REPORT
ON THE WATER LEVELS OF THIRLMERE LAKES

P053.R1

OCTOBER 2011

Pells Consulting

Pells Consulting

ABN 74 978 620 434
Phone: 02 4381 2125
Fax: 02 4381 2126
The Old Post Office
49 Lakeside Drive
MacMasters Beach NSW 2251
www.pellsconsulting.com.au

Our Ref: P053.L3

19 October 2011

THE WATER LEVELS OF THIRLMERE LAKES

This report addresses the question as to why Lakes Gandangarra, Werri Berri, Couridjah and Nerrigorang contained almost no water as of October 2011; with Nerrigorang having dried completely by December 2009, and Gandangarra and Werri Berri by September 2011. Is this a natural, climate phenomenon, or have some other influences come to play?

This study has taken 12 months and has been funded only by Pells Consulting. Considerable assistance has been received from many members of the local community in the Picton-Thirlmere area.

Philip Pells
FTSE BSc(Eng) MSc DSc(Eng) FIEAust MASCE

Steven Pells
BE(Civil) Hons, MEngSc

CONTENTS

CHAPTER 1. INTRODUCTION, UNIQUE FEATURES, AND HISTORICAL BACKGROUND

1.1 Origins and Financing of this Study

This study had its origins in a chance conversation, in 2009, between Philip Pells and a friend who lives in Picton NSW, and who mentioned apparent unusual drying of the Thirlmere Lakes. Philip knew next to nothing about these lakes but was intrigued by claims that the lakes were unique in the geomorphology of the Sydney Basin, were part of the Greater Blue Mountains World Heritage area[1] (UNESCO, Ref 917, 2000), and were not far from longwall panels of Tahmoor Colliery (see Figure 1.1).

Few places, said to be unique, warrant that attribute, but after some background reading it became clear that the Thirlmere Lakes warrant that epithet. It also became clear that water levels in the lakes had dropped substantially over the past decade, to the extent that locals who had used the area for recreation were voicing concern in the media[2].

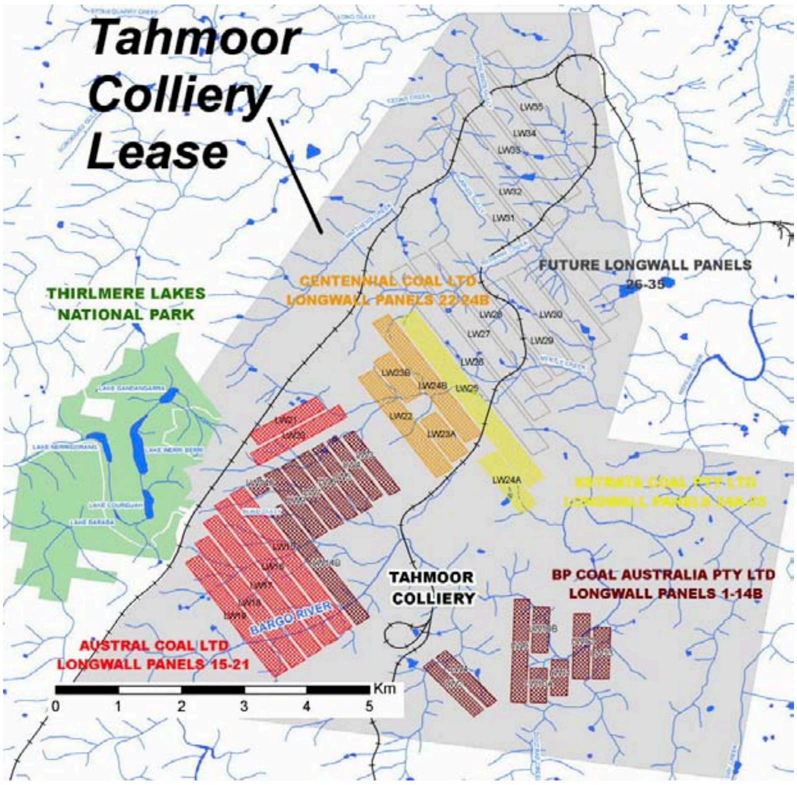


Figure 1.1: Thirlmere Lakes in relation to Tahmoor Colliery (from NSW Office of Water, 2010)

---

[1] *The Greater Blue Mountains Area consists of mostly forested landscape on a sandstone plateau inland from central Sydney, New South Wales. The property is made up of seven national parks as well as the Jenolan Caves Karst Conservation Reserve. These are the Blue Mountains, Wollemi, Yengo, Nattai, Kanangra-Boyd, Gardens of Stone and Thirlmere Lakes National Parks.*
The World Heritage Committee inscribed the Greater Blue Mountains Area under natural criteria (ii) and (iv), namely: Australia's eucalypt vegetation is worthy of recognition as of outstanding universal value. The site contains a wide and balanced representation of eucalypt habitats from wet and dry sclerophyll, mallee heathlands, as well as localised swamps, wetlands, and grasslands. (UNESCO, 2000)

[2] Macarthur Chronicle 2 March 2010.
Australian Broadcasting Corporation (ABC) News, 11 October 2010.
Sydney Morning Herald (SMH) 23 October 2010.

This study commenced in October 2010. It was not commissioned by any party and has been entirely funded by Pells Consulting. Throughout the study period we sought, and received, the co-operation of individuals and organisations having knowledge of, or particular interest in, the lakes. These included:

1. Parks and Wildlife Group (Office of Environment and Heritage, Department of Premier and Cabinet).

2. NSW Office of Water (Department of Trade and Investment, Regional Infrastructure and Development).

3. University of New South Wales, School of Biological, Earth and Environmental Sciences, (Dr Scott Mooney).

4. Macquarie University (Dr Patricia Fanning).

5. University of Wollongong, School of Earth and Environmental Science (Dr Chris Fergusson).

6. Rivers SOS.

7. Xstrata Coal.

8. The Rackleyft family (owners of land around Lake Nerrigorang from 1923 until sale to Parks and Wildlife).

Historical terrestrial photographs of the lakes were received from D.Hunt, J.Sheppard, P. Rackleyft, O. Johanessen, J. Pratchett, M. Juske, A. Jansz and Parks and Wildlife.

Major sources of factual data were:

(i) Annual Environmental Management Reports by Austral Coal, Centennial Coal, and Xstrata Coal, from 2004 to 2011.

(ii) Aerial photographs, purchased from NSW Land and Property Information Division.

(iii) Honours Thesis by Patricia Vorst (nee Fanning), 1974.

(iv) NSW Office of Water, Thirlmere Lakes Groundwater Assessment, 2010.

(v) Thirlmere Lakes National Parks. New Plan of Management, November 1997.

Other sources of factual information are cited at the appropriate points in this report.

Five progress reports were issued during the course of the study and made available, for information, to the eight groups listed above. The reports represented factual information collected during the progress of the study. No comments on those reports were expected, nor received. They are reproduced in their original forms in Appendices A to E of this report.

All analyses and all interpretations given in this report are the work of Pells Consulting. Critical analyses, particular the rainfall-runoff modelling of Chapter 5, have been reviewed by independent specialists.

The intention was to make this study as close to pure science as possible[3]. We have set out to separate facts from computations and interpretations. We think that others, given those facts, and using currently accepted methods of analyses, will reach the same conclusions we have documented. However, we remain cognisant of the nature of true science, as embodied in the following quotation:

> *"Contrary to popular belief, good scientists don't seek to prove a hypothesis true. We make every possible effort to prove it wrong by subjecting it to the most withering attacks we can dream up. This refusal to accept a new idea until it has run the gauntlet of testing is the very reason scientific 'truth' is as reliable.."*
>
> *Dr Paul Fitzgerald*
> *University of California, 2008.*

We would like to think that this study will survive the "gauntlet run", but that must still be faced and accepted.

1.2 Unique Geomorphology and Age

In the radar image from the Space Shuttle, the Thirlmere Lakes appear as a tiny, and apparently inconsequential U-shaped valley in the Southern Highlands; see Figure 1.2.

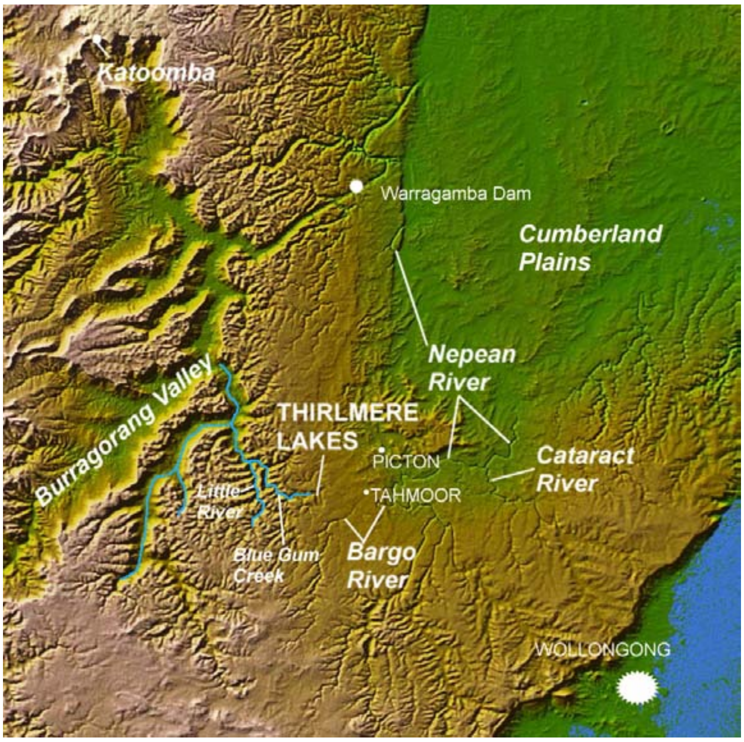


Figure 1.2: Space Shuttle radar image of southern part of the Sydney Basin.

---

[3] *Those long chains of reasonings, quite simple and easy, which geometers are accustomed to using to teach their most difficult demonstrations, had given me cause to imagine that everything which can be accompanied by man's knowledge is linked in the same way, and that, provided only that one abstains from accepting any for true which is not true, and that one always keeps the right order for one thing to be deduced from that which precedes it, there can be nothing so distant that one does not reach it eventually, or so hidden that one cannot discover it.*
Renè Descartes (1596-1650)

In this rather odd valley, are four lakes and one swamp-lake (see Figure 1.3). They are named, from upstream to downstream:

- Lake Gandangarra
- Lake Werri Berri
- Lake Couridjah
- Lake Baraba (a swamp-lake)
- Lake Nerrigorang

The local population know Werri Berri as the ‘boating lake’, Couridjah as the ‘swimming lake’, and Nerrigorang as ‘Rackleyft’s lake’[4].

