peat bulk density was calculated as 0.15 grams/cubic centimetre, whereas the bulk density for the underlying sands and clays (1 gram/cubic centimetre) was significantly different to peat bulk densities (Table 9.1). Significant differences in moisture and organic matter (OM) content between the peat and underlying clays were also identified, with the moisture and OM content of the peat at 97% and 79%, respectively; while the moisture and OM content of the sands/clays was 77% and 23 %, respectively (Table 9.1).

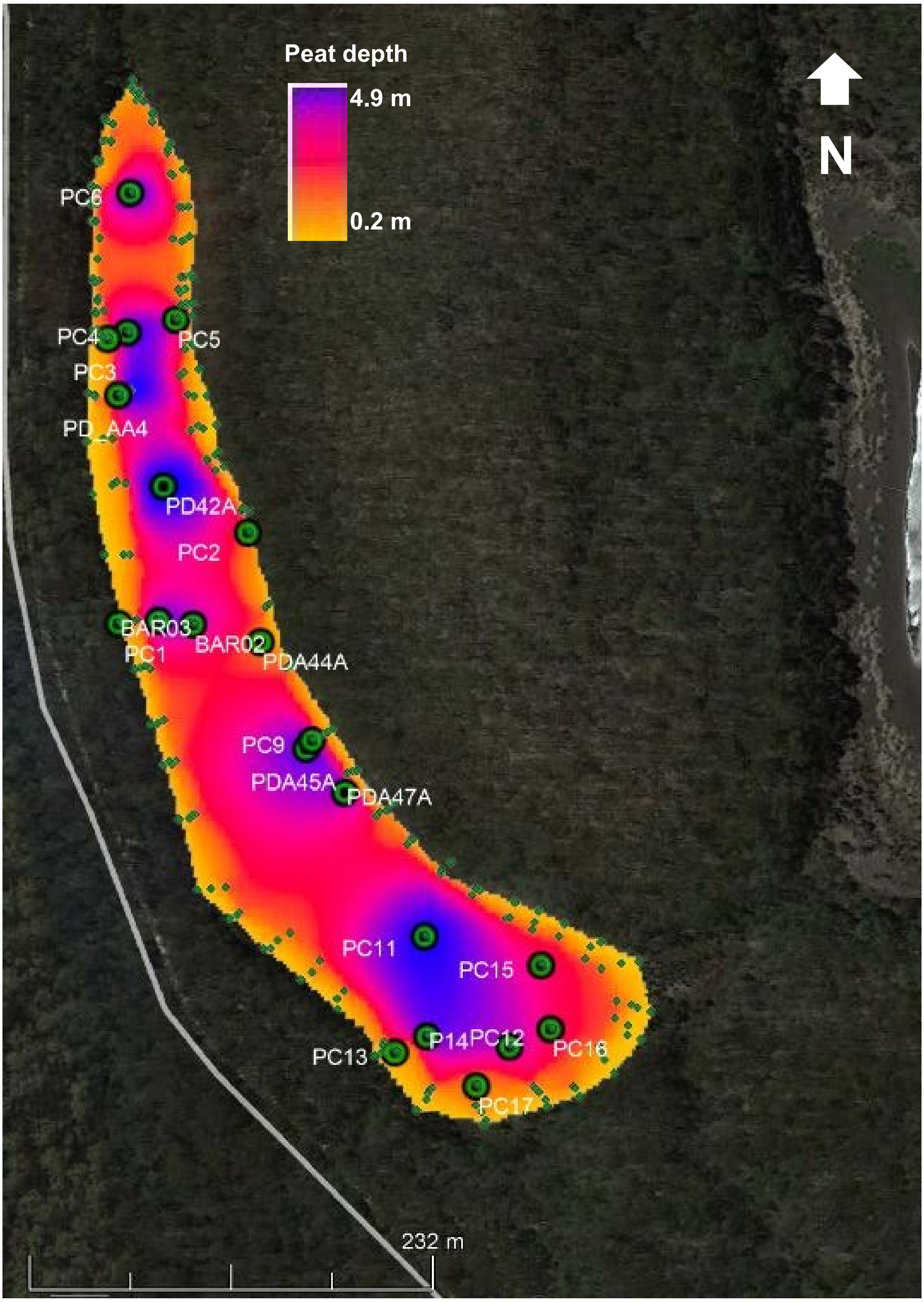


Figure 9.2 Interpolated peat depths and core locations[37]

The total peat volume of the lake was calculated at ~154,400 cubic metres with a total water holding capacity of 150 (±17.3) megalitres.

[37] Relative to edge samples, samples from the centre of the lake are somewhat under-represented, which may have some influence on the interpolated peat depths between points.

Table 9.1 Statistics for Lake Baraba peat sampling

	Sample size	Minimum	Maximum	Mean (±SD)
Peat depth (m)	243	0	4.9	1.4 (±0.9)
Peat bulk density (g/cm^3)	38	0.08	0.35	0.15 (±0.06)
Sand/clay bulk density (g/cm^3)	18	0.2	1.4	1 (±0.3)
Peat moisture content (%)	31	65	113	97 (±11)
Sand/clay moisture content (%)	18	14	130	77 (±22)
Peat organic matter content (%)	32	41	94	79 (±14)
Sand/clay organic matter content (%)	25	7	63	23 (±19)

9.3 Discussion

Peat-forming systems such as Thirlmere Lakes are significant water storage reservoirs within the landscape. The water storage capacity of the peat in Lake Baraba was calculated to be more than three times the surface water volume that was recorded after an east coast low rain event in June 2016 (Shengyang Chen pers. comm.). This means the peat holds considerably more water than the lake itself at high water levels. The remarkable water holding and storage capacity of the peat in this lake may go some way to explaining the recent resilience of Lake Baraba to drought, relative to the other Thirlmere Lakes. Historically water levels in Lake Baraba have not aligned well with the other lakes in the Thirlmere system (see historical aerial photographs in Figure 9.3 below). During the most recent drought from 2017–2019, Lake Baraba maintained surface water longer than all other Thirlmere Lakes, drying completely at the surface towards the end of 2019 (Figure 9.4).

Figure 9.3 Historical aerial photographs between 2012 and 2019 showing surface water maintenance in Lake Baraba when the other Thirlmere Lakes went dry

Climate change projections for eastern Australia in the 21st Century are for increased temperatures, evapotranspiration and decreased soil moisture (Dowdy et al. 2015). Drought duration is also expected to increase over the course of the 21st century (Dowdy et al. 2015). These predictions could potentially lead to impacts on peat-forming systems and their ability to store water (Bloomfield et al. 2003; Cowley et al. 2019; Roulet et al. 1992). In Lake Baraba and the Thirlmere Lakes more generally, prolonged lower water levels due to reduced rainfall recharge could result in significant decomposition of organic matter within the peat matrix, which can cause the peat to dry out and compress, further reducing the ability of the peat to store water (Cowley et al. 2016; Joosten et al. 2012; Leifeld et al. 2012).

Figure 9.4 Lake Baraba 20 September 2019

Note the lack of visible surface water[38], but moisture evident in the surface peat layer.
Photos: M Krogh

Activities such as underground mining, groundwater extraction and urbanisation have also lowered water tables within peatlands and swamps both in Australia and overseas (Cowley et al. 2019; Holden et al. 2006; Luscombe et al. 2016; Worrall et al. 2007). Irrespective of whether the cause of degradation is climate change or human disturbance, the secondary consequences of changes in hydrological function on these systems can lead to the permanent loss, or significant impairment of these peat systems (e.g. Keith et al. 2021). The recovery time from such disturbances can be long, assuming restoration is possible and irreversible change has not occurred. Widespread peatland loss through desiccation, channelisation and fire is common in many places (Evans & Warburton 2011; Holden et al. 2011; Ise et al. 2008; Page & Hooijer 2016; Price 2003; Tomkins & Humphreys 2006; Turetsky et al. 2015; Wösten et al. 2006). For example, work on *Sphagnum* peatlands suggests that once the hydrological function of a peat-forming system is altered (e.g. via channelisation), it may take up to 10 years to re-establish a stable high water table and up to 30 years for a functioning ecosystem that accumulates peat after appropriate restoration actions are emplaced (Gorham & Rochefort 2003; Hope et al. 2009; Lucchese et al. 2010; Whinam et al. 2003). With climate change it is highly likely that the water storage capacity of peat-forming systems will be most impacted during dry periods and droughts. Additionally, the vulnerability of these systems to human impacts such as groundwater interference and urbanisation may exacerbate these changes and the potential for recovery. The capacity for peat to recover after drought and/or human disturbance has not yet been investigated in these systems. Robust conservation and rehabilitation measures are needed to ensure the resilience of these systems in the future.

[38] Although some water was still observable at the centre of the lake in the photogrammetry images of October 2019 (see Chen et al. 2020).

10. Water levels, water quality and zooplankton in Lake Werri Berri and Lake Nerrigorang

Lake Nerrigorang October 2014. Photo: M Krogh

10.1 Introduction

Wetlands including lakes provide important habitats for a variety of terrestrial and aquatic biota (Norman 2003; Kingsford et al. 2016). An understanding of biological diversity (biodiversity) and productivity in relation to water availability and quality is important in ecological management of such systems (Whigham & Jordan 2003; Verhoeven et al. 2006). In particular, water level changes can lead to significant changes in water quality (e.g. turbidity), habitat extent and structure, especially in small shallow lakes, where various impacts of water level changes on aquatic invertebrates have been reported (e.g. Zohary & Ostrovsky 2011). Prolonged decreases in water levels can increase the loss of aquatic habitats. The viability of resting eggs and species diversity of aquatic invertebrates are negatively impacted by increasing dry periods and decreasing areal extent of wet lake sediments (Mageed & Heikal 2006; Zohary & Ostrovsky 2011).

The aims of the *Water levels, Water Quality and Zooplankton in Lake Werri Berri and Lake Nerrigorang* research project were to:

- survey Lake Werri Berri and Lake Nerrigorang for zooplankton, and
- investigate any relationships between zooplankton community composition and water quality and water depth.

This chapter is revised from the paper:

Kobayashi T, Krogh M, Li H, Shiel RJ, Segers H, Ling J, Hunter SJ and Pritchard T 2020, Zooplankton species richness and abiotic conditions in Thirlmere Lakes, New South Wales, Australia, with reference to water-level fluctuations, *Australian Zoologist*, vol.41, no.1, pp.107–123, doi.org/10.7882/AZ.2020.020.

In relation to the water quality and zooplankton of Thirlmere Lakes, Horsfall et al. (1988) reported the physical and chemical conditions, and zooplankton, in four of the five lakes. They noted the oligo-mesotrophic (low to moderate nutrients) condition of the lakes and the dominance of certain species of rotifers, cladocerans and copepods amongst the zooplankton. However, the associations between the hydrological conditions, especially lake water level, and the biota of Thirlmere Lakes largely remain unknown.

In this study, we examined the species richness of zooplankton and the association between zooplankton species richness and lake water levels, comparing the zooplankton species composition and water quality of the lakes with those documented in previous studies (Stanisic 1972; Horsfall 1985; Horsfall et al. 1988) to help identify any notable recent changes in the lakes.

Box 10.1 – Zooplankton

Zooplankton are animals that float in the water but cannot swim against a current and are mostly microscopic in size. The important groups of freshwater zooplankton are rotifers (wheel animals), cladocerans (water fleas), copepods, protozoans and larval fish. They occupy an intermediate level in aquatic food chains and play a significant role in energy and nutrient transfer from plants to animals in aquatic ecosystems.

A field survey was conducted in Lake Nerrigorang and Lake Werri Berri, two of the five Thirlmere Lakes, approximately monthly from February 2014 to March 2015 (12 observations in total for each lake). Using a tube water sampler, water samples (0.5 litres each) were collected in each lake at three different locations near the shore areas at about mid depth, corresponding to 0.1−0.3 metres depth below the surface, depending on the lake water level.

In the field, water temperature and dissolved oxygen were measured and water samples taken back to the laboratory for other physico-chemical analyses. Nutrient concentrations (total nitrogen, total phosphorus. oxidised nitrogen, ammonia nitrogen, dissolved organic nitrogen, dissolved inorganic phosphorus and dissolved organic phosphorus) were also measured. The mean water level (metres) in Lake Nerrigorang and Lake Werri Berri was estimated between two consecutive sampling dates using daily water level data available from the WaterNSW real-time continuous water monitoring network[39] (site no. 212063 for Lake Nerrigorang and site no. 212067 for Lake Werri Berri).

Zooplankton samples were collected by towing a conical plankton net (mouth diameter: 40 centimetres; mesh size: 63 micrometres) around near the shore areas (both open and littoral/vegetated) for about 20 minutes. In very shallow areas (<40 centimetres depth), the zooplankton samples were collected by holding the rim of the net. A single composite sample was produced at each sampling occasion in each lake. All specimens were preserved in 70% ethanol. In the laboratory, zooplankton specimens were sorted, examined and identified. Species diversity was estimated for each sample as the total number of taxa present belonging to either Rotifera, Cladocera or Copepoda (Calanoida and Cyclopoida).

[39] Real-time water data, accessed 5 December 2018

10.2 Water level and water quality

During the study period, the mean water level tended to decrease in both lakes (Figure 10.1). Apart from the mean water level and water temperature, the physical and chemical conditions in Lake Nerrigorang showed distinct peaks and troughs, relative to those in Lake Werri Berri (Figure 10.1). The summary statistics (mean, standard error or SE, and range) of water level and water quality are shown in Table 10.1.

Table 10.1 Summary statistics for abiotic conditions of Lake Nerrigorang and Lake Werri Berri from February 2014 to March 2015

	Lake Nerrigorang	Lake Werri Berri
Mean water level (MWL, m)	0.43±0.06 (0.12–0.77)	0.99±0.04 (0.75–1.21)
Water temperature (WT, °C)	19.8±0.9 (9.9–26.5)	21.3±1.0 (10.5–29.7)
Dissolved oxygen (DO, mg L^{-1})	4.3±0.4 (0.1–8.5)	6.0±0.2 (4.2–8.2)
pH	4.7±0.2 (3.1–7.6)	6.3±0.1 (6.0–7.1)
Conductivity (COND, µS cm^{-1})	364.5±33.9 (161.7–988.0)	200.2±3.3 (173.3–241.6)
Turbidity (TURB, NTU)	21.5±5.9 (1.2–130.0)	4.1±0.3 (1.6–9.1)
Oxidised nitrogen (ON as NO_x-N, µg L^{-1})	7.4±1.3 (1.2–26.0)	3.9±0.4 (1.1–9.9)
Ammonia nitrogen (AMM as NH_3-N, µg L^{-1})	4271.8±501.1 (111.0–9434.0)	114.6±29.8 (5.8–612.0)
Dissolved organic nitrogen (DON, µg L^{-1})	1082.6±151.8 (302.8–2950.1)	1503.4±50.1 (1044.4–2134.5)
Total nitrogen (TN, µg L^{-1})	5644.1±463.9 (506.0–9913.0)	1895.0±56.8 (1359.0–2439.0)
Dissolved inorganic phosphorus (DIP as PO_4-P, µg L^{-1})	2.6±0.4 (0.4–6.9)	1.7±0.1 (0.6–4.2)
Dissolved organic phosphorus (DOP, µg L^{-1})	12.7±1.3 (5.2–25.4)	9.0±0.4 (5.7–16.6)
Total phosphorus (TP, µg L^{-1})	38.1±4.3 (13.1–92.4)	26.2±1.0 (18.0–40.6)

Mean±SE and range in parentheses are shown; n = 33–36 except for MWL where n = 12.

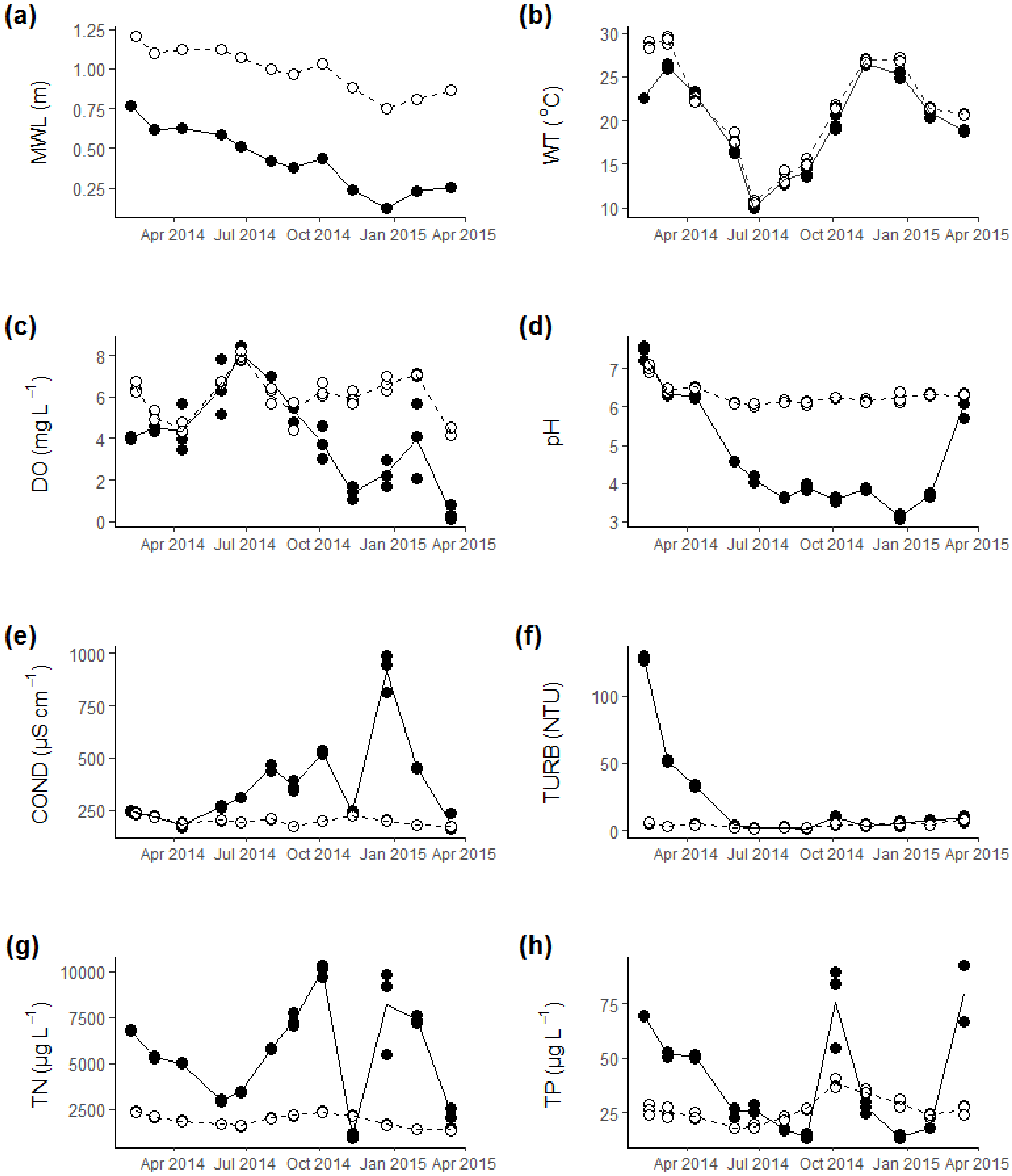


Figure 10.1 Temporal changes in water level and water quality in Lake Nerrigorang and Lake Werri Berri: (a) mean water level (MWL, m), (b) water temperature (WT, °C), (c) dissolved oxygen (DO, mg L^{-1}), (d) pH, (e) conductivity (COND, µS cm^{-1}), (f) turbidity (TURB, NTU), (g) total nitrogen (TN, µg L^{-1}) and (h) total phosphorus (TP, µg L^{-1})

Closed circles with solid line, Lake Nerrigorang and open circles with dashed line, Lake Werri Berri. For the full results, refer to Kobayashi et al. (2020).

A principal component analysis (PCA) with a correlation bi-plot was used to depict the relative separation of lake samples onto a two-dimensional plane (Figure 10.2). The first two principal components explained about two-thirds of the variation in the data. This analysis demonstrated the non-overlapping distribution of results for the two lakes[40].

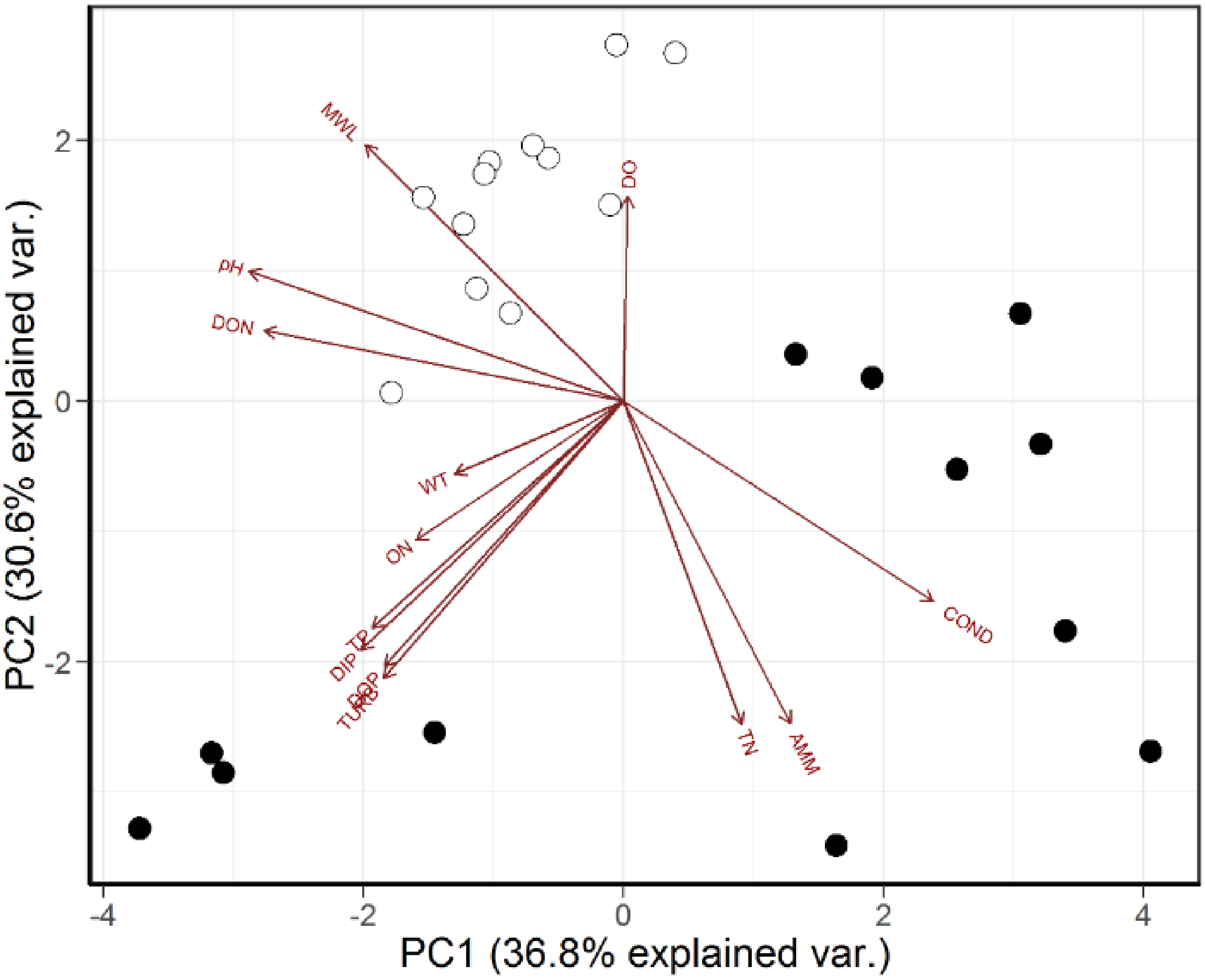


Figure 10.2 PCA with a correlation bi-plot projecting observations of the samples, based on water level and water quality variables (Table 10.1)

Closed circles, Lake Nerrigorang; open circles, Lake Werri Berri.

[40] Further explanation of the methodology and interpretation is available in Kobayashi et al. 2020.

10.3 Zooplankton

A total of 66 taxa of zooplankton was found from Lake Nerrigorang and Lake Werri Berri (Table 10.2). Of these, rotifers were most diverse (47), followed by cladocerans (15) and copepods (4), excluding unidentified juveniles. The two lakes shared 36% of the taxa in total.

Table 10.2 Zooplankton species richness in Lake Nerrigorang and Lake Werri Berri

Group	Total	Nerrigorang	Werri Berri	Common species between two lakes	Common species between two lakes (%)
Rotifera	47	29	35	17	36
Cladocera	15	9	12	6	40
Copepoda	4	1	4	1	25
Total	**66**	**39**	**51**	**24**	**36**

Of the rotifers, *Notommata saccigera,* recorded in Lake Werri Berri, was recorded for the first time in Australia (Figure 10.3). *Lecane rhytida* in Lake Nerrigorang and *Keratella javana* and *Rousseletia corniculata* in Lake Werri Berri were the first records in New South Wales (Figure 10.4).

Temporally, zooplankton species richness fluctuated in the range 2–20 (median: 6) in Lake Nerrigorang and in the range 11–20 (median: 17) in Lake Werri Berri, with a significant difference in median species richness between the two lakes (paired-samples Wilcoxon test: P = 0.0085, n = 12). Zooplankton species richness was significantly and positively correlated with mean water level in Lake Nerrigorang (r_s = 0.77, P = 0.0031). However, no significant correlation was found between these variables in Lake Werri Berri (P > 0.5) (Figure 10.5).

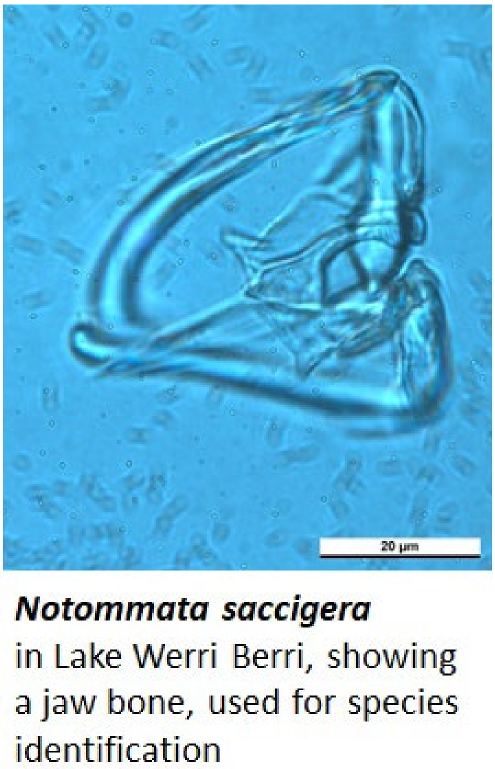


Figure 10.3 *Notommata saccigera* found in Thirlmere Lakes
Photomicrograph: T Kobayashi

Keratella javana
in Lake Werri Berri

Rousseletia corniculata
in Lake Werri Berri, showing a jaw bone in top right-hand side corner, used for species identification

Lecane rhytida
in Lake Nerrigorang

Figure 10.4 Other rare rotifer species found in Thirlmere Lakes
Photomicrographs: T Kobayashi

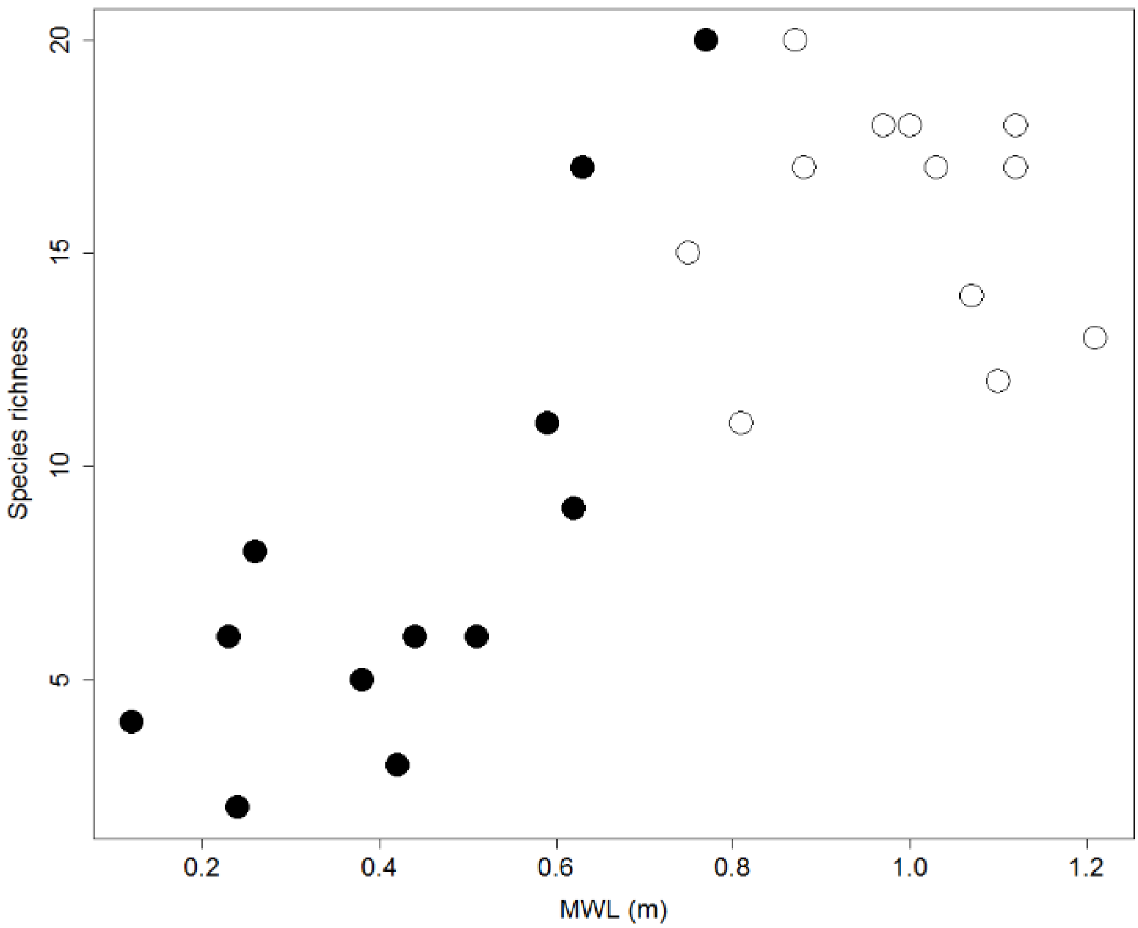


Figure 10.5 Relationship between zooplankton species richness and mean water level (MWL, m)
Closed circles, Lake Nerrigorang and open circles, Lake Werri Berri. A significant association was found between zooplankton species richness and MWL but only for Lake Nerrigorang (Spearman's rank correlation coefficient r_s = 0.77, P = 0.0031).

10.4 Discussion

Overall, the physical and chemical conditions of Lake Nerrigorang and Lake Werri Berri differed greatly between the two lakes, except for water temperature, with higher values of the physical and chemical conditions in Lake Nerrigorang. Horsfall et al. (1988) reported some of the physical and chemical conditions in four of the five Thirlmere Lakes (excluding Lake Baraba), noting that the four lakes had similar conditions in the 1980s, with levels of conductivity of 144 and 149 microsiemens/centimetre, pH of 5.6 and 5.7, total phosphorus of 10.2 and 13.0 micrograms/litre, and total nitrogen of 181 and 233 micrograms/litre for Lake Nerrigorang and Lake Werri Berri, respectively (Lake 5 and Lake 2 of Table 1 in Horsfall et al. 1988). Compared to these values, our results for Lake Nerrigorang and Lake Werri Berri are comparable with respect to conductivity, pH and total phosphorus, but were significantly higher with respect to total nitrogen (mean: 5644 and 1895 micrograms/litre for Lake Nerrigorang and Lake Werri Berri respectively in this study).

Relatively diverse zooplankton inhabit Lake Nerrigorang and Lake Werri Berri. In comparison with previous studies of Thirlmere Lakes by Horsfall et al. (1988), we did not record the cladoceran *Daphnia lumholtzi*, or the copepods *Calamoecia tasmanica* and *Mesocyclops albicans* in Lake Nerrigorang and Lake Werri Berri. One may speculate that the absence of the limnetic (open-water) *D. lumholtzi* (Timms & Morton 1988) and *C. tasmanica,* a coastal dune-lake species (Timms 1973), during this study may reflect increased drying or significant differences in water quality of the lakes (e.g. pH, turbidity, nutrients, dissolved organic matter or humic substance) (cf. Timms 1973; Kobayashi et. al. 2012). The absence of the cladoceran *Bosmina meridionalis* from the densely vegetated Lake Nerrigorang is not surprising, since *B. meridionalis* is an essentially eulimnetic/limnetic species, requiring open water habitats (Timms 1968; Shiel 1976) and during field sampling, the water surface of Lake Nerrigorang was occupied by *Nymphaea* sp., a floating-leaved plant that covered much of the water's surface. The copepod *Mesocyclops albicans* appears to be replaced by the congener *Mesocyclops australiensis* in Lake Werri Berri.

A significant positive correlation between zooplankton species richness and mean water level is consistent with the view that excessive water level fluctuations affect the ecological state of lake biota (Leira & Cantonati 2008). However, no significant correlation was found between zooplankton species richness and mean water level in Lake Werri Berri. During this study, the mean water levels of Lake Nerrigorang and Lake Werri Berri showed a similar decreasing trend, but the two lakes had a large difference in overall mean water level (0.43 and 0.99 metres respectively) and a nearly non-overlapping range of mean water level (0.12–0.77 and 0.75–1.21 metres respectively) (Figure 10.). We hypothesise that there may be a threshold water level, below (or above) which relative stability of zooplankton species richness decreases (or increases) in Thirlmere Lakes. Such a threshold water level is approximately 0.70–0.80 metres, judging from our observational results as shown in Figure 10.. Further data are needed to test the robustness and applicability of this 'threshold water level' hypothesis in Thirlmere Lakes.

Water level fluctuations may affect the development of aquatic vegetation communities in Thirlmere Lakes, and other shallow lakes, contributing to water quality changes (e.g. Scheffer 2001; Moorman et al. 2017). The proposed 'threshold water level' may affect not only species richness but also species composition of the lake zooplankton communities in Thirlmere Lakes, by means of changing the spatial extent of littoral (vegetated) and limnetic (open) water habitats within the lakes as well as influencing the water quality of the lakes[41]. Riley et al. (2012) pointed out the importance of the 'ecological character' descriptions of Thirlmere Lakes, with the aim of maintaining and avoiding any adverse or unacceptable change in the ecosystem of the lakes.