There is also Dry Lake to the north of the Thirlmere Lakes. It is part of the Cedar Creek catchment.

Figure 1.3: 1:25,000 topographic maps of the Thirlmere Lakes.

Some of the locals refer to the lakes as the crystal lakes because the water was usually so clear that floors of the lakes could be seen through many metres of water[5].

When the railway reached the Picton-Mittagong area in 1863, the Thirlmere Lakes became a popular area for outings[6] from Sydney, rivalling train travel to the upper Blue Mountains. The lakes remained a popular recreation area for people from Picton, Tahmoor and surrounding towns until recent times (see Figures 1.4 and 1.5).

[4] The Rackleyft family owned the parcel of land that includes this land from before WW2 until they sold it to the State.

[5] Helen Rackleyft, personal communication.

[6] In February 1873, Henry Parkes, Premier of NSW, entertained 200 delegates, attending the Inter-Colonial Conference, to a luncheon in a marquee beside the lakes, after a journey by special train. (F.B. Knox, Camden Historical Society).

Figure 1.4: Lake Werri Berri, June 2008 (Julie Sheppard photo).

Figure 1.5: Lake Nerrigorang, 1980 (Olive Johanessen photo).

However, it is not their aesthetics that make the Thirlmere Lakes unique, it is their geomorphology and sedimentation history.

Figure 1.6 shows the drainage river flow directions in the vicinity of the lakes. However, they were not always so, and prior to the opening of the Tasman Sea, some 80 million years ago[7], Cedar Creek, and its tributary through Dry Lake, flowed in the opposite direction, through Thirlmere Lakes and down Blue Gum Creek.

[7] Branagan & Packham, Field Geology of NSW, 2000.

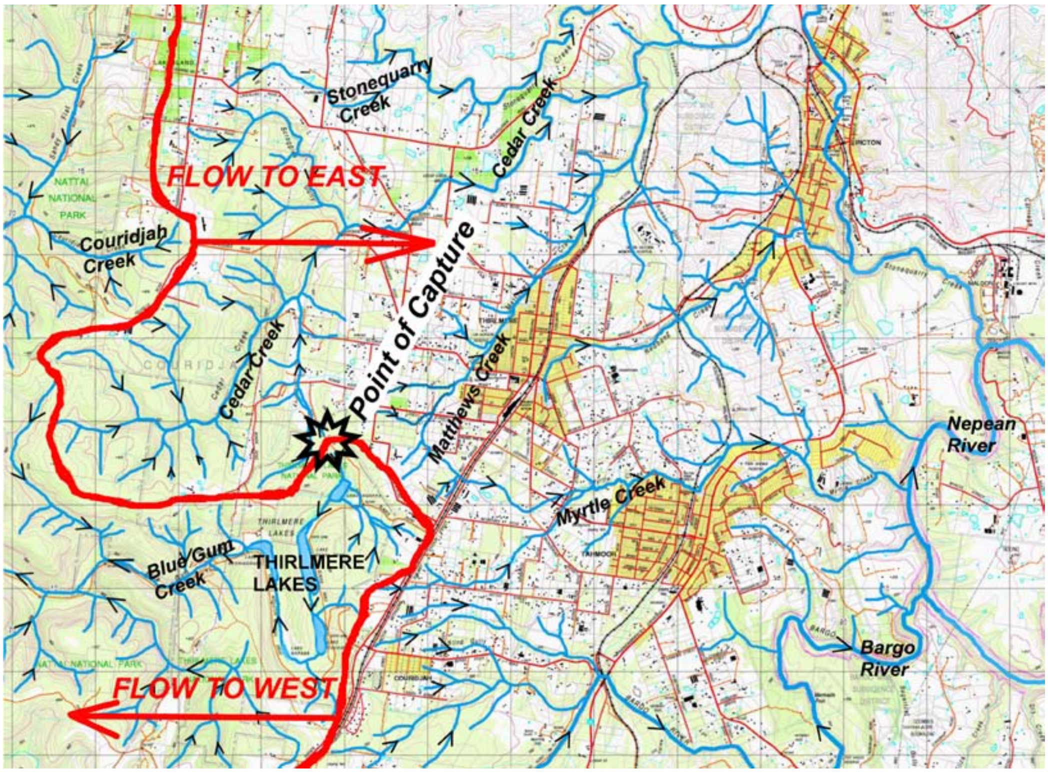


Figure 1.6: River flow directions.

Patricia Fanning[8] postulates an ancient "Thirlmere River", flowing from east to west, that carved out a paleovalley in which the lakes now sit, the lakes now being underlain by about 50m of Recent sandy clays and peats. The point of 'capture' of this 'Thirlmere River' is between Lake Gandangarra and Dry Lake (see Figure 1.6).

The key matter arising out of this geological history is that deep soils beneath the lakes provide a unique, continuous record of plant life, climate impacts, and the more recent impacts of humans, dating back to many hundreds of thousands of years.

Whilst Lake Baraba is of least concern to most of the community, because it is neither pretty nor useful, it is probably the most important of the lakes from the scientific viewpoint[9]. It is one of only 33 sites in the Australian, South East Asian and Pacific regions that have a record of vegetation during the last glacial maximum (ice age), 18,000 to 25,000 years ago. It provides a detailed source of information of plant and tree types, and fire records, to beyond 43,000 years ago. This information is important in understanding the impact of humans (Aboriginals and European) on the flora of SE Australia[10].

A detailed analysis of a 6.35m long continuous core from the lake bed, by Black et al, shows a major change in the stratigraphy at a depth of about 4m, where peat (60% to 90% organics), changes to black and yellow clays (< 20% organics). This change has been dated at about 8,000 years ago (see Figure 1.7).

[8] P. Vorst (nee Fanning) Honours Thesis "Thirlmere Lakes, N.S.W.: Geomorphic Environment and Evolution" Macquarie University, 1974.

[9] Black, M. P., Mooney, S. D. And Haberle, S. G. "*The fire, human and climate nexus in the Sydney Basin, eastern Australia*". The Holocane, Vol 17, No. 4.

[10] Black, M. P., Mooney, S. D. And Martin, H. A. "*A> 43,000 – year vegetation history from Lake Baraba, New South Wales, Australia*". Quaternary Science Reviews, Vol 25, 2006.

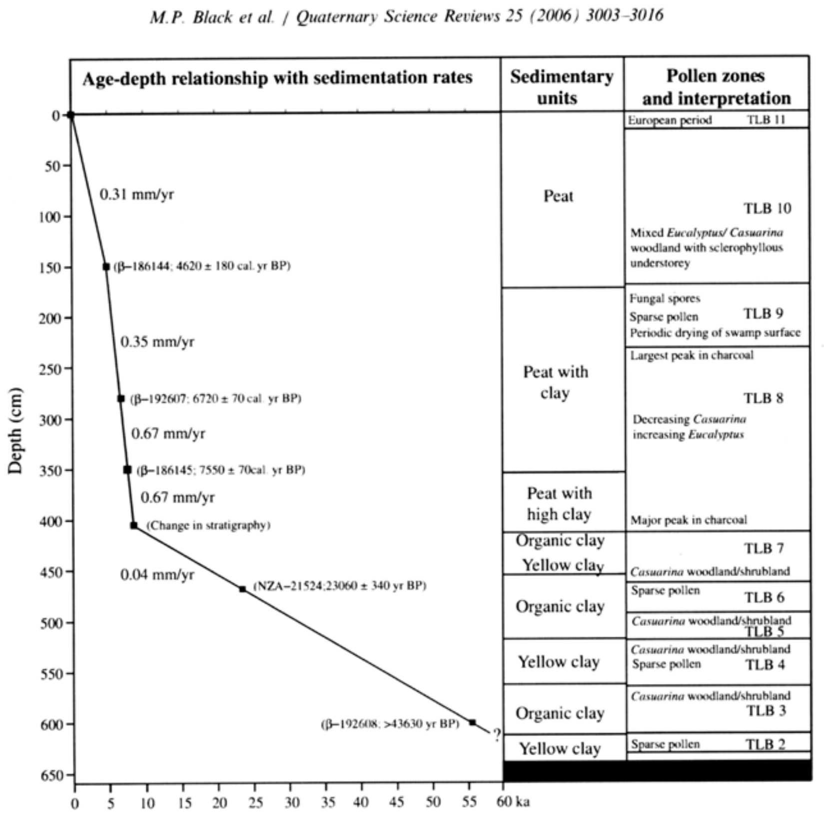


Figure 1.7: Profile in Lake Baraba from Black et al.

Quite remarkably, analyses of pollen from the core clearly showed the presence of *Pinus* species to a depth of about 100mm, showing the starting point of European influence.

The importance of the lake system is summarised well in the NPWS Plan of Management (1997) from which the following text is extracted.

> Thirlmere Lakes National Park was established to protect a small system of five perennial freshwater lakes of considerable geomorphological and biological significance.
>
> Freshwater lakes or river overflows are poorly conserved around Sydney. Thirlmere Lakes, and Marley Lagoon in Royal National Park, are some of the few surviving and relatively unpolluted examples of this ecological system which provide habitat for freshwater plants such as floating herbs, rushes and waterlilies. The park's five lakes lie within a deeply entrenched valley meander which is "perched" above the Burragorang Valley to the west and the Cumberland Basin to the east.
>
> Small lakes and wetlands, under normal conditions, will steadily evolve towards dry land by infilling with sediments. In the case of the Thirlmere Lakes the combination of size and configuration of the lakes catchment area has slowed the aging process.
>
> 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 15 million years old makes Thirlmere Lakes an outdoor laboratory of considerable scientific importance.

Accordingly, the aquatic habitats within Thirlmere Lakes National Park support many organisms which are restricted or almost restricted to this one lake system. There are a number of planktonic and bottom-dwelling protozoans (single celled animals or colonies of single celled animals) present, both along the shores and in the limnetic zone (the top layer of open lake waters which is penetrated by light). Crustaceans are an important part of the bottom-dwelling fauna and are an integral part of the lake ecology.

A freshwater sponge *Radiospongilla sceptroides* present in the lakes is thought to be found only within the Warragamba Catchment Area. This sponge is of particular ecological significance because it produces its own green pigment, and reflects the perennial status of the lakes by the absence of gemules (a process of asexual reproduction by the budding off of cells). Nowhere else in Australia has any species of sponge been found which abstains from gemmulation, which is necessary for adapting to the changing conditions normally associated with the ageing process of lakes.