[41] It is noted that by the end of 2019 – beginning of 2020, all surface water in the five lakes had evaporated completely and lake levels were not restored until the rains of February 2020.

Although the scope of this study was limited to monitoring of Lake Nerrigorang and Lake Werri Berri, two of the five Thirlmere Lakes over one year, we found distinct water quality and zooplankton species composition differences between the two lakes. In comparison with previous limnological studies (Horsfall et al. 1988), we found a major increase in total nitrogen concentrations in Lake Nerrigorang and Lake Werri Berri and recorded rare rotifer species in both lakes. It is worth pointing out that even when Lake Nerrigorang and Lake Werri Berri become dry at the surface, with no surface water available, we would expect the dry lake sediments to hold viable egg banks (Kobayashi et al. 2018) that would lead to the emergence of the zooplankton community once it rains and the lakes fill.

11. Wetland vegetation of Lake Werri Berri

11.1 Introduction

Wetland vegetation is an important component of wetland ecosystems and plays a vital role in their function (Mitsch & Gosselink 2007; Sainty & Jacobs 2003; Boulton et al. 2014). Wetland-adapted plant species are present in most wetland types and are one of the most conspicuous features of a wetland. They are sensitive to the effects of floods, droughts and other extreme climatic events with their function and composition relying on a delicate balance between precipitation, temperature, evapotranspiration, runoff and hydrology (water depth and inundation; Davis & Ogden 1994). Importantly they offer essential habitat as well as food resources, for other species. They stabilise sediments, store water through the organic matter they create, help form microclimates under their canopies, as well as many other functions that can mitigate the short-term effects of climate extremes (Mitsch & Gosselink 2007).

Lake Werri Berri, the focus of this chapter, has a conspicuous fringe of grey sedge (*Lepironia articulata*) forming a halo or ring around the lake. Grey sedge is an important component of coastal wetlands in New South Wales, as well as other states of Australia (Harden 1993; Stephens & Sharp 2009; Marshall & McGregor 2011), south-east Asia (Domyos & Te-chato 2013; Wurochekke et al. 2014; Syukor et al. 2015) and Madagascar (Shaji et al. 2009). Grey sedge (*Lepironia articulata*) stabilises wetland banks because of its robust form, with both submerged and emergent portions of culms that are more rigid and of a greater diameter than other sympatric sedge species (Sim et al. 2008). It forms important vertical structural habitat for birds (McFarland 1988), fish and aquatic invertebrates (Bensink & Burton 1975; Arthington et al. 1986), and frogs (Ingram & Corben 1975), and offers a hard, stable substrate for periphyton (McGregor 2007). Its stems are also used as a food source by freshwater turtles (Georges 1982), while the seeds are eaten by water fowl. It has been used by indigenous cultures (in Australia and overseas) as a floating device, snorkel and weaving product (Slockee 2010; Wunbua et al. 2012). Grey sedge also plays an important role in nutrient and heavy metal removal (Sim et al. 2011; Syukor et al. 2015). Grey sedge also contributes organic biomass to the sedimentary peat layers within the lakes.

In 2019, the department initiated a preliminary wetland vegetation survey for Lake Werri Berri.

The aims of this research project were to:

- evaluate species presence and regeneration potential of the seed bank at Lake Werri Berri
- understand changes in the wetland vegetation over time at Lake Werri Berri, and
- better understand the effectiveness of survey methods, including vegetation plot surveys, soil seed bank experiments and citizen science engagement.

11.2 Methodology

To evaluate the regenerative potential and change in wetland vegetation over time at Lake Werri Berri, several research strategies were adopted. These included (a) documenting the extant vegetation in 20 X 20 metre plots as a baseline for future monitoring; (b) digitising wetland areas using high resolution photogrammetry; (c) glasshouse germination experiments for the soil seed bank to investigate the viability of the seed bank; and (d) trialling a citizen science program for mapping wetland vegetation and fauna.

Lake Werri Berri is mapped (Figure 11.1) on the SCIVI (South Coast Illawarra Vegetation Integration) vegetation database produced using ArcMap 10.4 (Tozer et al. 2006). These vegetation datasets integrate data from existing databases (P5MA and Southern CRA), aerial interpretation and on ground validation (Tozer et al. 2006). It was updated in 2014 (DPIE 2014) to improve mapping consistency.

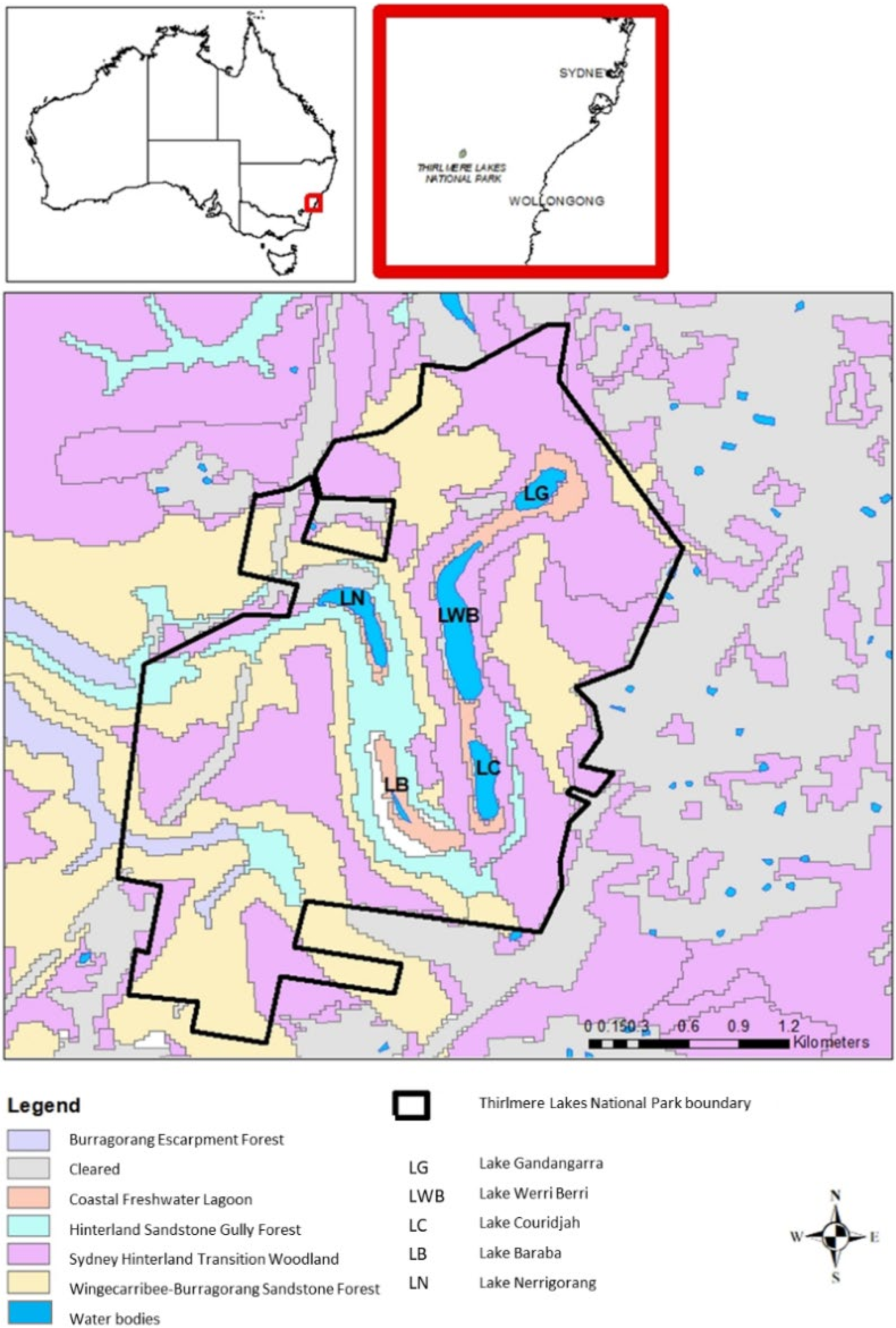


Figure 11.1 **Location map of Lake Werri Berri (LWB) with vegetation map units identified from the Southeast NSW Native Vegetation Classification and Mapping – SCIVI, VIS_ID 2230**

11.3 Vegetation plots and soil seed bank studies

Wetland vegetation at Lake Werri Berri was surveyed following the Biodiversity Assessment Methodology (OEH 2018 – BAM Operational Manual Stage 1; Sivertsen 2009). Since Lake Werri Berri was dry at the surface at the time of survey, a 20 x 20 metre plot was placed (4 September 2019) within each of three zones within the lake margin (Zone A: centre of lake and frequently inundated; Zone B: 25 metres from the centre of the lake and less frequently inundated; and Zone C: at the edge of the continuous tree–shrub canopy layer that is only inundated when the lake is full) (Figure 11.2 & Figure 11.3). The species present, their abundance and percent cover were recorded for each plot. Growth forms of native species were assigned using the lookup table developed in the BAM Calculator (accessed 21/11/2019). Voucher specimens were preserved of most species as part of the quality control process.

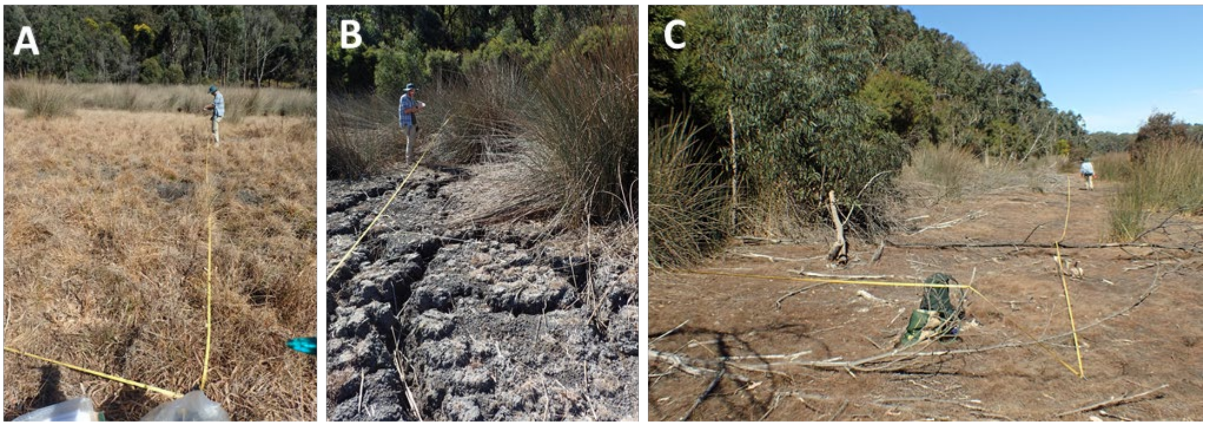


Figure 11.2 Vegetation survey plots (20 m X 20 m), 4 September 2019 (a) Zone A in the centre of Lake Werri Berri; (b) Zone B 25 m from the edge of the forest; and (c) Zone C at the edge of the forested area

Historical aerial photographs were sourced from the department's spatial historical aerial photographs for the years 1962–2004, and from Nearmap Australia (accessed November 2019) for the years 2010–2019 in either JP2, TIF or JFIF formats. All images were georeferenced in ArcGIS 10.4. The historic aerial photographs were used to calculate the area of *Lepironia articulata* cover, surface area of water and the wetland area inside the edge of the wooded area (defined by the presence of trees and shrubs) by digitising discrete polygons. Areas (in square metres) were calculated using ArcGIS automation tools, and then converted to hectares (ha) for reporting. *Lepironia* was recognised in the aerial photographs by its distinctive colour and texture.

The soil seed banks from the three zones in Thirlmere Lakes were also sampled to verify the viability and species present in the seed bank. These zones were the same as for the vegetation plot surveys (see Figure 11.2). In each of these zones, six replicate core samples were collected within a 5 X 5 metre area. Cores were collected using a Russian D-corer to a depth of 0.5 metres (Figure 11.4). Each 50 centimetre core was separated into 5 x 10 centimetre depth segments (0–10, 10–20, 20–30, 30–40, 40–50 centimetre depth) to determine whether seeds were still viable at different depths. Each bag was a composite of six replicates for each depth. To limit contamination between depth, zone and transect samples, all equipment was wiped clean between each core. A total of 30 soil samples (3 zones, 5 depths, 2 transects) were collected for the germination trial.

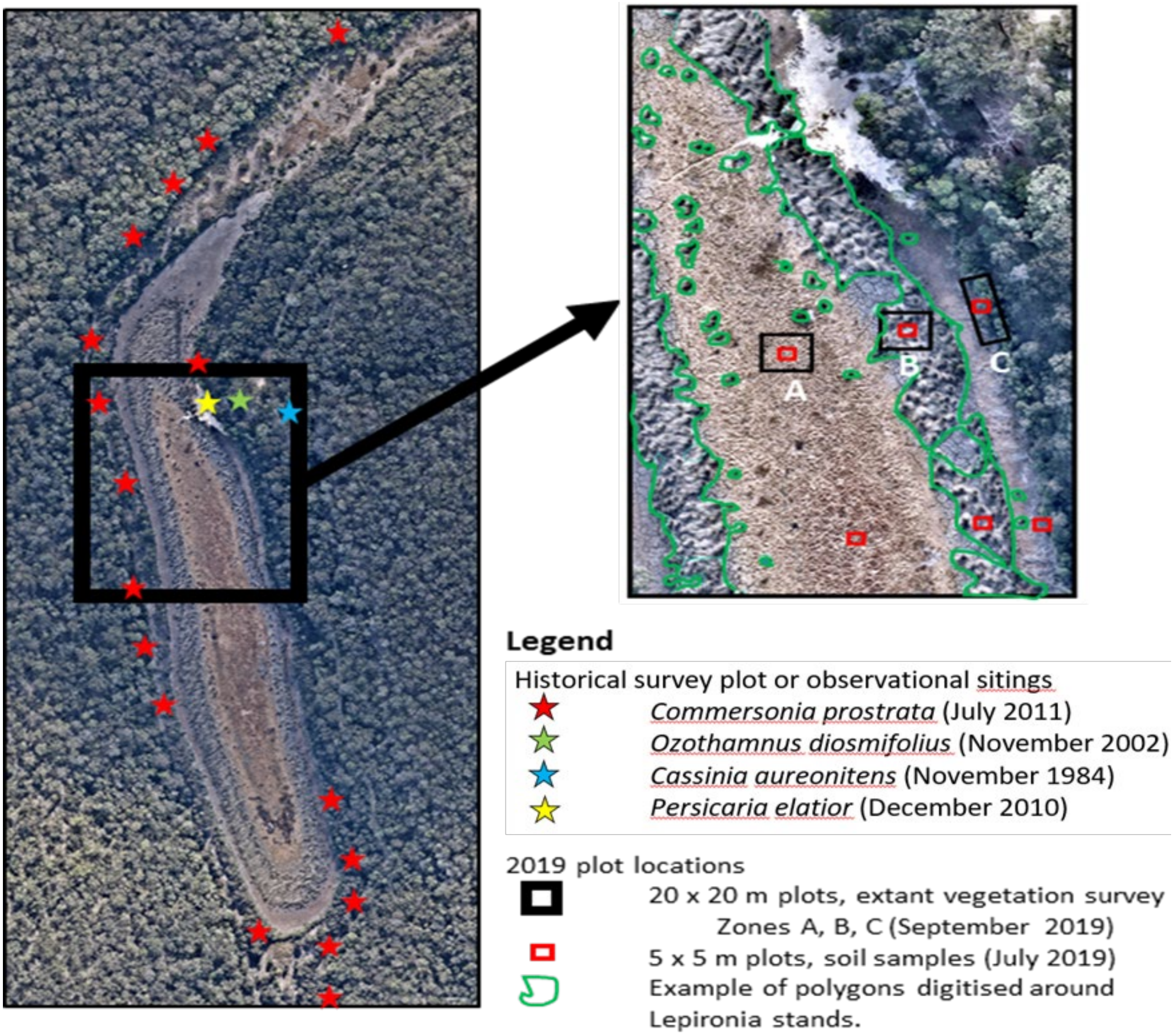


Figure 11.3 Location of plots sampled within Lake Werri Berri: (a) historical observational records in BioNet (accessed 6 September 2019); (b) extant vegetation plots of 20 x 20 m, and soil samples taken from 5 x 5 m plots taken in 2019

Aerial photograph from 29 July 2019 (Nearmap Australia, accessed November 2019).

In the greenhouse, each soil sample was placed in a round plastic bucket (20 centimetres diameter, 20 centimetres depth), with water level kept at the soil surface (i.e. waterlogged) with dechlorinated water. Temperature was kept at a constant 26°C, with light maintained on a 12-hour cycle. Seedlings were counted weekly. After 106 days the experiment was terminated, and plants were transplanted to grow to maturity to aid identification of species.

Tailored survey forms were also developed for the citizen science component including safety and member registration, as well as the collection of wetland flora and fauna data. Photos and descriptions from PlantNet (accessed 2019) of the common plants (examples in Figure 11.5) and audio recordings of frog calls that occur in Thirlmere Lakes area were also added to the forms to aid in their recognition.

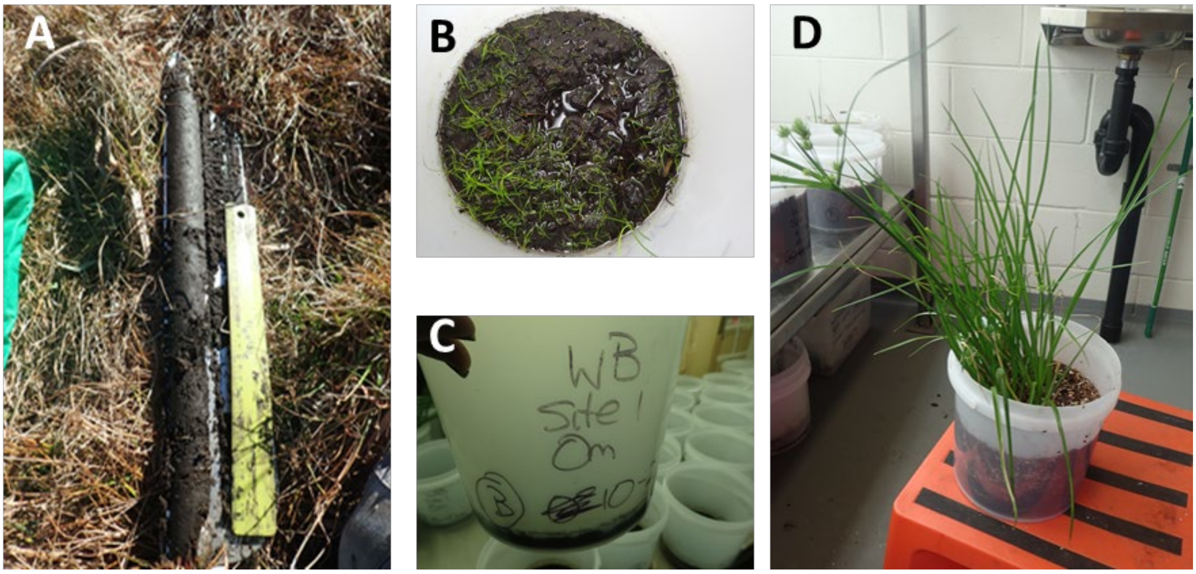


Figure 11.4 **(a) Example of a core soil sample taken at Lake Werri Berri; (b) germination of seeds at day 86 (10/10/2019); (c) labelling of buckets; and (d) day 107 *Cyperus* sp. (31/10/2019)**

Figure 11.5 **Plant photos and description of native species *Lepironia articulata* to aid recognition for citizen scientists**

Description from PlantNet (May 2020).

11.4 Vegetation survey results

The three vegetation zones in the lake were distinct: the centre of the lake was devoid of any trees or shrubs and large grey rush tussocks (Zone A); the area surrounding the lake consisted of a halo or ring of *Lepironia* (Zone B); and the edge of the lake included scattered trees and shrubs and bare ground, but not a continuous tree canopy (Zone C).

The centre of the lake (Zone A) was dominated by a ground cover of grasses, sedges and herbs, mostly *Juncus planifolius, J. prismatocarpus*, and *Philydrum lanuginosum* (frogsmouth) (Figure 11.6; the full species list can be found in Table B.1, Appendix B), although there was significantly more dead leaf material than living material and minimal bare ground exposure. The peat was observed to be damp under the dried leaf matter. The species recorded in this zone were all species that are water dependent (that is, wetland indicator species with WPIL codes less than 2.33), except for a few opportunistic species (catsear weed: *Hypochaeris radicata* and *Leptospermum trinervium* seedlings; Figure 11.6).

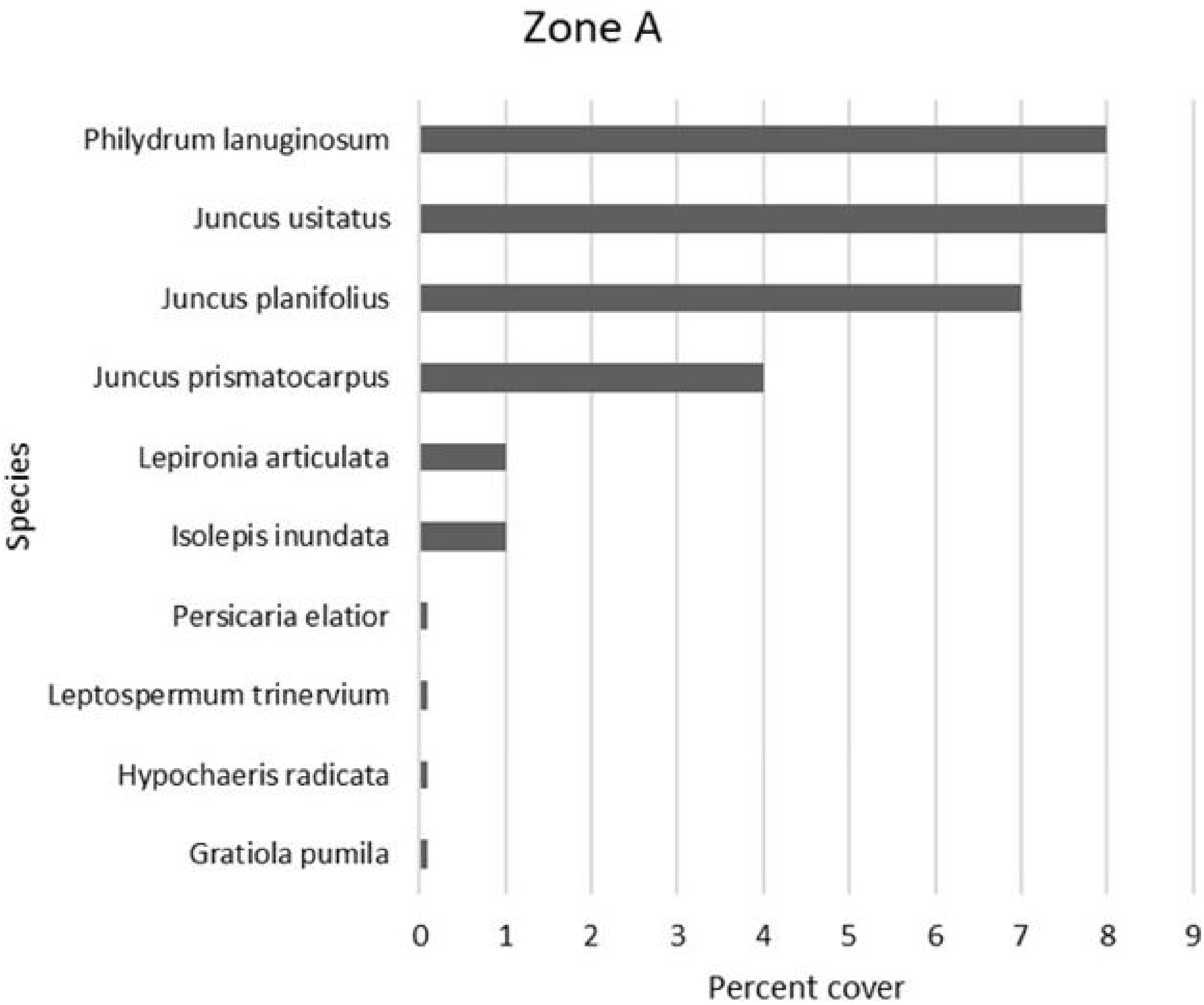


Figure 11.6 Percent cover of species recorded in the 20 x 20 m plots surveyed on 4 September 2019 at Zone A, centre of the lake

Approximately halfway between the centre of the lake and the edge of the continuous tree–shrub canopy layer (Zone B: 25 metres from the centre of the lake) is the *Lepironia* zone. Here, the sediment was dry with large fissures that extended up to 1–1.5 metres depth, mainly with exposed bare ground, except where the collapsed *Lepironia* culms covered the ground. The grey sedge *Lepironia articulata* dominated this zone, occasionally with other species that dominated Zones A and C (Figure 11.7). The species unique to Zone B were the fern-like species, often found underneath the collapsed *Lepironia* leaves, including *Calochlaena dubia* (soft bracken or rainbow fern) and *Pteridium esculentum* (common bracken fern) (Figure 11.7). Both ferns are not considered obligate water dependent wetland species as they can occur in areas other than wetlands.

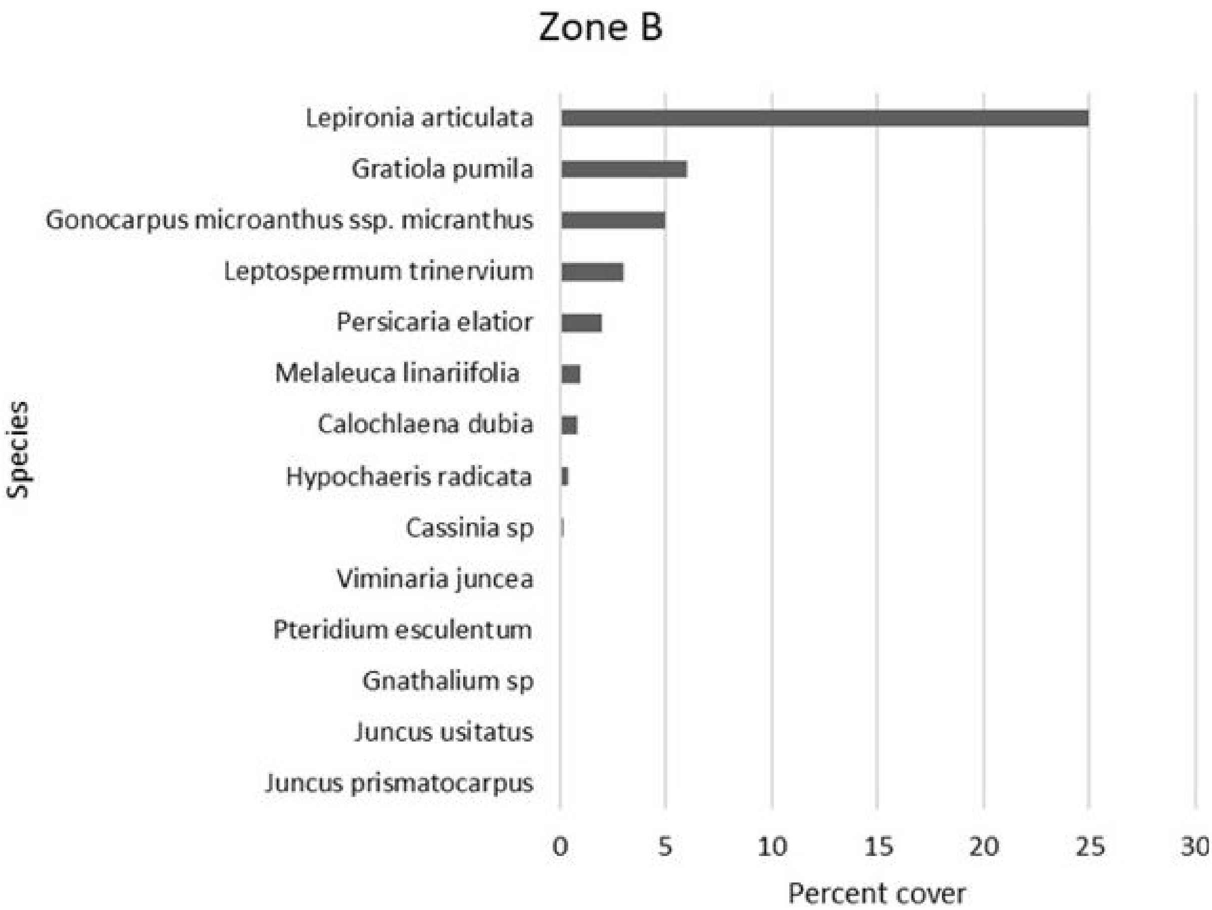


Figure 11.7 Percent cover of species recorded in the 20 x 20 m plots surveyed on 4 September 2019 at Zone B, 25 m from the centre of the lake

Zone C, from the *Lepironia* zone to the continuous tree–shrub canopy layer (~50 metres from the centre of the lake), was mainly exposed bare ground with densely packed dried peat and few fissures. Where vegetation occurred in this exposed area, it was dominated mainly by the creeping raspwort *Gonocarpus micranthus* ssp. *micranthus*, while closer to the edge of the continuous tree–shrub canopy layer were the occasional *Lepironia* tussocks and *Leptospermum trinervium* (flaky-barked tea-tree) (Figure 11.8). This zone was represented mainly by species that preferred drier niches and reflects the lower frequency and duration of inundation in this zone. Some of these species are potentially a remnant of when the lake's water levels were higher.

Of the 31 plant species recorded in the survey plots in the three zones of Lake Werri Berri, 14 species were classified as water dependent or wetland indicator species. Not surprisingly, most of these wetland species were collected from historically inundated zones (Zones A and B) and are species that can tolerate fluctuations of water presence or absence without major changes in morphology. A full species list is provided in Table B.1, Appendix B.

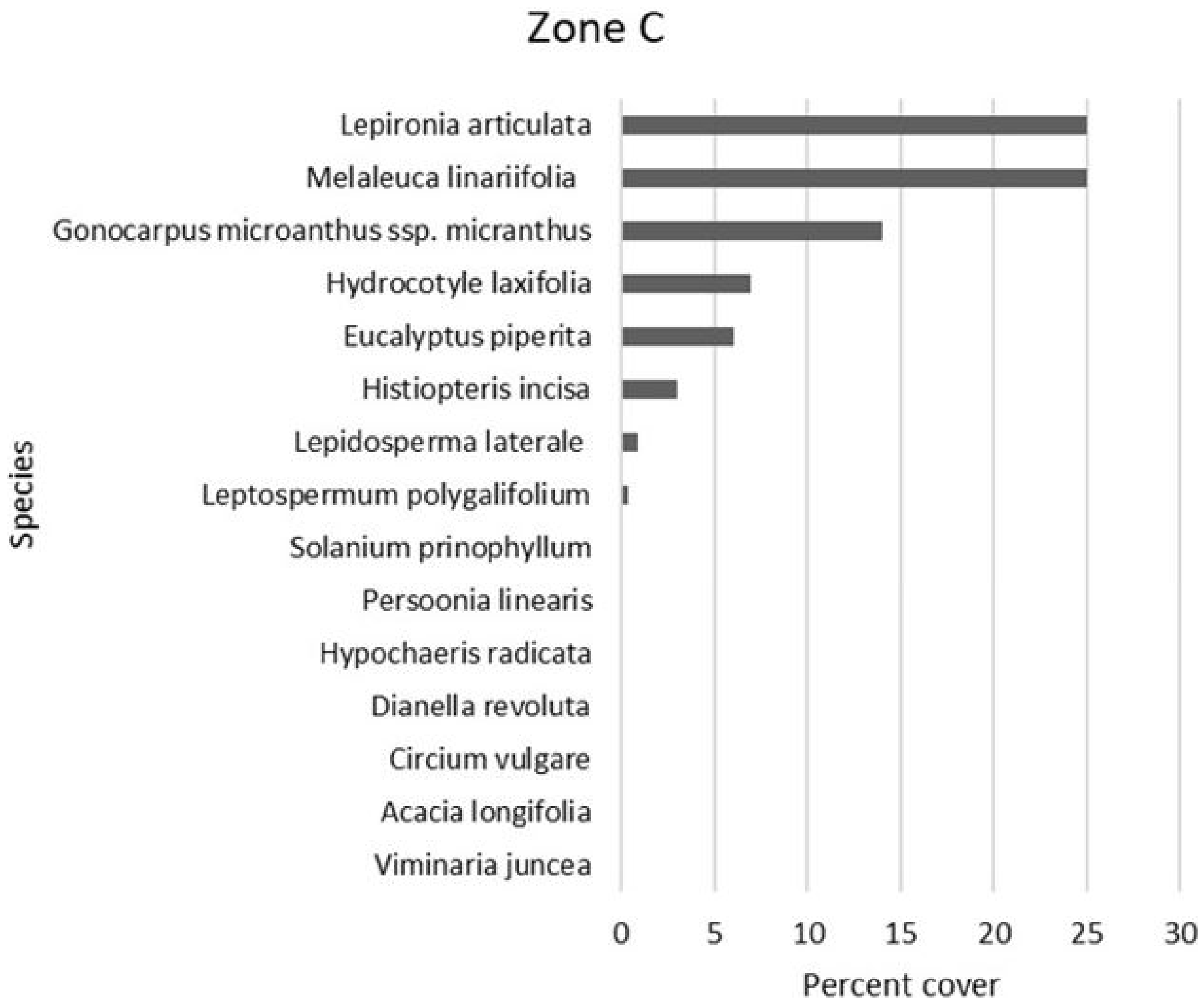


Figure 11.8 Percent cover of species recorded in the 20 x 20 m plots surveyed on 4 September 2019 at Zone C, 50 m from the centre of the lake

11.5 Calculating the area of *Lepironia* cover, surface area of water and the wetland area inside the wooded area since 1962

Area of *Lepironia articulata* cover, surface area of water and the wetland area inside the wooded area was calculated from 20 high-resolution aerial photographs from 1969–2019 for Lake Werri Berri (data presented in Table B.2, Appendix B). *Lepironia* cover fluctuated between 0.4 and 5.4 hectares with a significant decline in the cover of *Lepironia* in 2002, 2006 and 2010 coinciding with wildfires in 2002 and the Millennium Drought. From the data available, the cover of surface water area from 1969 until 2004 usually remained above 9 hectares despite some notable declines in rainfall during the same time (BoM 2015). From 2010–2019, there was a notable drop in the area of surface water cover (and the area within the tree boundary). From 1969–2020 there was a contraction of the area within the tree boundary (Figure 11.9), with the appearance of woody vegetation particularly evident from 2014 imagery (Figure 11.10).