Perhaps the most striking feature of the lakes is the occurrence of extremely large numbers of planktonic midge larvae belonging to the genus *Chaevorous* which are known to occur only in a few other lakes in Australia. The lakes and their margins provide examples of relatively undisturbed aquatic and fringing plant communities now considered rare in New South Wales. The tall sedge *Lepironia articulate* (see Figure 1.8) reaches the southern limit of its range in Thirlmere Lakes and the rare relative of the water-lily *Brasenia schreberi* (see Figure 1.9), though uncommon in the Sydney region, is well established at Thirlmere Lakes.

Figure 1.8: Tall sedge *Lepironia articulate*

Figure 1.9: Water-lily *Brasenia schreberi*

1.3 European History

The earliest known record of European discovery of the Thirlmere Lakes is an entry in the diary (14 March 1798) of the second 'Wilson[11] expedition', sent out by Governor John Hunter. It reads[12]:

> "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 rockery 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."

In December 1802 George Caley, who was following the tracks of the explorer Francis Barrallier, became disoriented and headed southward; coming upon the lakes. He believed that he was the first white man to discover them as the diaries of Wilson's expedition had been taken back to England with Governor Hunter.

The details of Caley's discovery are as follows[13]:

> *'At Stonequarry Creek (see Figure 1.6), Caley saw the tracks of Barrallier'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 depôt. Caley was not aware of the exact location of this depôt, 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 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 depôt or his tracks, and returned to Stonequarry Creek.'*

The area was at this time part of the reserve for the government owned "wild cattle of the cow pastures". The superintendents of the wild cattle may have also been some of the earliest visitors to the lakes.

An article in the Royal Australian Historical Society (RAHS, Vol 27, 1941) records the following regarding the name of the area:

> *'William Russell says that the native name of the lakes was Narre-ga-rang, because the soil around them is not firm. The name is said to mean a "shaky place".'*[14]

---

[11] John Wilson was an ex-convict and almost certainly the first white man to have visited what is now the Bargo area. Following his release from servitude Wilson chose to wander in the bush with the Aborigines rather than work in the settlement. Wilson was, however, sent on two official expeditions in Sydney's south west during 1798 and it was during the second trip that the Thirlmere Lakes were discovered.

[12] Cambage, R. H., "*Exploration Beyond the Upper Nepean in 1798"* Proc. Royal Australian Historical Soc. Vol 6, 1920.

[13] R. Else Mitchell, "*George Caley: His Life and Work*". Proc. Royal Australian Historical Soc. Vol 25, Part 6, 1939.

[14] We can testify to this description because in September 2011, by jumping on the exposed peat bed of Lake Nerrigorang we set a large area oscillating like a huge water bed.

A statement relative to the lakes appeared in the Sydney Morning Herald of September 30, 1867. After referring to the visit of the Governor of the day and a number of Ministers of the Crown to the lagoons, the report continues:

> '*The very existence of the these vast reservoirs of fresh water which lie in a secluded valley on the north side of the line was not known until about fifteen months ago, since which time they have attracted considerable attention from the fact that some parties have supposed that the large supply found there might conveniently be made available for the city.'*
>
> (RAHS Vol 27, 1941)

On 24 September 1867 the Governor, Sir John Young, appointed a Commission to inquire into the best method of supplying Sydney with water. This Commission investigated the potential of the "Couridjah Lagoons" together with a number of other catchments but eventually, and in 1869 recommended the Upper Nepean System to the east of Bargo and Appin[15].

The later history of Thirlmere Lakes is tied to the history of railways on the Southern Tablelands during the late nineteenth century and early this century. When the main southern railway line was extended to Mittagong in 1867 a pumping station was established above the third lake (Couridjah) and channels were constructed to connect the various lakes. The Couridjah pumphouse was constructed at that time to supply water from the lakes to the steam engines which used the southern railway to Mittagong (see Figure 1.10).

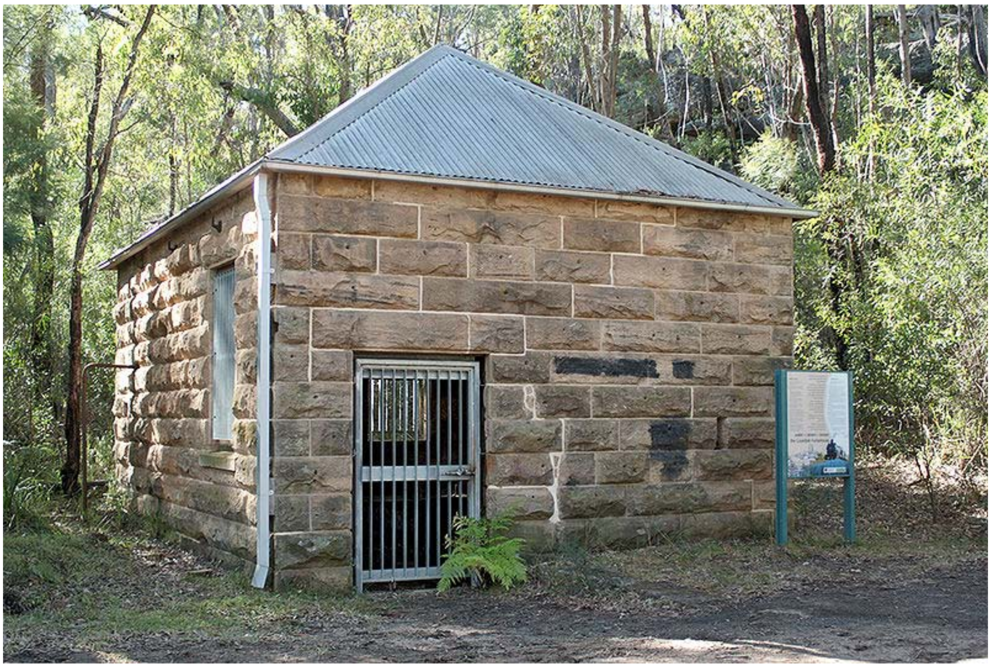


Figure 1.10: The Couridjah Pumphouse.

The railway station served by the pumphouse was initially named "Couridjah" but later changed to Picton Lakes. This station served the Bargo district until the township of Thirlmere grew large enough to acquire a store, bakery and a hotel of its own.

[15] Report of Commission Appointed to Inquire into the Supply of Water to Sydney and Suburbs, Sydney Gov. Printer, 1969.

At one time there was a proposal[16] that Picton and its extensive railway depot obtain water from Thirlmere Lakes and sufficient 10cm water pipes were accumulated to extend a water line along the railway track to Picton. However the town of Picton was incorporated as a municipality in 1895 and a water supply was brought from a small reservoir on the Bargo river which was constructed in 1899[17]. It was thought that the lakes would not have been a reliable source of supply as it had been reported that they were nearly dry in the 1902 drought.

Picton Municipal Council persuaded the Railways Department to change the name of Picton Lakes Station back to Couridjah and, in 1960, the name of the lakes changed from Picton Lakes to Thirlmere Lakes.

During the early decades of this century, and after considerable agitation from local residents, Wollondilly Shire Council built an unsealed access road through the park and named it W.E. Middleton Drive

Ainsley Atkinson[18] documents the following additional information.

> *“In the past the lake has been used for high-impact recreational activities such as water skiing. In the 1950s a road was constructed adjacent to the lake to improve access. Arsenic-based herbicides were used to clear natural vegetation from the lake margins, making it more attractive for watersports. At the same time the five lakes were connected by an artificial channel, increasing the effective length of the "lake" for skiers. These "improvements" resulted in accelerated erosion, increased arsenic concentrations in the sediment and sediment disturbance.*

Power boating and skiing were barred in about 1990.

In connection with this study, Mr David Hunt and Dr Philip Pells, separately interviewed a Mr Ron Silm whose father started Cedar Creek Orchards(about 4km NE of the lakes). Mr Silm gave the following information:

- *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 water for Picton Lakes Village in Couridjah which was a Dept of Health enterprise 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.*

- *Ron remembers, as a 16 or 17 year old (~ 1944) being able to ride his horse across a dry floor of Lake Werri Berri, which, he says, was largely covered in water couch.*

- *During some of the dry times in the 1980's Ron[19] obtained a permit to pump out of the N extension to the swimming lake across the watershed into the Cedar Creek catchment which then flowed down to his orchard beside Cedar Creek.*

---

[16] Sydney Morning Herald, 27 August 1881.
[17] Appendix 5, “*The Water Supply, Sewerage and Drainage of Sydney*”, 1961.
[18] National Parks Journal, Vol 44, No.1, Feb. 2000.

- *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 level in the lakes.*

1.4 Lake Water Levels as of September 2011

In early February 2010, Lake Nerrigorang was empty and Lake Werri Berri contained less than a metre of water and was partly covered in algae (see Figure 1.11). At that time Lake Couridjah still covered about 75% of its full plan area, and Lake Baraba was as it always is, a swamp with a small central pond (see Figure 1.12).

Figure 1.11: Lake Nerrigorang (left) and Lake Werri Berri (February 2010) – Near Map Photo.

[19] In his original discussion with David Hunt, Ron said that this pumping occurred in the 1950's. However, in a subsequent interview with Philip Pells, his wife suggested this occurred in the 1980's.

Figure 1.12: Lake Baraba (left) and Lake Couridjah (February 2010) – Near Map Photo

In June 2011, Lake Nerrigorang was still empty (see Figure 1.13) and was the same in September 2011 (see Figure 1.14).

Figure 1.13: Lake Nerrigorang, June 2011 (Pells photo).

Figure 1.14: Lake Nerrigorang, 5 September 2011 (Pells photo)

In August 2011, Lake Werri Berri contained a film of water over its central area (see Figure 1.15). On 21 September 2011 it was dry.

Figure 1.15: Lake Werri Berri, August 2011 (Pells photo).

On 22 September 2011, Lake Couridjah contained less than 100mm depth of water in its central area (see Figure 1.16).

Figure 1.16: Lake Couridjah, 22 September 2011 (Pells photo).

There were no water lilies (*Brasenia schreberi*) in Gandangarra, Werri Berri, Couridjah and Nerrigorang and no visible freshwater sponges. However, there was such dense growths of sedge (*Lepironia articulata*) that it was close to impossible to walk from the lake areas into the surrounding bush, or to the centre of Lake Baraba.

Why are the lakes so empty? Is it a natural, climatic, phenomenon, like the levels in Lake George. Or has some other influence come to play? These are the questions explored in the remainder of this report.

CHAPTER 2. HISTORICAL DROUGHTS AND HISTORICAL LAKE LEVELS

2.1 Drought Analysis

For the present purpose drought is considered only in terms of rainfall. Other factors, such as temperature, play roles in humans' responses to rainfall deficits but are not used in the evaluation presented herein.