At the time of this preliminary study, mean estimates of the surface area of water based on a digital elevation model (e.g. Chen et al. 2021) were unavailable and the process of estimating water surface area from aerial images is acknowledged as one of the larger uncertainties in this preliminary study. Here, area was approximated using polygons by the researcher (JL), and the focus of the study was on the relative area of water to the relative area of *Lepironia,* placing less reliance on an absolute area for either.

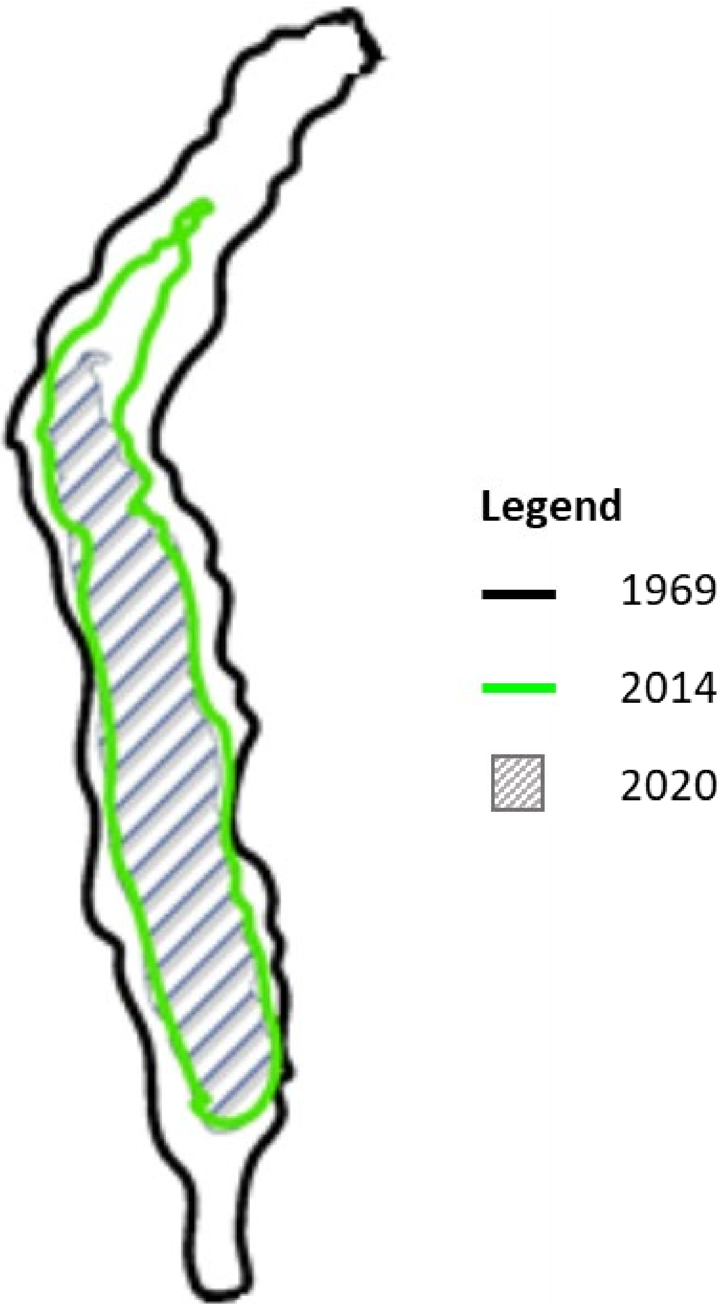


Figure 11.9 **Digitised wetland boundary for 1969, 2014 and 2020 showing the encroachment of the trees and shrubs during the period from 1969–2020**

Figure 11.10 Aerial photographs of the northern end of Lake Werri Berri showing the encroachment of shrub species from 2014 onwards (red arrows)

11.6 Seed bank germination experiment

All 30 soil samples (2 transects x 3 zones x 5 depths) had viable seeds, although not all seedlings survived until the experiment was terminated. The highest number of seedlings germinated from the Zone A samples in the centre of the lake and the lowest number from the Zone C samples closest to the continuous tree–shrub canopy layer (Figure 11.11). Monocot seedlings dominated the centre of the lake (Zone A) (Figure 11.12), while dicot seedlings dominated the drier edges (Zone C) (Figure 11.13).

Overall, there were differences in the number and type of seedlings that germinated from soil samples taken from the three different zones of Lake Werri Berri. For both zones within the centre of the lake (A and B), the highest number of seedlings (440 and 100 seedlings, respectively) germinated in the 0–10 centimetre depth zone and this was dominated by monocots, mainly rushes and sedges (Juncaceae and Cyperaceae; Figure 11.12).

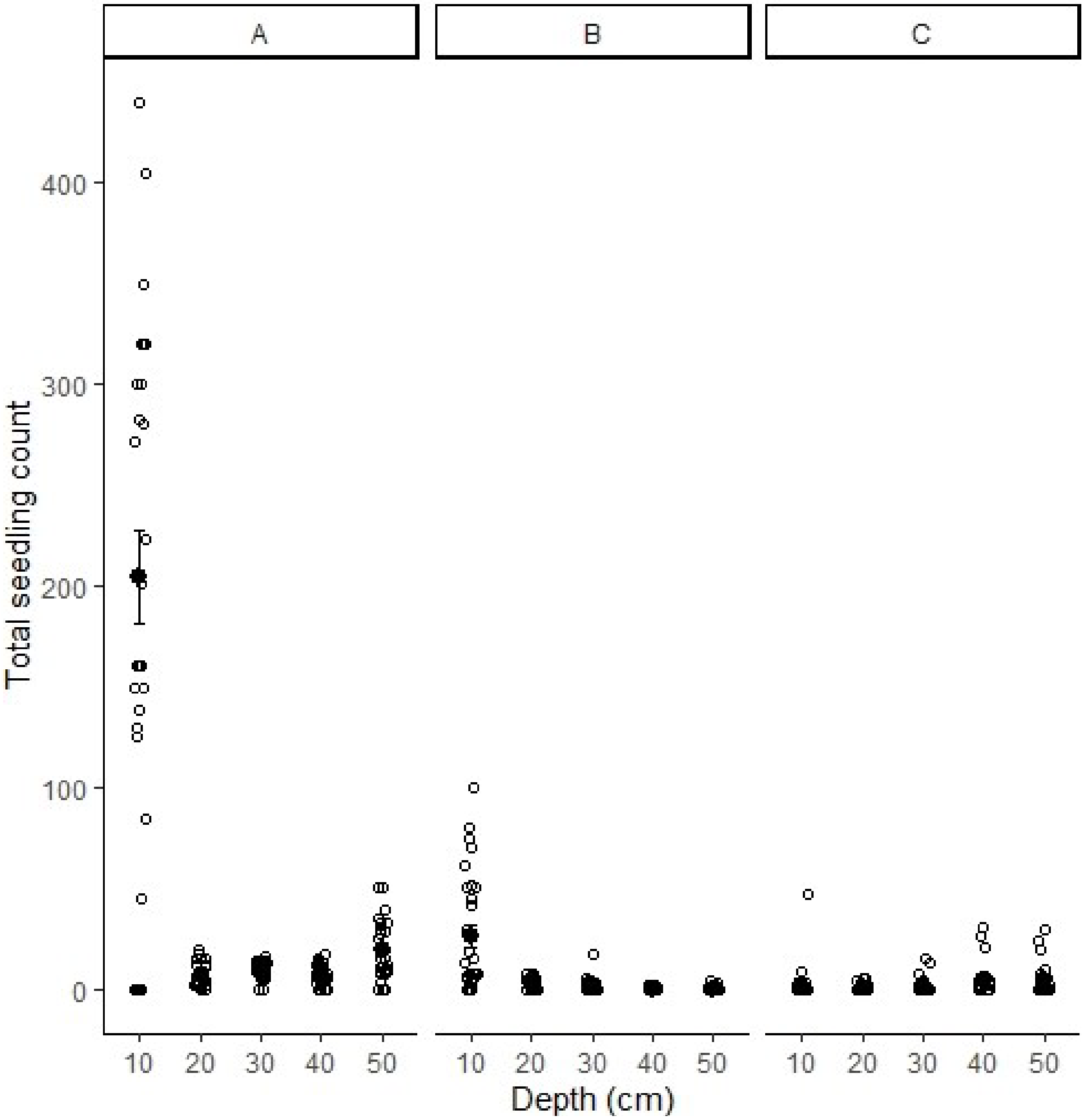


Figure 11.11 Total number of seedlings that germinated from each of six replicate samples from two transects from the three zones (A, B, C) within Lake Werri Berri for five different depths (0–10, 10–20, 20–30, 30–40, 40–50)

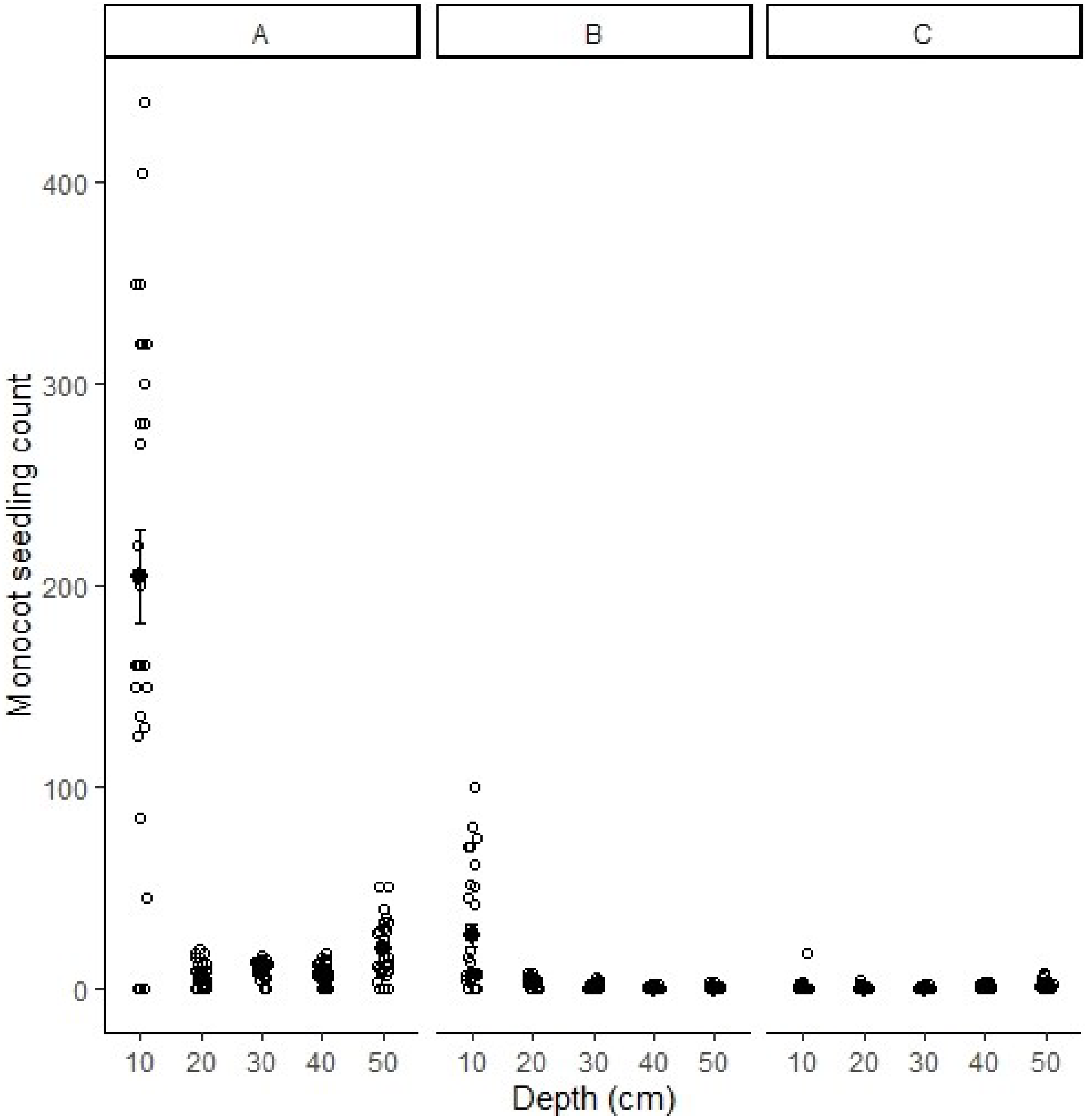


Figure 11.12 Number of monocot seedlings that germinated from each of six replicate samples from two transects from the three zones (A, B, C) within Lake Werri Berri for five different depths (0–10, 10–20, 20–30, 30–40, 40–50)

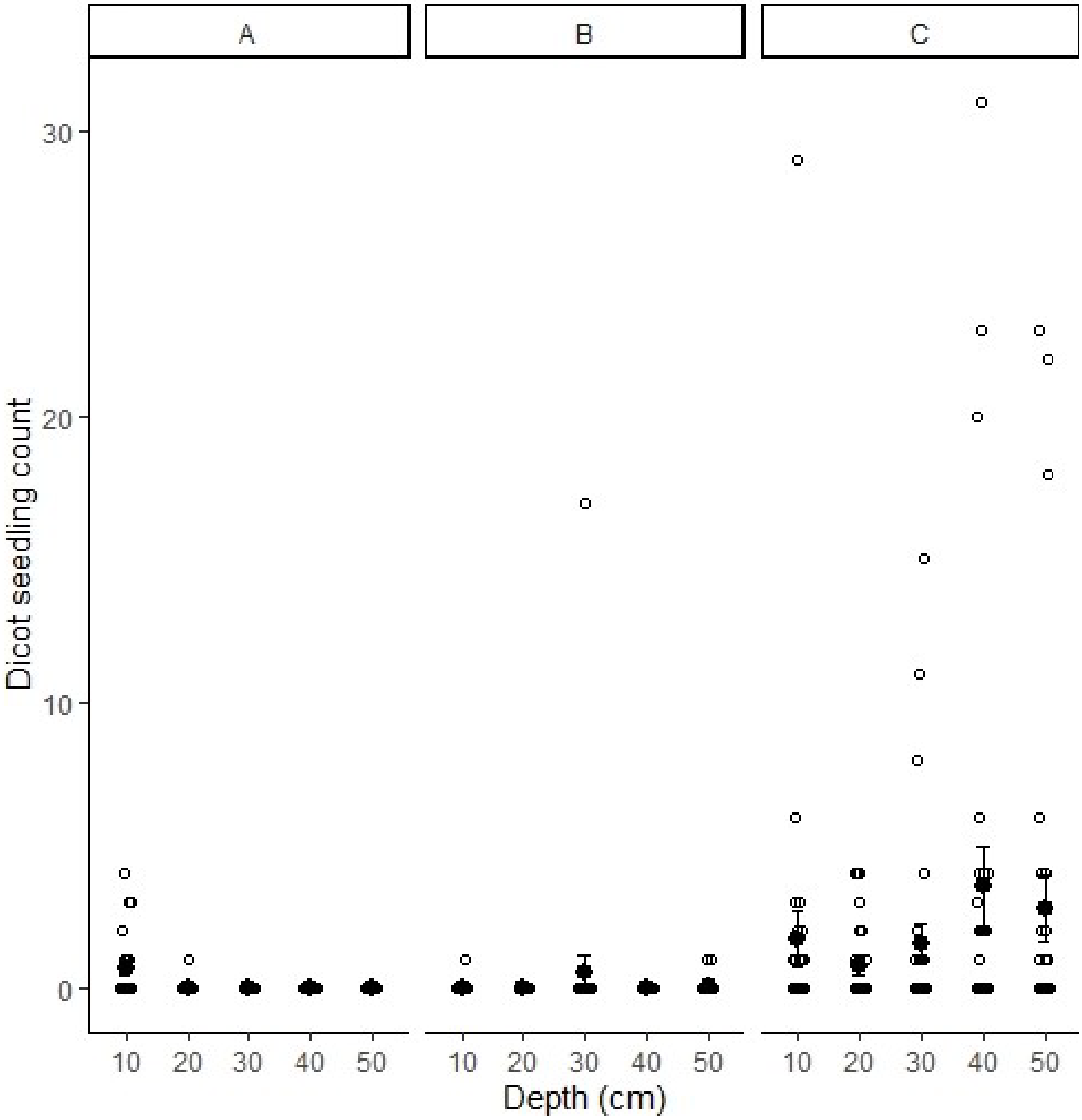


Figure 11.13 Number of dicot seedlings that germinated from each of six replicate samples from two transects from the three zones (A, B, C) within Lake Werri Berri for five different depths (0–10, 10–20, 20–30, 30–40, 40–50)

11.7 Discussion

This survey was the first 20 x 20 metre plot data recorded within the wetland boundary at Thirlmere Lakes National Park. Six species not recorded in previous surveys (Rose & Martin 2007; BioNet, accessed 6/9/2019) included *Gratiola pumilo, Juncus planifolius, J. prismatocarpus, J. usitatus, Isolepis inundatas* and *Viminaria juncea*. To highlight the diversity and variability of wetland plants, the author (JL) had previously sampled 1 x1 metre quadrats along the edge of Lake Werri Berri in 2001 and 2002 when water levels were high, and recorded a number of species that were not recorded in 2019, nor in previous surveys. These included *Juncus cognatus* (introduced), *Eleocharis sphacelata, Baumea arthrophylla, Lepidosperma longitudinale* and *Baloskion gracili*. The lack of wetland species recorded in the BioNet database is likely because its traditional focus has been on terrestrial vegetation, rather than the wetted areas within lake inundation zones.

The vulnerable species *Persicaria elatior* was also recorded and later observed growing in Zones A and B (November 2019, January 2020). The endangered dwarf kerrawang (*Commersonia prostrata*) was observed in February 2020 growing at the southern end of the lake.

Analysis of the aerial photographs of Lake Werri Berri since 1969 identified that *Lepironia* distribution occurs towards the edge of the water inundation zone and does not occur in the deeper parts of the lake (Zone A). This agrees with Harden's (1993) records of it growing in a maximum water depth of 1 metre in New South Wales, although it has been recorded considerably deeper (up to 5.5 metres) in Queensland wetlands (Bensink & Burton 1975; Marshall & McGregor 2011).

Lepironia articulata is resilient to changing conditions and changes in hydrology. Its decline in area between 2002 and 2010 coincided with the Millennium Drought and it subsequently increased in area after the rain events in 2013. Field observations also found *Lepironia* occurring between Lakes Werri Berri and Couridjah and Gandangarra that was not observed in the available high-resolution aerial photography. Anecdotal observations identified water flow from Lake Gandangarra to Lake Werri Berri during the 2016 east coast low, the February 2020 and the March 2021 rain events (M Krogh, *personal observations*). This water exchange was not evident in the available aerial photography.

While limitations in the accuracy of the water surface area calculations are noted, the relative water surface area in Lake Werri Berri reflected the variable climatic conditions across New South Wales and Australia more broadly (especially during the Millennium Drought). The dry weather conditions, from the El Niño period from 2014–2016 and the extreme dry spell in 2019 to early 2020, are reflected in the very low water levels at Lake Werri Berri during this period, where the dry spell in 2019 to early 2020 led to all surface water being lost at Lake Werri Berri. The 2019 dry spell had the lowest annual rainfall (251.5 millimetres) on record in New South Wales and the highest mean temperature[42].

The relatively dry period from 2000–2010 enabled opportunistic trees and shrub seedlings to establish in the peat, and then continue to survive through to the 2018–19 dry period. The increased incidence of trees and shrubs in what had previously been a distinct zone of more frequent inundation dominated by rushes and sedges suggests a move towards a drier successional state. This included the establishment of shrubs such as the flaky-barked tea-tree *Leptospermum trinervium* and the flax-leaved paperbark *Melaleuca linariifolia* in areas of the lake that were historically inundated or dominated by emergent wetland species such as *Lepironia articulata*. The continuing growth of these native shrubs potentially indicates a response to the changes in hydrology over the past two decades. *Leptospermum trinervium* is considered a terrestrial species and is usually found widespread in heath, scrub and dry sclerophyll forests on well drained sand and sandstone-based soils of eastern Australia (Krauss 1994; VICFLORA, accessed 31/5/20) and is often associated with non-water dependent species (Hunter 2004; Hunter & Bell 2013). *Melaleuca linariifolia* grows in heath and dry sclerophyll forest as well as in moist or swampy ground (PlantNet, accessed May 2020).

The presence of trees and shrubs in the centre of the lake is not unprecedented in Lake Werri Berri. Anecdotal reports and photographs also show the presence of trees and shrubs in the centre of Lake Werri Berri in 1958–59 (Figure 11.14). These trees and shrubs likely established themselves during the long El Niño drought event of the 1940–50s, and were subsequently inundated and died with rain events in the mid-1950s (BoM 2020). This drying of the wetland and growth of woody vegetation, and then its subsequent decline when the water returned, reflects the dynamic nature of the wetland vegetation. The encroachment of woody vegetation into this herbaceous wetland acts as an early indicator of a regime shift to a drier successional state, which is typical of many wetland systems.

[42] Climate change and variability: Tracker: Australian timeseries graphs (bom.gov.au) (accessed 15/7/2021).

Figure 11.14 Photograph of Lake Werri Berri in 1958–59 showing trees growing in the centre of the lake

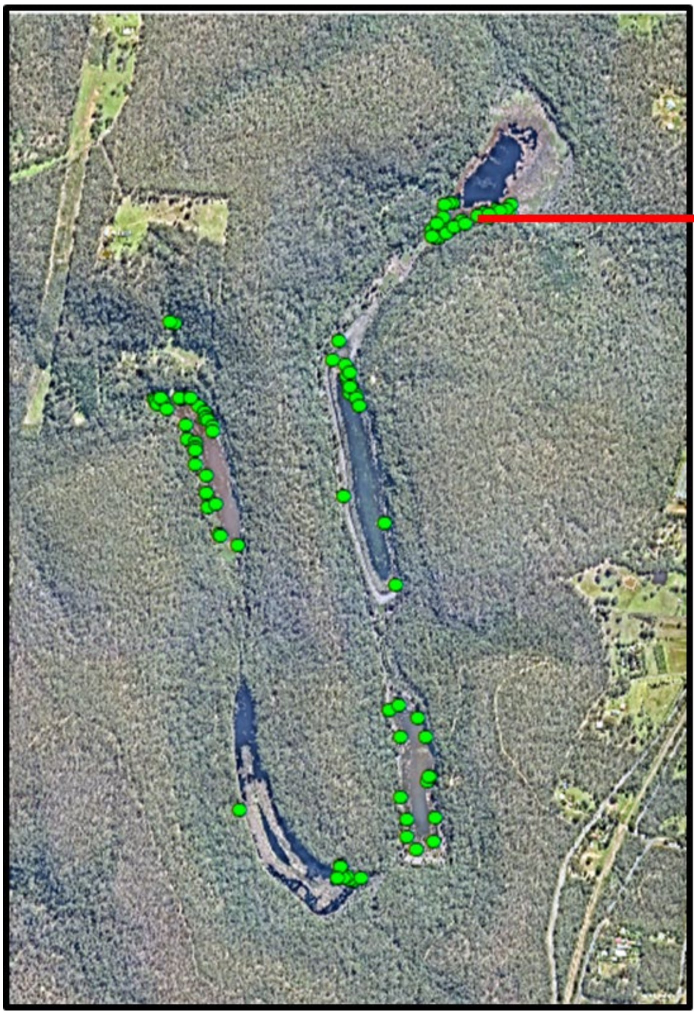
Photograph courtesy Philip Pells

In the germination experiment, there was evidence of a viable soil seed bank from all zones of Lake Werri Berri at all depths (up to 50 centimetres deep). Viable seedlings occurred more frequently in the inundated zone of the wetland (Zone A) and in the top 10 centimetres of the sediment. Most seedlings germinated within the first 25 days of incubation with a decline in the number of seedlings until about day 54 when abundances stabilised.

Seeds have a limited viable lifetime within wetland sediments; hence, the longevity of the seed bank of amphibious plants is important to their survival, especially in temporary wetlands (Brock 1998, 2011; Leck & Brock 2000). Seed banks of some wetland plant species have been shown to still be viable after 10–12 years (Brock 2011; Kelleway et al. 2020). As a pilot project, sediment depth was assumed to be a proxy to the age of the sediment; however, this assumption requires further investigation since it was observed that large cracks and fissures (especially in Zones A and B) likely resulted in mixing of the sediment layers and seed banks during the 2018–19 drying phase. Sediment ageing of deeper sediment samples has been completed (Cohen et al. 2020) but not at the shallow depths used for this seed bank project.

Identification of the seedlings to genus/species was compromised by several factors, with none of the seedlings having matured within the 106-day period of the experiment. The dicotyledons did not survive beyond the germination phase due to the waterlogged inundation regime and most monocotyledons did not grow to maturity (fruiting) within the six-month window, despite transplantation to potting mix. Future studies could consider various water regimes to account for the different inundation requirements of different species. The limited number of monocots that could be identified included *Isolepis inundata*, *Philydrum lanuginosum*, *Lepidosperma laterale*, *Juncus prismatocarpus* and *J. planifolius*. Interestingly, no *Lepironia* grew from seed despite dominating the cover of extant vegetation. Further investigation of the genetic composition of *Lepironia* at a local and regional scale is currently underway. Harvesting of current seed populations to determine viability is also recommended. Seed bank germination studies from other areas of Thirlmere Lakes, including areas that have potentially not been inundated for 50 years, would also be interesting. This preliminary seed bank study highlighted the resilience of the seed bank to recent periods of drought and the resilience of the wetland vegetation community with subsequent inundation.

The use of mobile technology for data collection as part of the citizen science program was found to be an ideal method to help verify wetland species and confirm the presence of individual *Lepironia* tussocks and tree and shrub species in the usually wetted areas of Thirlmere Lakes (e.g. Figure 11.15 & Figure 12.1). The main issues with the mobile application identified by the community members were primarily technical, since the application could only be downloaded on android devices, with associated issues when the mobile device was old/out-dated. Resolution of these issues might include funding for project specific android devices, with the application pre-installed. COVID-19 restrictions and lack of accessibility due to high water levels, especially in Lake Baraba, prevented more extensive surveying. Management of the data (including photographs) is also labour intensive and should be considered in the resourcing of future surveys/monitoring. This preliminary citizen science study demonstrated the potential for citizen science projects like this to create continued community awareness and engagement in understanding and describing the wetland ecology of Thirlmere Lakes.



Location:	150°32'43.239"E 34°13'1.739"S
Field	Value
FID	57
Shape	Point
FieldProgr	Thirlmere Lakes monitoring
date	28/07/2020
StartTime	11:26:00 AM
laty	-34.217217
longx	150.545427
FieldStaff	PaulaRichardson
OtherField	Jennie Wiles
SiteID	Gandangarra
altitude	329
accuracy	5
WaterLevel	Edgeofwater
PlantsMost	Lepironiaarticulata
PlantsOthe	Noplants
comments	

Figure 11.15 Survey locations (green dots) mapped in 2020 to show distribution across Thirlmere Lakes, with an example of the information from one point

Figure 11.16 Locations (green stars) of common eastern froglet (*Crinia signifera*) recorded at Thirlmere Lakes in June and July 2020

12. Discussion

The *Thirlmere Lakes Research Program* was an innovative collaboration between government scientists and leading scientific researchers from UNSW, UoW and ANSTO. The overall aims of the program were to:

- provide a detailed understanding of the hydrological dynamics of Thirlmere Lakes
- use that knowledge to promote best management practices for Thirlmere Lakes and the national park
- collate existing and new knowledge on Thirlmere Lakes into a Thirlmere Lakes database
- transfer knowledge gained in the program to agencies, land managers, relevant stakeholders and the community, and
- maximise the educational and training opportunities of the program.

12.1 Coordination and management of the Thirlmere Lakes Research Program

An IAWG that included scientists from the department, OCSE, DPE Water and Sydney Catchment Authority was initially tasked with providing the strategic direction for research into the hydrology of Thirlmere Lakes. This resulted in a knowledge gaps assessment report (*The Mysterious Hydrology of Thirlmere Lakes,* OEH 2016) and recommendations to seek proposals for research collaborations that addressed the key knowledge gaps.

Researchers with relevant expertise were subsequently invited to submit proposals focused on the program's themes and topics. In June 2017, formal research agreements were established with the successful proponents: UNSW, UoW and ANSTO. Researchers from these organisations were asked to collaborate to help fill the key knowledge gaps.

The five research themes of the *Thirlmere Lakes Research Program* were:

- Geological mapping and geophysical surveys of the Thirlmere Lakes area (UNSW – Lead Researchers: Dr Wendy Timms/Dr Martin Andersen)
- Environmental isotopes investigations into periodic and recent water losses from Thirlmere Lakes (ANSTO – Lead Researcher: Dr Dioni Cendón)
- Thirlmere Lakes: the geomorphology, subsurface characteristics and long-term perspectives on lake-filling and drying (UOW – Lead Researcher: Dr Tim Cohen)
- Surface water – groundwater interaction (UNSW – Lead Researcher: Dr Martin Andersen)
- Developing an integrated water balance budget for Thirlmere Lakes to provide a detailed understanding of hydrological dynamics (UNSW – Lead Researcher: Associate Professor Will Glamore).

The IAWG provided continued oversight throughout the length of the *Thirlmere Lakes Research Program*, with the project management being undertaken by the department. The results and final reports from the researchers were peer-reviewed by an expert panel specifically set up for the program, consisting of George Gates PSM and Professor Neil Saintilan.

Throughout the duration of the program, regular updates to the community were provided through newsletters and a series of annual Science Days, where information and results from the research investigations were provided as they arose. Community feedback on progress was sought and questions encouraged. Presentations and demonstrations were also given to school groups and community organisations. The major findings of the *Thirlmere Lakes Research Program* are detailed below.

12.2 Major findings

Thirlmere Lakes are a unique and vulnerable ecosystem. The lakes are located near the top of the Blue Gum Creek catchment and have limited inflows from surrounding catchments. Their size and relatively shallow depths mean that minor changes in water levels can lead to the significant exposure of lakebed sediments.

The five lakes of Thirlmere Lakes National Park lie within a deeply entrenched valley meander which is 'perched' above the Burragorang Valley to the west and the Cumberland Basin to the east. The biological significance of the lakes arises because only a small percentage of lakes reach this age without undergoing evolution to dry land and terrestrial ecosystems. The great age and geomorphic stability of Thirlmere Lakes have therefore enabled many aquatic organisms to evolve in isolation. The probability that the lakes are around 15 million years old makes Thirlmere Lakes an outdoor laboratory of considerable scientific importance. The aquatic habitats within Thirlmere Lakes National Park support many organisms that are restricted or almost restricted to this one lake system.

The depth of unconsolidated material under the lakes is greatest at the Lake Nerrigorang end of Thirlmere Lakes and is in the order of 30–40 metres (268–282 metres AHD). At the Dry Lake/Lake Gandangarra sill the depth of fill is ~15 metres (295 metres AHD). This suggests a net western gradient in the underlying bedrock, presumably representing past river gradients of the valley prior to uplift and prior to the formation of the lakes. The age of the alluvial fill valley within the Thirlmere Lakes is at least 300,000 to 500,000 years, but this represents a minimum age only as these dated samples come from one-third to half the depth of the valley fill sequence (Cohen et al. 2020).

The Thirlmere Lakes have become separate lakes via alluvial fan aggradation that has formed sandy or organic sills separating the five lakes. Both lake floors and the sills have been aggrading through time, but the existing chronology would suggest the lakes have become distinct and separate waterbodies since the last interglacial (e.g. since 125,000 years ago; Cohen et al. 2020).

Water levels and volumes in the Thirlmere Lakes are primarily reliant on rainfall in the catchment because (Chen et al. 2020):

- the lakes are near the top of the catchment and have limited inflows from surrounding catchments
- the lakes have a small catchment area compared to their size
- there is a limited connection to deep groundwater, and
- the lakes are shallow, so even a minor change in water levels can lead to the significant exposure of lakebed sediments.

The recent droughts are not unprecedented and Thirlmere Lakes have dried intermittently over the last 120 years of records. Evidence of a major drying period for the lakes was also identified in the sediments and dated as far back as 12,000–21,000 years ago.

The available evidence suggests the Thirlmere Lakes waterbodies are highly susceptible to drying out. Previous droughts, including the Federation Drought, World War II Drought and the Millennium Drought have all seen extended periods of low or no water within the lakes. In recent times, these dry periods have been relatively short-lived and eventually the lakes have refilled, usually as a response to major rainfall events. The most recent of these major rainfall events have been the June 2016 east coast low, the February 2020 rain event (described as a trough with embedded low-pressure circulations) and the March 2021 rain event (described as a blocking high-pressure system in the Tasman Sea combining with a low-pressure system off north-west Australia feeding a large volume of moist tropical air into the east).

The lake sediments are comprised of an upper peat sequence that has started to accumulate over the last 12,000 years. These organic-rich sediments represent the modern Thirlmere Lakes and this unit varies in thickness from up to 5 metres in Lake Baraba to an average of ~2–3 metres in the other lakes. The peat layer has very low bulk density, very high moisture content and total organic carbon (TOC) contents of up to 40%, including fine charcoal and macrophyte remains. The sediments are also characterised by a large proportion of epiphytic diatoms and a substantial biogenic component (chironomids and midge remains). These attributes, combined with low $\delta_{13}C$ and $\delta_{15}N$ values, and C:N ratios of approximately 20, indicate a stable peat system in a swamp like setting, under the modern/Holocene climate (Cohen et al. 2020).

The Holocene peat unit grades into a distinct oxidised silty clay that underlies all lakes. This unit represents a distinctive marker horizon in the lake sediment formation and also varies in thickness across and within a given lake. This unit has been dated in two lakes (Lake Couridjah and Lake Werri Berri) to be 21,000 to 12,000 years (the last glacial maximum [LGM] and the deglacial) and represents evidence of a significant hydrological change, where Thirlmere lakes dried and the lake sediments were sub-aerially exposed and weathered (oxidised). This unit signifies *catastrophic drying* at Thirlmere Lakes at the time and it also currently acts as a local aquitard, based on the obvious saturated zone of sediment immediately overlying it (Cohen et al. 2020).