Rainfall records for the area have been developed from the following primary sources:

- Picton Council rainfall record, which goes back, with some gaps, to 1889;
- Parramatta rainfall record that commences in 1832 but has gaps until 1858;
- Rackleyft family records from Lake Nerrigorang from 1987 to 1997; and
- Queensland Gov. of Natural Resources Data Drill records created for the Thirlmere Lakes from 1889, based on interpolation from all surrounding records.

The writer has extended the Data Drill records back to 1858 in order to extend the drought analysis. A comparison of the Drill record with the Rackleyft records at Lake Nerrigorang shows good agreement for the period 1987 to 1997. Drought analysis from 1889, using the Drill record, gives the same answers as using the Picton Council records.

Progress Report No.1 (given in Appendix A) discusses the recurrence intervals (frequency) of droughts with durations up to 1 year. It is reasonably obvious (see Office of Water report of December 2010) that the Lakes would be affected by longer duration droughts. Therefore we have considered droughts of 3 year and 5 year duration.

Table 2.1 gives the ranking of independent 5 year duration droughts. By 'independent' is meant drought sequences that were quite separate events. The worst two droughts were the 'Federation Drought' and the 'WW2 Drought'. The 5 year drought ending 2006 is ranked No.6. Thus even though this recent drought is sometimes discussed within the community as the "worst in memory", that simply represents the limitations of "living memory".

The "WW2 Drought" is very relevant to the "2006" drought because total rainfalls over the preceding 5 years were very similar (see Table 2.1).

TABLE 2.1
RANKING OF INDEPENDENT 5 YEAR DURATION DROUGHTS AT THE THIRLMERE LAKES

INDEPENDENT 5-YEAR DROUGHT ENDING	TOTAL RAINFALL (mm)
1909	2487
1942	2543
1885	2912
1926	3025
1947	3191
2006	3231
1982	3350
1899	3396
1997	3543
1968	3611
1919	3711
1932	3811
1869	3826
1937	3890
1904	3921
AVERAGE 5 YEAR RAINFALL	4021mm

A good idea of the severity of particular drought periods is gained when one considers 'overlapping' 5 year droughts. This is illustrated in Table 2.2. This table shows clearly that whilst the period 1905-1909 (Federation Drought) was the worst 5 year drought, the WW2 period generated the next five worst, but overlapping, 5 year drought periods. The drought of 2002 to 2006 only comes in at No.21.

TABLE 2.2
OVERLAPPING 5 YEAR DROUGHTS

YEAR RANGE (OVERLAPPING DROUGHT YEARS)	CUMULATIVE RAINFALL (mm)
1905-1909	2487.3
1938-1942	2542.5
1940-1944	2543.5
1939-1943	2544.5
1941-1945	2545.5
1937-1941	2546.5
1881-1884	2912.5
1904-1908	2918.7
1936-1940	2942.8
1882-1886	2954.0
1942-1946	2992.8
1922-1926	3024.7
1906-1901	3025.8
1935-1939	3055.5
1880-1884	3056.6
1884-1888	3128.8
1902-1906	3144.4
1907-1911	3164.5
1901-1905	3182.4
1943-1947	3190.7
2002-2006	3231.0
1944-1948	3235.3
1903-1907	3263.6
1920-1924	3271.4
1908-1912	3314.3
1978-1982	3350.3

Blue = WW2 Drought
Green = 1920's Drought
Red = Federation Drought
Beige = 1880's Drought
White = Recent Drought

Table 2.3 shows the ranking of 3 year duration independent droughts. In this case the three year period ending 1941 was worst, the Federation Drought second, and the three year ending 2004 ranks 8th.

TABLE 2.3
3 YEAR DURATION INDEPENDENT DROUGHTS

YEAR ENDING 3-YEAR DROUGHT	CUMULATIVE RAINFALL (mm)
1941	1317
1909	1464
1924	1658
1886	1680
1944	1732
1903	1755
1982	1822
2004	1832
1883	1847
1897	1876
1906	1919
1920	1920
1938	1921
1994	1963
1947	2043
2010	2087
1967	2149
1930	2182
1876	2212
1979	2217
1927	2227
1997	2234
1867	2262
1913	2262
1959	2278
1889	2396
2001	2398
1973	2407
AVERAGE 3 YEAR RAINFALL	2412

2.2 Historical Lake Levels

2.2.1 Measurements

As far as we have been able to determine, water levels in the five Thirlmere Lakes have never been measured and we have found no previous attempts at interpreting historical levels based on proxy data. By proxy data we mean aerial photographs, terrestrial photographs and anecdotal information.

In contrast to the Thirlmere Lakes, water levels in Lake George, a similar small-catchment enclosed system, comprise the longest record of measured water levels in Australia (see Figure 2.1). The fact that the Lake George levels respond entirely to catchment rainfall, and losses by evaporation and seepage has been demonstrated by White[20] and Jacobson et al[21].

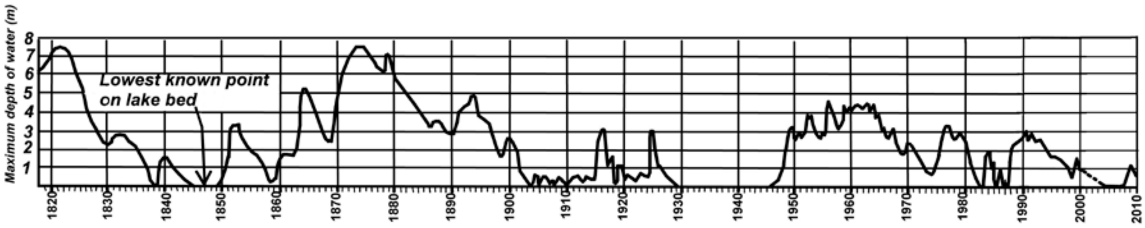


Figure 2.1: Lake George water level record.

2.2.2 Proxy Data

Table 2.4 summarises the information that has been collected to assist in developing historical lake water levels. We, particularly, acknowledge the many people who have sent us old family photographs and we, particularly, acknowledge verbal information from the Rackleyft family and from Ron Silm and his wife. Photographs referenced in Table 2.4 are given in the Progress Reports in the appendices to this report.

TABLE 2.4
THIRLMERE LAKE LEVEL OBSERVATIONS

YEAR	DATE	LAKE NAME	OBSERVATION	PERSON OR DATA SOURCE
1798	14/3/1798	All	Wilson, Collins and a third young man find three deep valleys with large ponds of water . This is the first recorded discovery of the lakes by Europeans.	RAHS Volume 6 Part 7
1802		Uncertain	Caley finds one of the lagoons- plenty of water.	RAHS Volume 25 Part 6 of 1939
1860		Uncertain	Major floods in Picton, bridge over the stone quarry river swept away.	RAHS
1865		Uncertain	Record of the water in the lakes being very pure	SMH 14/3/1865

[20] Mary E. White (2000) *Running Down. Water in a Changing Land.* Kangaroo Press.
[21] Jacobson, G Jankowski and Abell R S. *Groundwater and surface water interaction at Lake George, NSW.* BNR J Aust Geol & Geophysics 12 161-190.

YEAR	DATE	LAKE NAME	OBSERVATION	PERSON OR DATA SOURCE
1867		All	Lakes considered to be a large water supply comprising "vast reservoirs"	SMH 30/9/1867
1881		All	Consideration being given to bring water from the Picton lakes to Picton	SMH 27/8/1881
1902		Werri Berri, Couridjah	Nearly dry, a local farmer, Mr Pfeiffer cut rushes to feed his stock so as to keep them alive	FB Knox, local historian of Picton
1902		All	Visit by MWS & DB to consider the possibility of tapping the Picton lakes for Sydney water supply	SMH 6/10/1902
1910		All	"Desolation no rain for months, water is scarce and mostly putrid with dead fish"	SMH 15/1/1910
1928		Werri Berri, Couridjah	Water level low	FB Knox, local historian of Picton
~1943		Werri Berri	As a 16 to 17 year old Ron remembers crossing Werri Berri on horseback and says that the lake floor was covered with "water couch" (Paspalum distichum)	Interview with Ron Silm and his wife Sept 2011
1944		Werri Berri, Couridjah	Lakes reported to be dry to the extent that Mr Robert Rackleyft could walk across to reach Nerrigorang	Verbal information from Helen Squires (nee Rackleyft)
1949	1/03/49	All	Water in all the lakes	Dept Lands Air Photo
1954	1/12/54	Werri Berri	Werri Berri continuous with Gandangarra	Mall Juske Photo
1955	5/07/55	Gandangarra	Werri Berri continuous with Gandangarra	Dept Lands Air Photo
1966	22/03/66	Werri Berri	Full	Dept Lands Air Photo
1966	22/03/66	Couridjah	Full	Dept Lands Air Photo

YEAR	DATE	LAKE NAME	OBSERVATION	PERSON OR DATA SOURCE
1974		All	Overflowing, fire brigade memo records that the access roads around the lakes was underwater in several places.	NPWS record from the fire department of 1974
1975	Jan-75	Nerrigorang	Full	Rackleyft photo (eel)
1975	2/04/75	Werri Berri	Full	Dept Lands Air Photo
1975	2/04/75	Couridjah	Full	Dept Lands Air Photo
1980		Nerrigorang	Full	Olive Johanessen photo (c/o Caroline Graham)
1983	27/10/83	Werri Berri	Full	Dept Lands Air Photo
1983	27/10/83	Couridjah	Full	Dept Lands Air Photo
1984	?/4/84	Couridjah	Water level about 1.5m below end of jetty	David Hunt photo
1987	1/03/87	Nerrigorang	Photo from mountain top , appears about 1m to 1.2m down	Rackleyft photo
1988	1/04/88	Nerrigorang	Full to edge lawn	Rackleyft photo (lawn edge)
1989	1/07/89	Nerrigorang	1.5m above edge - spread out over paddock	Helen and Paul Rackleyft (May 2011)
1989	10/04/89	Couridjah	Full	Hunt photo
1989	30/11/89	Couridjah	>95% Full	Hunt photo
1989	?/1/89	Couridjah	Water level about 1m below jetty end.	David Hunt photo
1989	?/4/89	Couridjah	Water level about 30cm below end of jetty.	David Hunt photo
1994	4/01/94	Werri Berri	Full	Dept Lands Air Photo
1994	4/01/94	Couridjah	90% to 95% Full	Dept Lands Air Photo
1994	1/04/94	Nerrigorang	About 1m down from 1/4/88 photo	Rackleyft photo (lake edge)
1995	1/07/95	Werri Berri	Eight feet from toe of sandstone wall	NPWS site officer (on site 1994 to 2011)
1998	4/10/98	Werri Berri	Water level about 1m below end of jetty.	Jeff Pratchett (Tahmoor local).