The oxidised silty clay layer unconformably overlies older lake sediments that are 60,000 to 100,000 years in age. The lake sediments are also characterised by episodic sandy lenses that have been deposited from the hillslopes into the centre of the lakes suggesting significant past erosion events. Such events are most likely linked to past fire as charcoal concentration is often, but not always, high in these deposits. There is a repetition of the organic and less organic facies at Thirlmere Lakes down sequence and the chronology would suggest up to three interglacial cycles of (discontinuous) lake sedimentation (Cohen et al. 2020).

When the lakes go dry at the surface and expose the uppermost peat sediments, there can still be significant amounts of water contained within the underlying peat. The water storage capacity of the peat in Lake Baraba was calculated to be more than three times the surface water volume recorded after the east coast low rain event in June 2016 (see Chapter 9 and Cowley et al. 2020). As drying continues, the water level in the underlying peat also declines. This peat water storage then needs to be refilled before surface water starts reappearing in the lakes. This was particularly evident in the February 2020 rainfall event.

Evidence from deep boreholes confirmed the presence of the Bald Hill Claystone approximately 100 metres below the lakes; however, it was found that the Bald Hill Claystone may not possess the aquitard properties previously assigned to it.

Prior to the *Thirlmere Lakes Research Program* there was uncertainty as to the depth and extent of the Bald Hill Claystone under the lakes. The deep boreholes drilled near Lake Nerrigorang confirmed the presence of the Bald Hill Claystone approximately 100 metres below the surface. However, mineralogical, chemical and mechanical analysis of Bald Hill Claystone core samples supplied from the installation of the department deep monitoring wells near Lake Nerrigorang, showed the claystone was brittle and unlikely to ‘self-heal’ where it is fractured. This means it is likely to be a poor aquitard, a result that contrasts with previous assessments and industry reports that assume the Bald Hill Claystone is an effective aquitard (McMillan et al. 2021).

No direct geological link (e.g. surface to coal seam faulting) between Thirlmere Lakes and Tahmoor Colliery was identified during the geological investigations. Faults and igneous intrusions have, however, been mapped in the seam-level workings of Tahmoor Colliery at a depth of about 400 metres. Further research is required into the potential for subsidence to interact with faults or cause regional movement on geological structures and the potential consequences this may have, especially in the vicinity of important natural wetlands like Thirlmere Lakes.

The geology report found that the strike direction of the two major fault zones identified at the surface at Thirlmere Lakes did not intersect with the mined longwall panels at Tahmoor Colliery or the associated subsidence zones. Additional lineaments were identified that intersected with the subsidence zone of the mine although these particular lineaments were not identified to come near Thirlmere Lakes. No evidence was found to classify these lineaments as volcanic intrusions nor displacement demonstrated to indicate geological faulting. However, the absence of evidence is not necessarily evidence of absence and linear geological features will exist (i.e. transverse faulting, small-scale displacement faults, or volcanic intrusions) at most if not all of these locations, but have simply not been able to be formally classified in the current set of studies (McMillan et al. 2021). Faulting at the coal seam level at Tahmoor Colliery has previously been identified (Pells & Pells 2017), but no linkages between faults in the coal seam and faults at the surface were found in the geology study (McMillan et al. 2021).

The Independent Expert Panel for Mining in the Catchment (IEPMC, 2019a,b) discussed geological structures, noting that a range of natural features and mining-induced deformations and their interactions needed to be carefully considered when assessing subsidence impacts on groundwater and surface water systems. This included the potential for mining to reactivate geological structures and/or enhance their conductivity and capacity to redirect fluid flow. There is increasing recognition of the potential for geological discontinuities to act as or become conduits for groundwater flow. Further research is required into the potential for subsidence to cause regional movement on pre-existing geological structures and the potential consequences this may have for groundwater and surface water systems, especially important natural wetlands like Thirlmere Lakes.

In the absence of evidence of direct hydrological links between the surface and the coal seams, movement of water through the rock strata will largely depend on the permeability/conductivity of the strata involved and the degree to which the lake system is connected with or disconnected from the groundwater aquifers. Over the period of study, the surface–groundwater connectivity study (TLRP2) found most parts of the lakebeds to have limited vertical groundwater–surface water connectivity at low lake levels. This suggests lake water levels were largely disconnected from the intermediate groundwater system in the Hawkesbury Sandstone during the relatively dry study period for the project. It is likely that under these conditions, the low-permeable lakebed layers were forming a ‘bottleneck’ controlling vertical flow and leakage (Anibas et al. 2021).

Since hydraulic conductivity in the clay layers and rock strata are usually very low (10^{-5}–10^{-7} metres per second or lower; see Pells & Pells 2012; Anibas et al. 2021), in the absence of fast flow pathways, water will move very slowly horizontally and vertically through the clay layers, Hawkesbury Sandstone and other strata underneath Thirlmere Lakes. Similarly, pressure changes in groundwater within the clays and shallow sandstones will likely occur very slowly, while changes at lower depths may be larger and faster. Unfortunately, due to the lack of consistent long-term monitoring of surface water and groundwater in appropriate areas and at different depths over time, it is still largely unknown how far and how fast the observed groundwater depressurisation over the longwall panels propagates to the west of the Tahmoor mining domain (i.e. towards Thirlmere Lakes). Time lags in groundwater responses at distance could be very important in determining impacts on the lakes themselves. It may also mean we are yet to see the full expression of mining-induced groundwater depressurisation in the area.

Input into the lakes is primarily rainfall-runoff from very small localised catchments and the main water loss from the lakes is evapotranspiration; together these are referred to as climatic factors. The water balance assessment suggests the primary driver of water level variation over the period of study was climatic. The water balance model accounted for approximately 83–98% of lake level variation during the period studied.

The water balance assessment (TLRP3, Chen et al. 2020) identified that the primary driver of water level variation over the period of study was climate. This was found to explain between 83 and 98% of lake level variation over the period studied, without specifically modelling surface to groundwater losses. Over the period of study, the surface–groundwater connectivity study (TLRP2, Anibas et al. 2021) found most lakebeds to have downward hydraulic gradients but limited downward seepage to groundwater at low lake levels for the sites studied, due to the low permeability of the lakebeds. This suggests that lake water levels had no fast flow path to the intermediate groundwater system in the Hawkesbury Sandstone. The implication is that lake water levels were largely disconnected from the intermediate groundwater system in the Hawkesbury Sandstone during the relatively dry study period for the project.

Whilst evaporation and transpiration dominated losses across all lakes during the drying period that persisted until early 2020, there remains a component of losses from each lake to groundwater. The proportions appear to be different for each lake and its stage of drying. While groundwater exchange is not the dominant process for the lakes, it can nevertheless still exert an influence on lake levels.

There is a large head difference between the alluvial groundwater and the piezometric head in the underlying Hawkesbury Sandstone that has persisted for the period of records. This occurs in wet and dry periods alike. Spatially variable downward gradients were identified in the study indicating there was some leakage from the Thirlmere Lakes into the underlying Hawkesbury Sandstone. This conclusion is supported by the findings of ANSTO (TLRP5, Peterson et al. 2020) who found the proportion of waters lost to groundwater appears to be different for each lake and its stage of drying. Apparent groundwater ages, isotopes and chemistry show that all deeper groundwater sampled (>20 metres) at the lakes and within the region is distinct from lake and shallow groundwater (<20 metres; Peterson et al. 2020). Any impacts on the lakes' water balance caused by changes to the groundwater system immediately below will likely depend on the degree to which the lake system is connected or disconnected. The state of connection between surface water and groundwater likely varies over time depending on whether the region is in a dry or wet climatic phase.

It remains unclear how fast and how far groundwater depressurisation above Tahmoor Colliery longwalls propagates to the west (i.e. towards Thirlmere Lakes). There is limited baseline data on groundwater levels prior to the mining that went closest to the lakes and there has been limited monitoring of groundwater levels between the mine and the lakes. Significant time lags in groundwater response at distance and the slow movement of water through rock strata (i.e. low conductivities) may mean the full effects of such depressurisations are yet to express themselves.

Groundwater responses to underground longwall mining are complex and can include increases in overburden transmissivity, declines in groundwater levels, increases in water level fluctuations, and decreases in spring flow (Krogh 2007). Unfortunately, due to the lack of consistent long-term monitoring of surface and groundwater in appropriate areas over time, it is still largely unknown how far and how fast the observed groundwater depressurisation over the longwall panels propagates to the west of the Tahmoor mining domain (i.e. towards Thirlmere Lakes). Recent groundwater monitoring at TNC36 identified relatively small impacts when mining was ~1.5 kilometres south of TNC36 (i.e. during mining of LWs 29–32). More recent mining of LW W1 (~500 metres east of TNC36) has now led to significant changes to aquifer levels in TNC36 (see Chapter 3 and SLR 2021). Time lags in groundwater responses at distance could also be very important in determining impacts on the lakes themselves and when they might become identifiable. Groundwater modelling for the Tahmoor South proposal (3–4 kilometres east of Thirlmere Lakes) predicted drawdowns in the Hawkesbury Sandstone (i.e. beneath the Thirlmere Lakes/Blue Gum Creek alluvium), peaking between one and five metres with maximum drawdown at the lakes due to Tahmoor South predicted to occur in 2070–2100 (i.e. 50–70 years in the future; HydroSimulations 2018, 2020). Such time lags in response to mining-induced groundwater depressurisation may mean the full consequences of aquifer depressurisation as a result of earlier mining in the Tahmoor mining domain are yet to occur.

Unfortunately, there remains very limited baseline knowledge of what the groundwater level conditions or the state of hydraulic connection in the Thirlmere Lakes area were during the relatively wet period from 1945–1975, and prior to mining commencing nearby. Higher groundwater levels would likely drive increased recharge contributions to the lakes, but this is a complex function of antecedent soil moisture conditions, rainfall amount and intensity (controlling how much rainwater will infiltrate or run off), and groundwater flow down the catchment.

Potential impacts from underground mining on the Thirlmere Lakes' water balance can be speculated based on accepted physical principles. For example, if the lake–groundwater system is connected to the Hawkesbury Sandstone groundwater systems then a decrease in the alluvium groundwater heads due to mining impacts will be directly related to an increase in the leakage rates from the lakes. In contrast, if the lakes are disconnected from the deeper groundwater systems in the sandstone, then changes in pressures or heads at depth are unlikely to have a direct effect on the leakage rates from the lakes or their water levels. Under such conditions, the low-permeability lakebed layers would form the 'bottleneck' controlling vertical flow and leakage (Anibas et al. 2021).

Longer-term monitoring of surface water, shallow groundwater and deeper groundwater is required to investigate surface water interactions with the shallow and deep groundwater aquifers under wetter climatic regimes. Improvements in the monitoring of regional groundwater aquifers is also needed.

Over the last five years, Thirlmere Lakes have experienced three major filling events: the June 2016 east coast low rain event, and the February 2020 and March 2021 rain events. Under future climate projections, New South Wales is expected to become hotter, and wetter in the north-east and drier in the south-west, with an increase in heatwaves and heavy rainfall.

Over the last 120 years, Thirlmere Lakes have oscillated between being dry (during droughts) and being relatively full (after major rainfall events). Over the last five years, Thirlmere Lakes experienced three major filling events: the June 2016 east coast low rain event, and the February 2020 and March 2021 rain events. Water levels in the lakes increased by between one and two metres in response to these events. The lakes behaved independently of one another until levels reached the point where connectivity between some lakes was established (lake levels higher than the intervening sills). Differences among lake responses to these events depended on the intensity and duration of the rainfall and whether the peat store was relatively full of water or the levels had been lowered significantly in response to drought. If the peat store water levels had been lowered, this peat water storage needs to be refilled before surface water will start reappearing in the lakes.

It is difficult to predict exactly how Thirlmere Lakes will respond to a changing climate, but it is likely the lakes will continue to oscillate between being dry (or nearly so) and maintaining higher water levels, largely dependent on the occurrence of droughts and the frequency, intensity and duration of major rainfall events.

Under future climate projections, New South Wales is expected to become hotter, and wetter in the north-east and drier in the south-west, with an increase in heatwaves and heavy rainfall. It is difficult to predict exactly how Thirlmere Lakes will respond to a changing climate, but it is likely the lakes will continue to oscillate between being dry (or nearly so) and maintaining higher water levels, largely dependent on the occurrence of droughts and the frequency, intensity and duration of major rainfall events. NARCliM (NSW and ACT Regional Climate Modelling) projections are being explored to try and understand what future climate changes may mean for the lakes.

The lake vegetation and aquatic fauna populations vary considerably in their individual responses to the major fluctuations in lake levels.

Vegetation and fauna populations vary considerably in their responses to lake levels. During the relatively dry period from 2000–2019, terrestrial plant species, including shrubs and trees, were found to have encroached into areas previously inundated and dominated by wetland species. After the recent rains of March 2021, these trees and shrubs are now inundated and it is likely they will subsequently die as a result. This is not the first time this has occurred, with photographic evidence from the 1950s showing dead trees in the centre of Lake Werri Berri (see Chapter 11). It is hypothesised that these trees may have established themselves during the World War II Drought, only to die after subsequent rainfall and inundation.

The aquatic fauna and flora are particularly vulnerable to periods of drought when all surface water may disappear and the peat at the surface becomes dried and desiccated. Despite the lack of water at the surface, water can still be found in the peat and, in the early phases of drying, wombats were observed to have dug down into the peat to access water. As the peat dries further, water levels in the peat continue to decline and large cracks and fissures can appear in the surface of the peat. Even though the lakes become dry at the surface, with no surface water available, the dry lake sediments are expected to hold viable egg banks (Kobayashi et al. 2018) that would lead to the emergence of the zooplankton community once it rains and the lakes refill. Dispersal and recolonisation by other macroinvertebrates (particularly those with an adult flying stage) is also likely to occur once the lakes refill.

This demonstrates that the Thirlmere Lakes wetlands are a dynamic ecosystem, with individual species responses varying according to climatic conditions and the frequency, extent and duration of inundation. Some species benefit from high lake levels and others from low lake levels. Some threatened species (e.g. dwarf kerrawang; Figure 12.1) appear to favour an intermediate zone and can potentially disappear from lake margins when lake levels are high.

Figure 12.1 Endangered dwarf kerrawang (*Commersonia prostrata*) growing at the southern end of Lake Couridjah
Photo: M Krogh

12.3 Conclusions

As a result of the *Thirlmere Lakes Research Program* investigations we can say:

- the Thirlmere Lakes can effectively be thought of as a set of 'leaky bathtubs'
- the primary driver of water level fluctuations over the period of study has been climate (rainfall and evapotranspiration)
- we can account for a high proportion of the water level variability without factoring in losses due to human activity
- whilst evaporation and transpiration dominated losses across all lakes during the drying period that persisted until early 2020, there remains a component of losses from each lake to groundwater
- there is a clear separation in water levels in the shallow bores (at ~15 metres depth) and the deeper bores (at ~100 metres depth). There are also clear differences in water chemistry in the shallow bores, deeper bores and in mine water, and
- we cannot rule out smaller (relative to climate) impacts of human activities (mining and groundwater extraction) and we will probably never be able to do this because baseline data captured prior to mining are inadequate and groundwater extraction in the area has increased (i.e. there is no reliable benchmark against which we can measure change).

In the longer term (years to decades):

- mining impacts on regional groundwater may affect lake water levels by reducing inflows to the lakes and by increasing the hydraulic gradients away from the lakes. Such impacts may take decades to express themselves in a measurable way
- anthropogenic climate change may also impact lake levels by affecting patterns of rainfall, evapotranspiration, and fire frequency
- because Thirlmere Lakes are a dynamic system that is very responsive to climate, it is likely the lakes will continue to oscillate between being dry (or nearly so) and maintaining higher water levels, largely dependent on the occurrence of droughts and the frequency, intensity and duration of major rainfall events, and
- during periods of no or low water, the peat underlying the lakes is extremely vulnerable to desiccation and fire. Management of recreational access and fire during such times is particularly important.

13. Shortened forms

ACARP	Australian Coal Association Research Program
AHD	Australian Height Datum
ANSTO	Australian Nuclear Science and Technology Organisation
BoM	Australian Bureau of Meteorology
CSE	NSW Chief Scientist & Engineer
DECCW	former NSW Department of Climate Change and Water
The department	NSW Department of Planning and Environment (formerly NSW Department of Planning, Industry and Environment)
DPE Water	Water group in the NSW Department of Planning and Enviornment
DPI	NSW Department of Primary Industries
DPIE	former NSW Department of Planning, Industry and Environment (now NSW Department of Planning and Environment)
ENSO	El Niño–Southern Oscillation
EPA	NSW Environment Protection Authority
EPL	environment protection licence
ET	evapotranspiration
FPF	fault propagation fold
IAWG	inter-agency working group
IEPMC	Independent Expert Panel for Mining in the Catchment
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IPC	Independent Planning Commission
LF	lithostratigraphic formation
LM	lithostratigraphic member
LW	longwall
MWL	mean water level
NOW	former NSW Office of Water
NPWS	NSW National Parks and Wildlife Service
OCSE	Office of the NSW Chief Scientist & Engineer
OEH	former NSW Office of Environment and Heritage (now part of NSW Department of Planning and Environment)
OM	organic matter
PCA	principal component analysis
TALC	Tharawal Aboriginal Land Council
UNSW	University of NSW
UoW	University of Wollongong

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14.12 Chapter 12. Discussion

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Appendix A: Coal mining near Thirlmere Lakes

Table A.1 Longwall dates and dimensions

Source: HydroSimulations 2020

Long wall	Date start	Date end	Void width (m)	LW length (m)	Elevation of BUSM (mAHD)	Ground elevation (mAHD)	Cutting height (m)		Depth of cover (m)			Ratio width/depth			HOF Tammetta H (mAHD)	Depth to Tammetta H (m)
							Mean	Max	Min	Mean	Max	Min	Mean	Max		
Historical panels																
1	2/03/1987	16/08/1987	190	1050	–127	273.2	2.1	2.6	381	401	419	0.5	0.47	0.45	174.8	98.4
2	17/08/1987	26/11/1987	190	1050	–119	282	2.1	2.1	380	402	408	0.5	0.47	0.47	157.5	124.5
3	21/03/1988	16/11/1988	180	1120	–129.2	293.9	2.5	2.6	414	423	431	0.46	0.45	0.44	191.7	102.2
4	5/02/1989	4/06/1989	170	1130	–123	297.9	2.6	2.7	412	421	427	0.46	0.45	0.44	192.1	105.8
5	5/06/1989	3/12/1989	180	1200	–115.8	298.4	2.5	2.8	402	414	423	0.47	0.46	0.45	199.8	98.6
6	4/12/1989	21/04/1990	180	1200	–110.1	298	2.4	2.7	399	408	417	0.48	0.47	0.46	187.1	111
7	16/07/1990	28/01/1991	180	1200	–105.4	295.3	2.3	2.5	386	401	412	0.49	0.47	0.46	170.1	125.2
8	17/04/1991	5/12/1991	200	1640	–140.8	271	2.5	2.7	386	412	426	0.49	0.46	0.45	215.9	55.2
9	6/12/1991	26/07/1992	180	1220	–94.5	300.6	2.2	2.3	383	395	403	0.5	0.48	0.47	158.8	141.8
10A	27/07/1992	3/12/1992	230	770	–134.7	277.3	2.7	2.9	400	412	416	0.47	0.46	0.46	274.4	2.9
10B	4/12/1992	16/05/1993	230	710	–150.2	247.4	2.4	2.5	382	398	418	0.5	0.48	0.45	228.6	18.8
11	17/05/1993	21/01/1994	235	560	–142.5	266.2	2.8	2.9	381	409	417	0.5	0.46	0.46	296.5	–30.2
12	22/01/1994	7/07/1994	230	1030	–166.1	244.2	2.6	2.9	393	410	434	0.48	0.46	0.44	259.7	–15.5
13	8/07/1994	11/11/1994	230	830	–170.6	240.3	2.7	2.9	398	411	421	0.48	0.46	0.45	276.6	–36.3
14A	31/01/1995	15/06/1995	235	215	–75.3	313.7	2	2.1	388	389	390	0.49	0.49	0.49	189	124.7
14B	16/06/1995	26/06/1996	235	2150	–91.9	295.2	2.2	2.2	373	387	393	0.51	0.49	0.48	204.3	90.9
15	27/06/1996	7/09/1997	235	2650	–87.4	297.9	2.1	2.3	357	385	402	0.53	0.49	0.47	200.6	97.3
16	8/09/1997	15/02/1999	235	2675	–74.1	304.3	2.1	2.2	340	378	392	0.56	0.5	0.48	193.4	110.9
17	16/02/1999	21/06/2000	235	2555	–63.3	312.1	2.1	2.3	327	375	389	0.58	0.51	0.49	193.3	118.8
18	22/06/2000	2/10/2001	235	2360	–52.6	316.1	2.1	2.3	319	369	387	0.59	0.52	0.49	193.7	122.4
19	3/10/2001	29/09/2002	235	2175	–44.3	316.6	2.1	2.3	306	361	410	0.62	0.53	0.46	193.3	123.2
20	30/09/2002	11/09/2003	235	1445	–103.9	302.8	2.2	2.4	393	407	435	0.48	0.47	0.44	218.9	84

Long wall	Date start	Date end	Void width (m)	LW length (m)	Elevation of BUSM (mAHD)	Ground elevation (mAHD)	Cutting height (m)		Depth of cover (m)			Ratio width/depth			HOF Tammetta H (mAHD)	Depth to Tammetta H (m)
							Mean	Max	Min	Mean	Max	Min	Mean	Max		
21	12/09/2003	30/05/2004	235	1080	–97.4	308.1	2.2	2.3	400	405	409	0.47	0.47	0.46	215.7	92.4
22	2/06/2004	11/07/2005	283	1875	–142.8	282	2.2	2.3	414	425	441	0.46	0.45	0.43	258.4	23.6
23A	7/09/2005	20/02/2006	283	775	–156.7	278.8	2.2	2.2	428	435	449	0.44	0.44	0.42	252.6	26.2
23B	15/03/2006	21/08/2006	283	770	–141.8	289.6	2	2.1	415	431	451	0.46	0.44	0.42	232	57.6
24B	15/10/2006	26/08/2007	283	2260	–153.2	287.2	2.1	2.3	420	440	457	0.45	0.43	0.42	239.7	47.4
24A	15/11/2007	19/07/2008	283	980	–166.4	271.6	2.2	2.3	428	438	462	0.44	0.43	0.41	256.2	15.4
25	22/08/2009	27/02/2011	283	3580	–164.8	278.6	2.2	2.5	422	443	462	0.45	0.43	0.41	252.4	26.1
26	30/03/2011	11/10/2012	283	3480	–175.3	274.4	2.2	2.5	422	450	474	0.45	0.42	0.4	259	15.5
27	8/11/2012	22/03/2014	283	3030	–183.3	272.6	2.2	2.5	424	456	491	0.45	0.42	0.39	263.9	8.7
28	24/04/2014	17/05/2015	283	2620	–196.7	263	2.2	2.3	421	460	513	0.45	0.41	0.37	253.2	9.9
29	29/05/2015	13/04/2016	283	2310	–209.5	255.8	2.2	2.3	424	465	498	0.45	0.41	0.38	257	–1.2
30	26/05/2016	13/04/2017	283	2310	–221.9	250.8	2.2	2.3	430	473	506	0.44	0.4	0.38	255.1	4.3
31	20/04/2017	17/08/2018	283	2340	–234.1	240	2.1	2.2	434	474	512	0.44	0.4	0.37	239.2	0.8
32	28/11/2018	29/08/2019	283	2376	–252	235.2	2.2	2.5	474	487	502	0.4	0.39	0.38	260.2	–25.1
Proposed panels																
W1	Oct-19	Aug-20	283	1870	–283	235	2	2.1	474	518	547	0.4	0.37	0.35	242.1	–7.1
W2	Aug-20	Apr-21	283	1675	–281	235	2	2.1	474	518	547	0.4	0.37	0.35	242.1	–7.1
W3*	May-21	Dec-21	283	1425	–266.5	236.3	2	2.1	472	503	531	0.4	0.38	0.36	229.5	6.7
W4*	Dec-21	May-22	283	915	–253.6	230.9	1.9	2	455	484	516	0.42	0.39	0.37	214.8	16.1

Notes:

LW = Longwall. BUSM = Bulli Coal seam. HOF = Height of (Connected) Fracturing (estimated using H calculated from Tammetta, 2013, as recommended in IEPMC, 2018).

*Mine plan for W3 and W4 is preliminary at this stage.

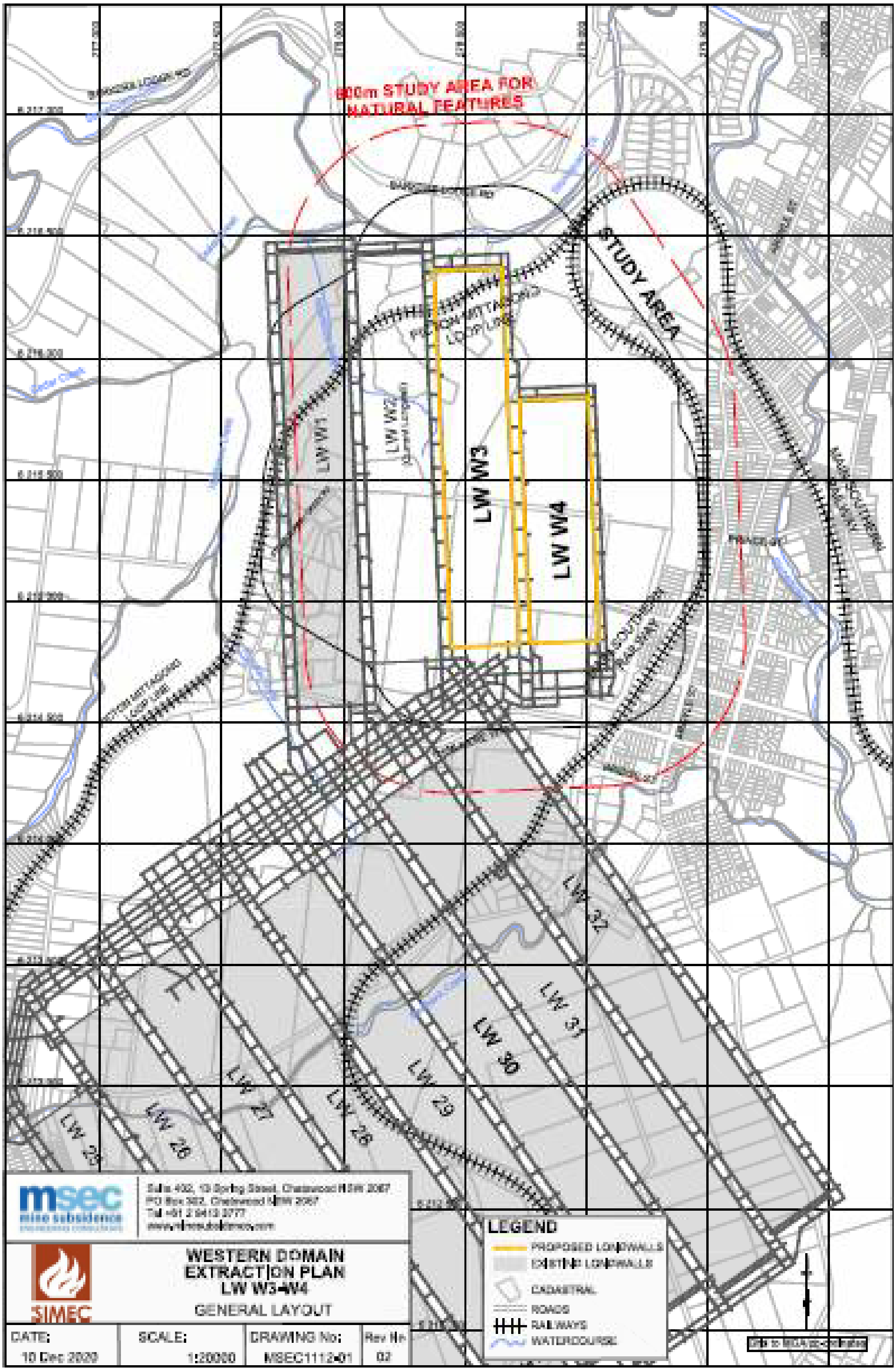

Figure A1.1 **Approved and proposed longwalls in Tahmoor North Area**

Source: MSEC 2021

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Appendix B: Wetland vegetation of Lake Werri Berri

Table B.1 Plant species list recorded from 20 x 20 m plots in Lake Werri Berri on 4 September 2019

WPIL (water plant indicator list) codes and WPFGs (water plant functional groups) from Ling et al. (2019).

Family	Scientific name	Common name	Zone	WPIL code†	WPFG†
Scrophulariaceae	***Gratiola pumilo* F.Muell.**		A B	1.67	Tda
Juncaceae	***Juncus planifolius* R.Br.**		A B	1.9	ATe
Juncaceae	***Juncus prismatocarpus* R.Br.**		A B	2.15	ATe
Juncaceae	***Juncus usitatus* L.A.S.Johnson**		A B	1.67	ATe
Cyperaceae	*Lepironia articulata* (Retz.) Domin	Grey rush	A B C	1.65	ATe
Myrtaceae	*Leptospermum trinervium* (Sm.) Joy Thomps.	Flaky-barked tea-tree	A B	5	
Philydraceae	*Philydrum lanuginosum* Banks & Sol. ex Gaertn.	Woolly waterlily, frogsmouth	A B	1.65	ATe
Asteraceae	*Hypochaeris radicata* L. [E]	Catsear	A C	5	
Cyperaceae	***Isolepis inundata* R.Br.**		A	1.97	Atl
Polygonaceae	*Persicaria elatior* (R.Br.) Sojak [E]	Tall knotweed	A	2.33	ATe
Cyperaceae	Unknown Cyperaceae 1		A		
Cyperaceae	Unknown Cyperaceae 2		A		
Cyperaceae	Unknown Cyperaceae 3		A		
Dicksoniaceae	*Calochlaena dubia* (R.Br.) M.D.Turner & R.A.White	Rainbow fern	B	3.65	Tda
Asteraceae	Cassinia sp.		B	5	
Asteraceae	Gnathalium sp. [E]	A cudweed	B	5	
Halagoraceae	*Gonocarpus micranthus* ssp. *micranthus* Thunb.	Creeping raspwort	B C	2.67	Tda
Myrtaceae	*Melaleuca linariifolia* Sm.	Flax-leaved paperbark	B C	3.33	Tdr
Dennstaedtiaceae	*Pteridium esculentum* (G.Forst.) Cockayne	Common bracken	B	4.8	Tdr
Fabaceae (Faboideae)	***Viminaria juncea* (Schrad.) Hoffmanns**	Native broom	B C	2.42	Tda
Fabaceae (Mimosoideae)	*Acacia longifolia* (Andrews) Willd		C	5	
Asteraceae	*Cirsium vulgare* (Savi) Ten. [E]	Spear thistle	C	5	
Phormiaceae	*Dianella revoluta* R.Br.	Blue flax-lily	C	5	
Myrtaceae	*Eucalyptus piperita* SM.	Sydney peppermint	C	5	

Family	Scientific name	Common name	Zone	WPIL code†	WPFG†
Dennstaedtiaceae	*Histiopteris incisa* (Thunb.) J.Sm.	Bat's wing fern	C	5	
Apiaceae	*Hydrocotyle laxiflora* DC.		C	3.32	ATl
Cyperaceae	*Lepidosperma laterale* R.Br.		C	3.2	Tda
Myrtaceae	*Leptospermum polygalifolium* Salisb.	Tantoon	C	5	
Proteaceae	*Persoonia linearis* Andrews	Narrow-leaved geebung	C	5	
Ulmaceae	*Trema tormentosa* (Roxb.) H.Hara	Native peach	C	5	
Solonaceae	*Solanum prinophyllum* Dunal	Forest nightshade	C	5	

Species highlighted in bold have not been recorded in the NSW BioNet database (accessed 6/9/2019) within 10 kilometres of Thirlmere Lakes (see also Supplementary Table A).

E = exotic species; V = listed as vulnerable under the NSW *Biodiversity Conservation Act 2016*

Zone A: centre of lake – frequently inundated; Zone B: 25 metres from the centre of the lake – less frequently inundated; Zone C:at the edge of the continuous tree–shrub canopy layer – only inundated when the lake is full.

‡ WPIL codes: 1–2.99, wetland indicator species; 3–3.99, discretional wetland indicator; 4–5, non-wetland indicator species. † Water plant functional group abbreviations are Sk, k-selected; Se, perennial – emergent; ARf, amphibious fluctuation-responders – floating; ARp, amphibious fluctuation-responders – morphologically plastic; ATe, amphibious fluctuation-tolerators – emergent; ATl, amphibious fluctuation-tolerators – low growing; ATw, amphibious fluctuation-tolerators – woody; Tda, terrestrial: damp places; Tdr, terrestrial: dry places.

Table B.2 Area of *Lepironia* cover, surface area of water and the wetland area inside the wooded area was calculated from 20 high resolution aerial photographs from 1969–2019

Date	Area of *Lepironia* cover (hectares)	Surface area of water (hectares)	Wetland area inside the wooded area (hectares)	Annual rainfall (millimetres)
Jun-69	2.6737	10.3754	13.4495	1213.1
Jun-72	2.9151	10.5637	13.2662	826
1975	3.0478	10.2058	14.3624	833.2
Jun-79	3.5462	10.5359	14.0388	394.6
Aug-80	4.2836	10.8819	14.2889	584
Oct-83	2.6557	9.6792	13.545	918
Sep-90	3.7697	9.9828	14.4286	216.6
Oct-94	5.4219	12.5408	14.8753	Not available
Nov-00	2.9888	12.6194	14.2702	567
Jan-02	0.8386	10.5082	14.9071	538.6
Nov-04	1.7642	11.3082	14.0557	702.9
Oct-06	0.5891	8.799	15.847	461.5
Feb-10	0.4057	2.2303	10.9247	829.1
Oct-14	2.3159	5.0171	7.1116	705

Date	Area of *Lepironia* cover (hectares)	Surface area of water (hectares)	Wetland area inside the wooded area (hectares)	Annual rainfall (millimetres)
Jun-15	2.8577	0.8922	7.2607	749.6
Feb-16	1.906	3.5189	7.5787	768.7
Aug-16	2.0953	8.1467	7.4397	768.7
May-17	2.6061	7.7247	7.06	619.7
Feb-18	2.6812	3.8905	7.541	510.2
Jul-18	2.9797	0.1286	7.3741	510.2
Jan-19	2.5089	0	7.541	408.2
Jul-19	2.1843	0	7.1465	408.2

References

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