YEAR	DATE	LAKE NAME	OBSERVATION	PERSON OR DATA SOURCE
2002	10/01/02	Werri Berri	After fire. Jeff comment: "Taken in the same post after the water level dropped, jetty burnt, which by this time was well out of water. I stand at 6ft and the water was well over my head, back in 1998 when you climbed up the ladder. At least a 7ft fall in the four years."	Jeff Pratchett (Tahmoor local).
2002	?/?/02	Nerrigorang	Lake appears to be lower (but hard to tell due to burnt reeds)	Olive Johannessen photo x 4 (c/o Caroline Graham)
2003	1/07/03	Nerrigorang	lake level drops unusually rapidly over a period of 3 months - waterline retreats 30 feet.	Paul Rackleyft (May 2011)
2005	20/12/05	Werri Berri	Full	Dept Lands Air Photo
2005	20/12/05	Couridjah	>95% Full	Dept Lands Air Photo
2008	13/06/08	Werri Berri	Water level high	Julie Sheppard photo of canoe
2009	31/10/09	Werri Berri	At 76% of full width at the widest part	Google Earth photo
2009	28/10/09	Couridjah	At 84% of full width at widest part	Google earth photo
2010	13/04/10	Werri Berri	At 50% of full width at widest part	Google Earth photo
2010	13/04/10	Couridjah	At 72% of full width at widest part	Google Earth photo
2010	13/10/10	Couridjah	Level at base of 4th (upper) post of old burnt out jetty	Julie Sheppard photo
2010	13/10/10	Nerrigorang	Dry	Caroline Graham photo
2010	6/09/10	Baraba	Dry	Caroline Graham photo
2010	8/10/10	Werri Berri	Very low water level	Caroline Graham photo
2010	6/09/10	Werri Berri	Dry	Caroline Graham photo
2010	17/11/10	Gandangarra	Water appears low	NPWS photo
2010	12/12/10	Gandangarra	Water appears low	NPWS photo
2010	17/11/10	Werri Berri	Water appears very low	NPWS photo
2010	12/12/10	Werri Berri	Water appears very low	NPWS photo
2010	17/11/10	Couridjah	Water level low	NPWS photo
2010	12/12/10	Couridjah	Water appears low	NPWS photo
2010	17/11/10	Nerrigorang	Dry	NPWS photo
2010	12/12/10	Nerrigorang	Dry	NPWS photo
2011	11/04/11	Gandangarra	Water appears low	NPWS photo
2011	11/04/11	Werri Berri	Water appears extremely low (dry)	NPWS photo

YEAR	DATE	LAKE NAME	OBSERVATION	PERSON OR DATA SOURCE
2011	11/04/11	Couridjah	Water appears low	NPWS photo
2011	11/04/11	Nerrigorang	Dry	NPWS photo
2011	9/05/11	Couridjah	Couridjah very low, Werri Berri almost dry	Differential GPS survey by Pells
2011	4/08/11	Couridjah	Julie Shepherd's monitoring position	Julie Shepherd photo
2011	22/8/11	All	Nerrigorang dry, Werri Berri very low, Couridjah <0.5m	Pells photos and Omnistar survey in RTK Float mode
2011	22/9/11	All	Nerrigorang dry, Werri Berri <50mm, Couridjah <100mm	Pells photos

2.2.3 Survey Basis for Evaluation of Proxy Data

In May and August 2011 we undertook survey measurements at the lakes using a combination of Omnistar differential GPS in RTK Float[22] mode, and optical levelling. The work in May involved measuring the water levels in Werri Berri and Couridjah.

The work in August was undertaken to measure:

- the floor levels of each lake;
- the outlet level from Lake Nerrigorang to Blue Gum Creek; and
- to provide absolute values to use in conjunction with Patricia Fanning's bathymetric data for development of depth-versus-storage curves for each lake.

At the time of the work Lake Nerrigorang was empty (see Figure 2.2), Lake Werri Berri was effectively empty (see Figures 2.3 and 2.4), Lake Couridjah had a maximum water depth of about 0.5m, and "Dry Lake" (Gandangarra) was dry.

At our request, Mr Paul Rackleyft inspected the bed of Blue Gum Creek downstream of the overflow point from Lake Nerrigorang. There was no water in the creek bed for about least 700m downstream of the overflow point.

[22] This gives plan positions with an absolute accuracy of about 0.1m, absolute vertical level to about 0.5m, and relative vertical level, in any 10 minute period, to about 0.1m.

Figure 2.2: Lake Nerrigorang, August 2011, P. Pells photo.

Figure 2.3: Lake Werri Berri, August 2011, P. Pells photo.

Figure 2.4: The last reflection in Lake Werri Berri, August 2011, P. Pells photo.

Figure 2.5 shows the position of the overflow point between Lake Nerrigorang and Blue Gum Creek.

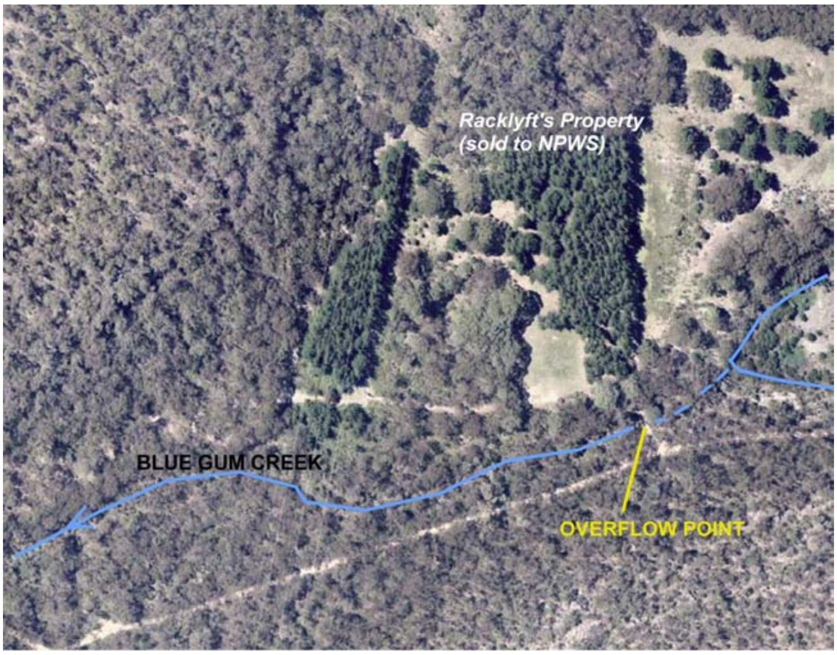


Figure 2.5: Overflow point between Lake Nerrigorang and Blue Gum Creek.

Figure 2.6 shows the locations of the survey points and Figure 2.7 gives a summary, in long section, and three cross-sections, of the levels that have been assessed from the survey. Figure 2.7 is also reproduced at A3 size as Figure 5.2 in this report.

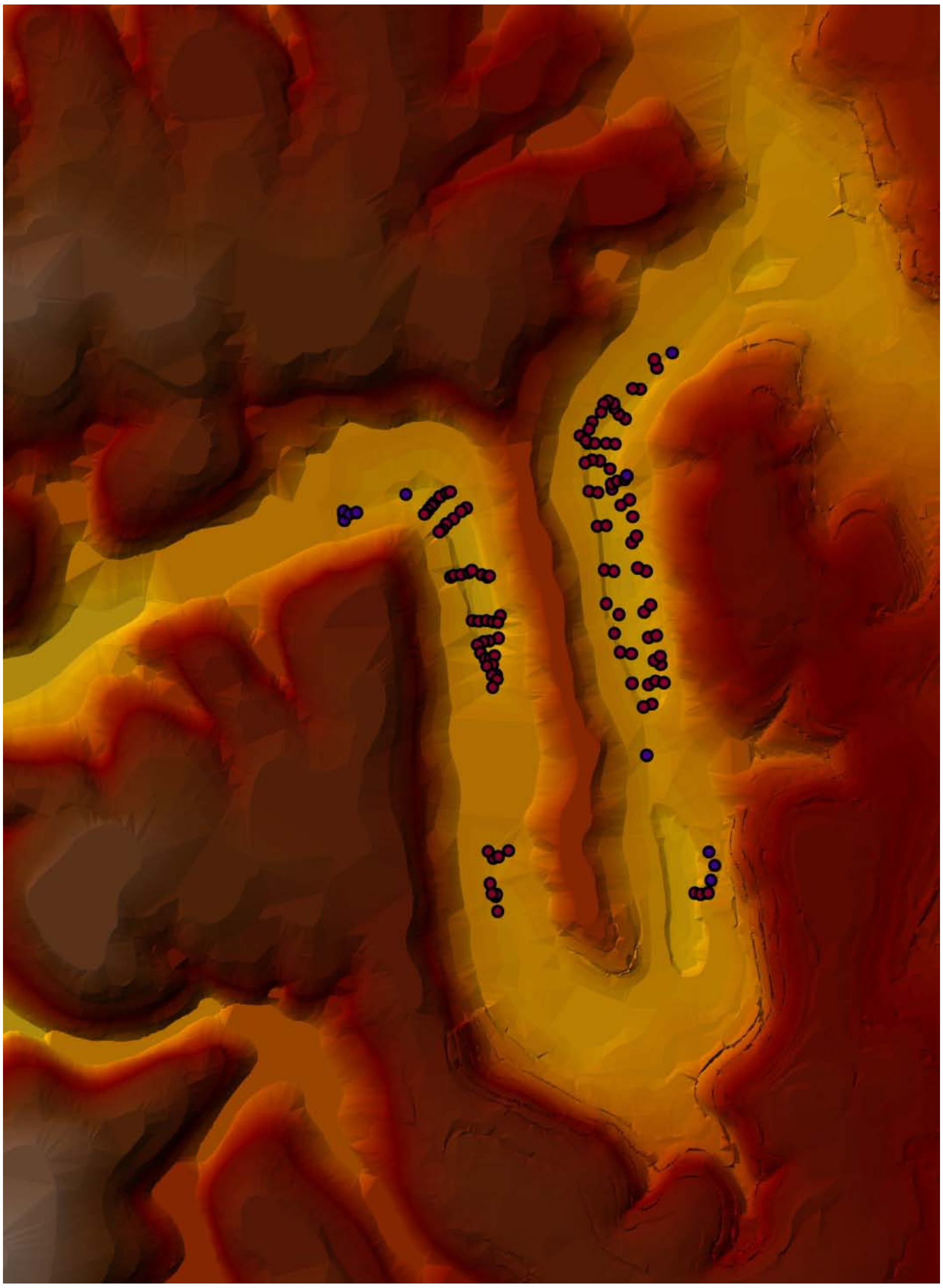


Figure 2.6: Thirlmere Survey.

Figure 2.7: Longitudinal and cross sections.

All the survey information and all borehole and geological structural data have being accumulated in GIS format.

The survey solved one puzzle, namely: why does Lake Baraba never fill up?

It transpires that the level of the peat in Lake Baraba (see Figure 2.8) is at or above the full water levels of the other lakes. In fact, the peat level in Lake Baraba is about 7m above the floor level of Lake Nerrigorang. Lake Baraba is, in effect, a valley fill swamp.

Figure 2.8: Lake Baraba, 22 August 2011 (P. Pells photo).

Key levels for the survey data used for evaluating terrestrial photographs are given in Table 2.5.

TABLE 2.5
SELECTED POINTS FROM THIRLMERE GPS SURVEY MAY & AUGUST 2011

POINT	NORTHING	EASTING	RL	NOTES
1	621477.1	273035.3	302.0	Section 1 0n peg ~0.3high
43	6210000.6	273205.2	306.1	2nd last point towards Baraba
44	6209980.2	273193.8	306.3	Last point towards Baraba
45	6210515.1	273515.1	302.9	Werri Berri edge
46	6210514.7	273515.2	303.4	Same as 45
47	6210535.3	273528.0	305.4	Werri Berri Peg
106	6210538.6	273548.1	307.6	Werri Berri bottom wall
107	6210548.8	273554.3	308.6	Werri Berri top wall
114	6209520.0	273195.3	307.0	Baraba
115	6209524.3	273209.2	306.9	Baraba
116	6209539.1	273235.9	307.1	Baraba
117	6209537.1	273180.7	307.4	Baraba
118	6209451.9	273187.0	307.7	Baraba
119	6209425.7	273737.3	303.7	COURIDJAH EDGE
120	6209425.7	273737.4	303.7	COURIDJAH EDGE

POINT	NORTHING	EASTING	RL	NOTES
121	6209423.5	273752.6	305.5	TREE LINE
122	6209426.0	273772.3	306.8	Wall bottom
123	6209425.9	273773.8	308.1	Wall top

The survey data described above, together with information given in Patricia Fanning's thesis (see Progress Report No. 4), and available contour data, have been used to generate contours at half metre intervals around Lakes Nerrigorang, Werri Berri and Couridjah. These contours have been used to assess lake levels from aerial photographs.

2.2.4 Assessed Historical Levels

In assessing historical lake levels we have followed three processes.

1. For aerial photographs we have overlain the photographs on the half metre contours around the lakes and thereby made an assessment of levels.

2. For terrestrial photographs we have assessed water levels in respect to the measured levels at the tops and bottoms of the stone walls at the Werri Berri and Couridjah picnic areas, and in respect to the bank and outlet levels at Nerrigorang.

3. For anecdotal information, and published words, we have made judgement decisions in relation to the measured floor levels and full levels of each lake.

We have treated Gandangarra, Werri Berri and Couridjah as a single water level because their natural interconnection was made even more intimate, in the early 1900's by the digging of slots.

Lake Nerrigorang has been treated as a separate water level because there is clear evidence that Lake Baraba acts to separate this lake from those upstream.

Figure 2.9 is one example showing the assessed level in Werri Berri based on the aerial photograph of 22 March 1966.

Figure 2.9: 22 March 1966 with level.

Figure 2.10 gives our assessment of historical lake levels.

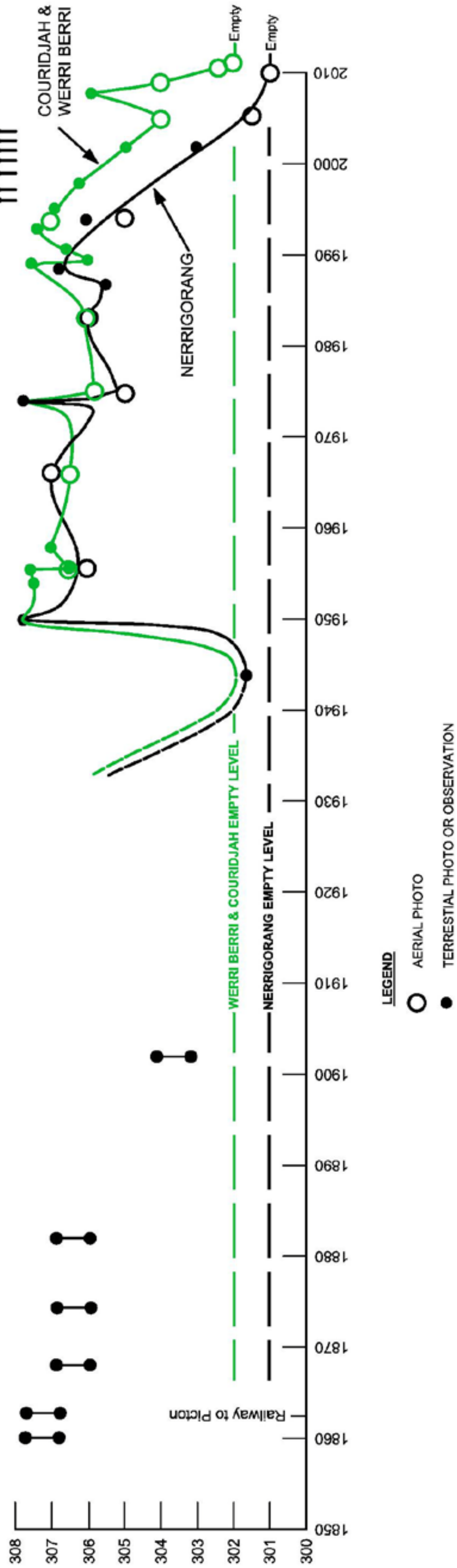


Figure 2.10: Assessment of historical lake levels.

3.1 Geological Setting

Figure 3.1 is part of the Wollongong-Port Hacking geological map that covers the area of the lakes. It shows the surface geology. It also provides contours of the base of the Triassic rocks (Hawkesbury Sandstone and Narrabeen Formation). The base of the Triassic is also the surface of the Permian coal measures, the top of which is marked by the Bulli Coal seam.

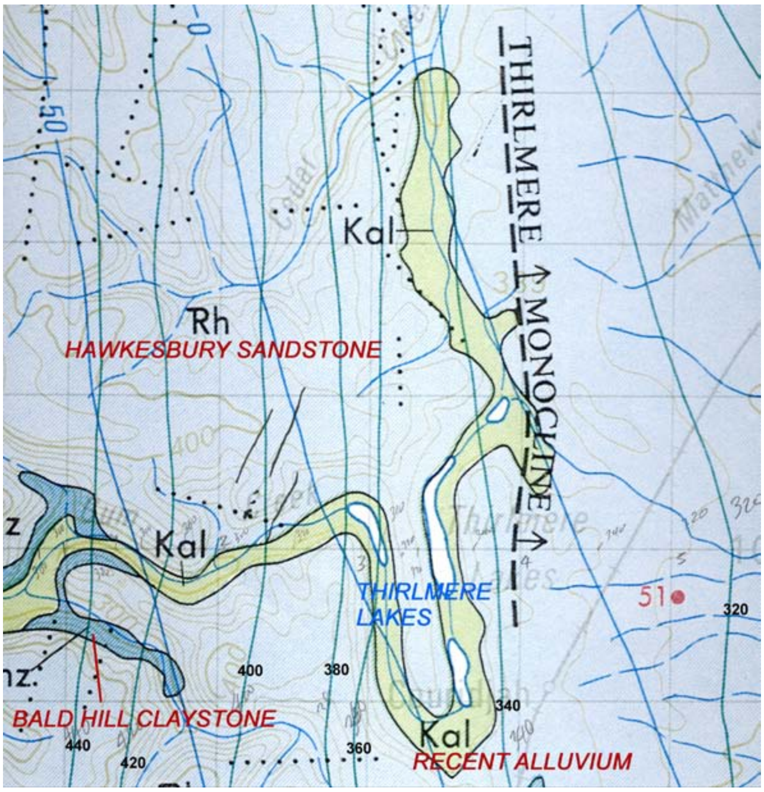


Figure 3.1: Part of Wollongong-Port Hacking geological map showing the area of the lakes.

3.2 Stratigraphy

Many boreholes have been drilled to the west of the lakes as part of coal exploration. Boreholes drilled for Clutha in the period 1975 to 1983 are available through the DIGS website of the Geological Survey of NSW. Forty two of these boreholes (see Table 3.1) were used to interpret the stratigraphy and faulting between west of the Thirlmere Lakes (272500mE) and east of the Nepean River (281500mE). From this borehole data, and outcrop geology shown on the 1969 geological map of the Burragorang Valley (see Figure 3.2), a stratigraphic, West-East, cross section was prepared, passing beneath the lakes (6210500mN). Portion of this section is given in Figure 3.3. the full section that extends to the Nepean River is several metres long at a legible scale and is not reproduced herein.

TABLE 3.1
LOCATIONS OF CLUTHA BOREHOLES

BORE	MGA		
	EASTING	NORTHING	RL
0001	277047.441	6207800.968	294.628
0002	274991.231	6206004.114	358.001
0003	277995.111	6210484.369	276.542
0004	274165.419	6207438.422	370.685
0005	279874.155	6210497.968	232.591
0006	274995.429	6210035.04	325.475
0007	281684.439	6207453.768	243.12
0008	278426.257	6209189.995	276.055
0009	276642.973	6210731.272	296.238
0010	276738.291	6209402.22	294.495
0011	280156.924	6208329.884	265.999
0012	280114.659	6205822.191	290.954
0013	279927.502	6208231.285	250.633
0014	281663.454	6209811.857	199.76
0015	280456.464	6207543.36	268.353
0016	279343.098	6208206.854	269.064
0017	275150.343	6208663.57	320.772
0018	278957.833	6206189.745	281.256
0019	275353.657	6207349.139	270.711
0020	277966.814	6208682.398	281.275
0021	277966.824	6208682.399	281.275
0022	279314.08	6208122.607	273.211
0023	278689.376	6208645.544	281.945
0024	278270.574	6208665.277	286.809
0025	279708.328	6208027.631	266.605
0026	277565.227	6208839.72	284.303
0027	278652.231	6208239.187	279.804
0028	278096.63	6208839.198	281.131
0029	278047.84	6207546.149	283.477
0030	276161.08	6210715.304	297.62
0031	279330.987	6208121.629	273.641
0032	278392.317	6207212.52	283.794
0033	278371.157	6207890.032	280.611
0034	278982.042	6210159.524	276.678
0035	277179.19	6208610.347	277.561
0036	274606.676	6206674.773	351.672
0038	277547.153	6208218.9	279.967
0039	275888.655	6209596.972	304.417
0040	276126.472	6208586.278	296.945
0041	277981.356	6209446.891	281.035

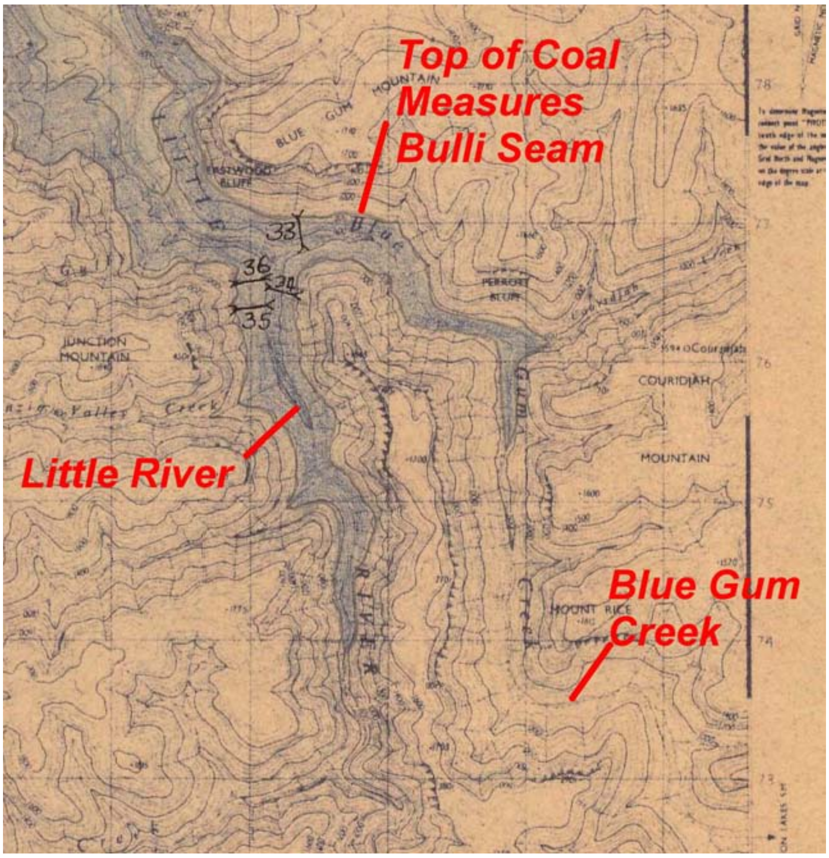


Figure 3.2: 1969 geological map of the Burragorang Valley showing outcrop geology.

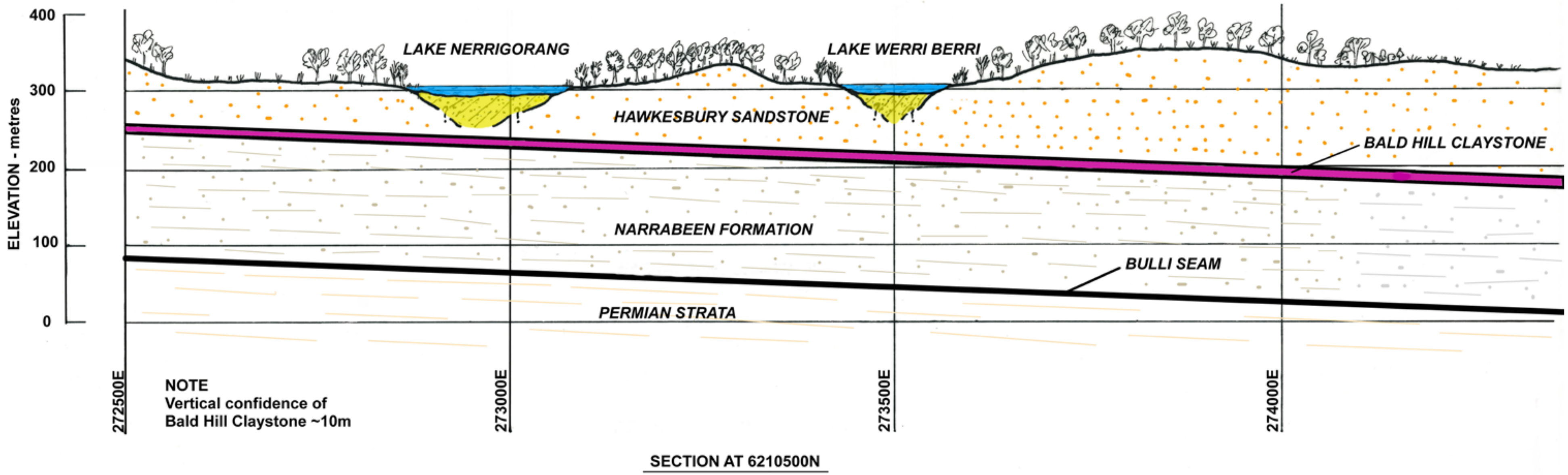


Figure 3.3: Stratigraphic, West-East, cross section passing beneath the lakes.

The following summary of the stratigraphy is taken from the 2010 NSW Office of Water report on the Thirlmere Lakes. The units are described from the Permian (Illawarra Coal Measures) upwards.

Illawarra Coal Measures. The Permian Illawarra Coal Measures have been described as interbedded sandstone, siltstone, claystone and coal layers with minor tuff and conglomerate horizons as well as intrusions. In the centre of the Sydney Basin, the coal measures are recorded as having a thickness of in excess of 500 m. Near the western margin of the basin, the coal measures are only a few metres in thickness, and are entirely absent in some localities to the southwest (e.g. Wingello and Penrose). The coal measures are subdivided into the basal Cumberland Subgroup and the overlying Sydney Subgroup.

Narrabeen Group. The Permo-Triassic Narrabeen Group is subdivided into two subordinate groups; the Clifton Subgroup and the Gosford Subgroup. The basal Clifton Subgroup is characterised by: light grey quartz-lithic sandstone units (Coal Cliff Sandstone); sandstone and conglomerate channel deposits (Scarborough Sandstone); pebbly sandstone (Bulgo Sandstone); and green to chocolate brown claystones (Wombarra Claystone, Stanwell Park Claystone, Bald Hill Claystone). The overlying Gosford Subgroup includes the characteristic marker horizon of the Garie Formation and the Newport Formation. The Garie Formation comprises cream pelletal claystone that grades upwards to a grey, fossiliferous, slightly carbonaceous claystone. The Newport Formation consists of light grey fine grained sandstone, interbedded with siltstones and minor claystones that have distinct dark grey to cream to purple colour variations.

Hawkesbury Sandstone. The Triassic Hawkesbury Sandstone is a major cliff-forming unit throughout the Southern Coalfield, and is particularly represented in the topography of the Illawarra Escarpment. This unit ranges in thickness from typically around 120 m in some locations to a maximum of 230 m in drilled core samples. The formation comprises predominantly quartzose sandstone, with less frequent intervals of siltstone and fine sandstone laminite, siltstone horizons and claystone bands. The sandstone exhibits variable grainsize between very fine to very coarse, but is most typically medium grained, and ranges from moderately to poorly sorted. Two depositional sandstone units are recognised within the formation; a ‘sheet sandstone facies’ and a ‘massive sandstone facies’ (Conaghan 1980). Intercalated thin mudstone and siltstone horizons have also been identified as ‘mudstone facies’.

Mittagong Formation. The Triassic Mittagong Formation is a thin sandstone, siltstone and laminite horizon that overlies the Hawkesbury Sandstone. It shares common characteristics with the upper parts of the underlying Hawkesbury Sandstone, as well as those of the basal section of the overlying Wianamatta Group shales.

Wianamatta Group. The Triassic Wianamatta Group comprises the basal Ashfield Shale, the Minchinbury Sandstone and the Bringelly Shale. The Ashfield Shale is a dark grey to black fossiliferous siltstone, grading to a laminite toward the top of the unit. The Minchinbury Sandstone is a thin persistent mappable horizon that separates the basal shale from the overlying shale strata. This unit is a quartz-lithic sandstone that is up to 6 m in thickness. The overlying Bringelly Shale contains minor carbonaceous claystone at the basal section, however the predominant strata comprise claystone, siltstone, laminite and sandstone.

It is important to note that the Bald Hill Claystone, which forms a key marker bed in the Narrabeen Formation (beneath the Hawkesbury Sandstone) may be a low permeability stratum.

It is typically a massive chocolate brown to red brown kaolinitic claystone with silty and sandy grey and mottled grey-brown zones. It contains minor laminated and thinly bedded siltstones and sandstones ranging in thickness from fractions of a metre to 3m.

Bembrick states that the mineralogy of the Bald Hill Claystone is unique to the red beds of the Sydney Basin. It consists predominately of kaolinite (50% to greater than 75%), with haematite as the principal "contaminant". Quartz and felspar may be present in minor quantities, but are frequently absent.

Its thickness ranges from:

- 15m at type section at Bald Hill
- 80m at Sutherland
- 80m at Malabar (at shoreline the top surface is 170m below sea level)
- about 100m at Bondi (top surface 120m below sea level)
- 65m at North Head (top surface 140m below sea level)
- 18m at Long Reef Point where the full unit is exposed in the cliff face.

Its thickness beneath the Thirlmere lakes is interpreted as about 20m to 25m.

Unconsolidated Sediments

The geologically-young, unconsolidated, sediments beneath the lakes have been interpreted by Patricia Fanning (nee Vorst, 1975).

Fanning made use of three procedures in an attempt to determine the depth and nature of the alluvium beneath the lakes. Firstly, boreholes were drilled using augers on a Gemco drilling rig which had a maximum penetration depth of just over 30m. Secondly, an attempt was made to use seismic methods to determine the profile of the underlying Hawkesbury Sandstone. Thirdly, an estimate of the shape of the underlying sandstone profile was made using geomorphic methods.

The locations of the boreholes are shown in Figure 3.4. Summary logs of the boreholes are given in Table 3.2 and shown diagrammatically in Figure 3.5.

Figure 3.4: Location of boreholes.

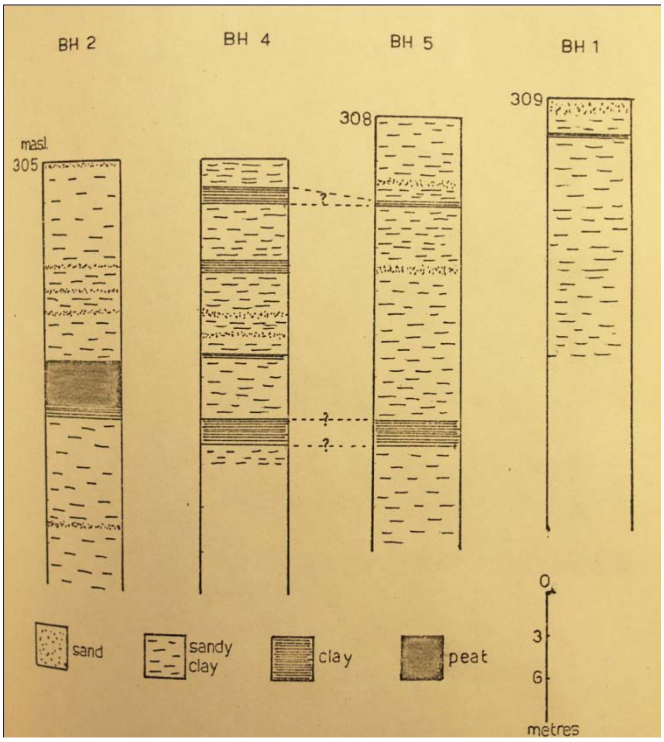


Figure 3.5: Diagram showing the summary of logs of the boreholes given in Table 3.2.

TABLE 3.2
SUMMARY OF LOGS OF THE BOREHOLES

HOLE NUMBER	DEPTH (M)	TEXTURE
BH1	1.0	Medium sand
	1.5	Sandy clay
	3.6	Sandy clay
	4.2	Clay
	5.1	Sandy clay
	18.0	Sandy clay
BH2	1.0	Medium sand
	3.0	Sandy clay
	7.5	Sandy clay
	7.8	Medium sand
	9.0	Sandy clay
	9.3	Medium sand
	11.3	Sandy clay
	12.0	Medium sand
	12.8	Clay
	14.3	Sandy clay
	17.3	Peat
	18.0	gl(??) clay
	25.5	Sandy clay
	26.0	No sample
	29.5	Sandy clay
BH4	0.5	Medium sand
	1.8	Fine sandy clay
	3.0	Clay
	3.6	Clayey sand
	6.0	Clayey sand
	6.9	Sandy clay
	8.4	Clay
	11.0	Sandy clay
	11.3	Clayey sand
	13.0	Sandy clay
	13.3	Clayey sand
	16.0	Clay
	18.3	Sandy clay
	20.0	Sandy clay
	21.0	Clay
	22.0	Sandy clay

HOLE NUMBER	DEPTH (M)	TEXTURE
BH5	1.6	Clayey sand
	3.3	Sandy clay
	5.0	Sandy clay
	6.6	Clay
	7.6	Sandy clay
	8.5	Sandy clay
	10.0	Sandy clay
	11.6	Sandy clay
	13.3	Sandy clay
	15.0	Sandy clay
	16.6	Sandy clay
	18.3	Sandy clay

Fanning's description of the seismic survey is as follows:

> "*A seismic survey was conducted under the direction of Mr. J. W. Tayton, School of Earth Sciences, Macquarie University, in order to determine, firstly, the depth of sediment in the valley and, secondly, the location(s) of sediment layers as revealed by changes in the velocity of the sound waves as they travelled through layers of different densities. The location of the survey transect is shown in Fig. 1.2.*
>
> *The bedrock cliffs on either side of the valley were found to continue at approximately the same angle beneath the overlying valley fill. However, interference with the sound waves because of the narrowness of the valley resulted in the bedrock base remaining undetected; its depth was calculated to be beyond 50 to 60 metres. Changes in velocity occurred at 2 to 3 metres, from 300 metres/sec. to 1,100 – 1,200 metres/sec., with a subsequent progressive increase with depth to about 2,000 – 2,100 metres/sec; the former reflects the change from unsaturated to saturated sediment (the velocity of sound waves in water is 1,400 metres/sec.), while the latter probably reflects increasing compaction of the sediments. Velocity changes were at approximately the same depth across the valley, which lead Mr. Tayton to believe (pers. comm.) that the zone of bedrock weathering had not been encountered; its profile would follow the outline of the bedrock valley sides, which would be reflected in a non-uniform depth of velocity change across the valley."*

Fanning used the shapes of the valley sides to conclude that the lake sediments are about 50m deep. She concluded:

> *"Thus, the bedrock valley is, as suspected, very deep and is filled with unconsolidated sediment which may be the products of a variety of depositional processes."*
>
> *Analyses of the deep clay layers were not undertaken because of the inability to remove all of the organic matter by treatment with hydrogen peroxide. However, their textural appearance strongly resembled that of clay layers encountered in cores extracted from the present lakes.*
>
> *There is a strong textural resemblance between the sandy clays in the boreholes and the surface material of the alluvial fans and debris slopes; one possible mode of deposition of this material is therefore via sheetwash form the adjacent hillslopes."*

3.3 Geological Structures

Near vertical dykes and faults in the area of the lakes have been interpreted from published information on structures mapped at seam level in the Tahmoor Colliery, and on published information on structures encountered during the construction of the Tahmoor decline and sinking of shafts 1, 2 and 3. (Fawcett and Rose, 1978, 3rd Australian Tunnelling Conf.).

Information from in-seam mapping was taken from Figure 3.7, which was available on the internet.

Figure 3.7: Tahmoor structures.

It is acknowledged that many structures encountered at seam level do not extend to the ground surface.

There is clearly a major NW-SE fault/dyke zone that cuts across the mine. For the purpose of communication we have termed this Tahmoor NW-SE strike-slip fault and intrusion zone, as "T1 Fault" in shorthand. It appears that the T1 fault played a role in the significant inflows that occurred during excavation of the Tahmoor decline[23]. A splay of the T1 fault was associated with overbreak in the No.3 shaft[24]. It is interpreted that this fault zone dips to the NE.

A second fault that is considered to be of relevance is the NW boundary fault (termed here the T2 fault), encountered in some drives, and postulated by Xstrata as extending to the SW (see Figure 3.7).

The information in Figure 3.7 regarding the T1 and T2 faults is transcribed onto Figure 3.8 in relation to the positions of the Thirlmere Lakes. If these structures extend to the lake area they could influence groundwater movement around and beneath the lakes.

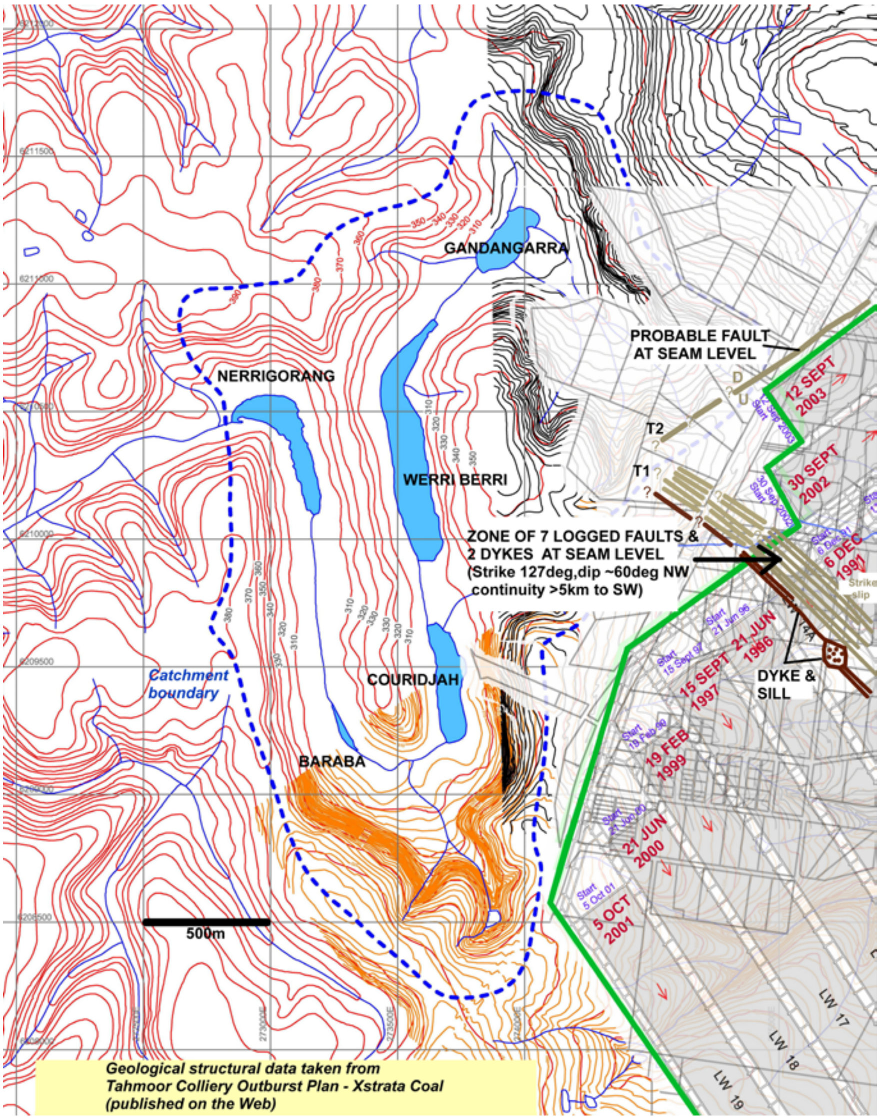


Figure 3.8: Structural geology.

23 Fawcett, D.H. and Rose, J.A.F. "*Groundwater problems encountered whilst sinking at Tahmoor Colliery*". 3rd Aust. Tunnelling Conference, 1978.

24 Pells, Sullivan, Meynink Pty Ltd, Report PSM16.R1, December 1993.

3.4 Hydrogeology

3.4.1 Area Unaffected by Mining

The hydrogeology of the area beneath and around the lakes is related directly to the stratigraphy (Section 3.2, above), the structural geology (Section 3.3, above), and the in situ permeability characteristics of the stratigraphic units, and the faults.

Almost all permeability data used for groundwater modelling in the Southern Coalfields comes from borehole packer tests. Such tests have limitations primarily related to the number and orientations of bedding planes, joints and shears intersected by the borehole over the particular test length. In the horizontally bedded strata vertical boreholes mostly intercept near horizontal bedding planes. Therefore the test results are biased towards measuring permeability in the horizontal direction. However, even in vertical boreholes, some test sections may include steeply dipping joints. This is even more likely where the tests are conducted in inclined boreholes. Thus some test results will reflect vertical and horizontal permeability.

The other limitation of typical packer testing is that the equipment is not usually sensitive enough to accurately measure hydraulic conductivity (permeability) values less than about 10^{-8} m/sec.

Accepting the above limitations, the packer testing remains the basis of numerical modelling of groundwater flows, although such modelling is calibrated, wherever possible, against measured field behaviour, such as measured mine inflows, or measured changes in groundwater pressures.

Figure 3.9 summarises in situ measurements, predominantly from borehole packer (Lugeon) tests, in the Southern Coalfields and off the coast of Sydney. Figure 3.10 shows the field measurements plotted versus depth.

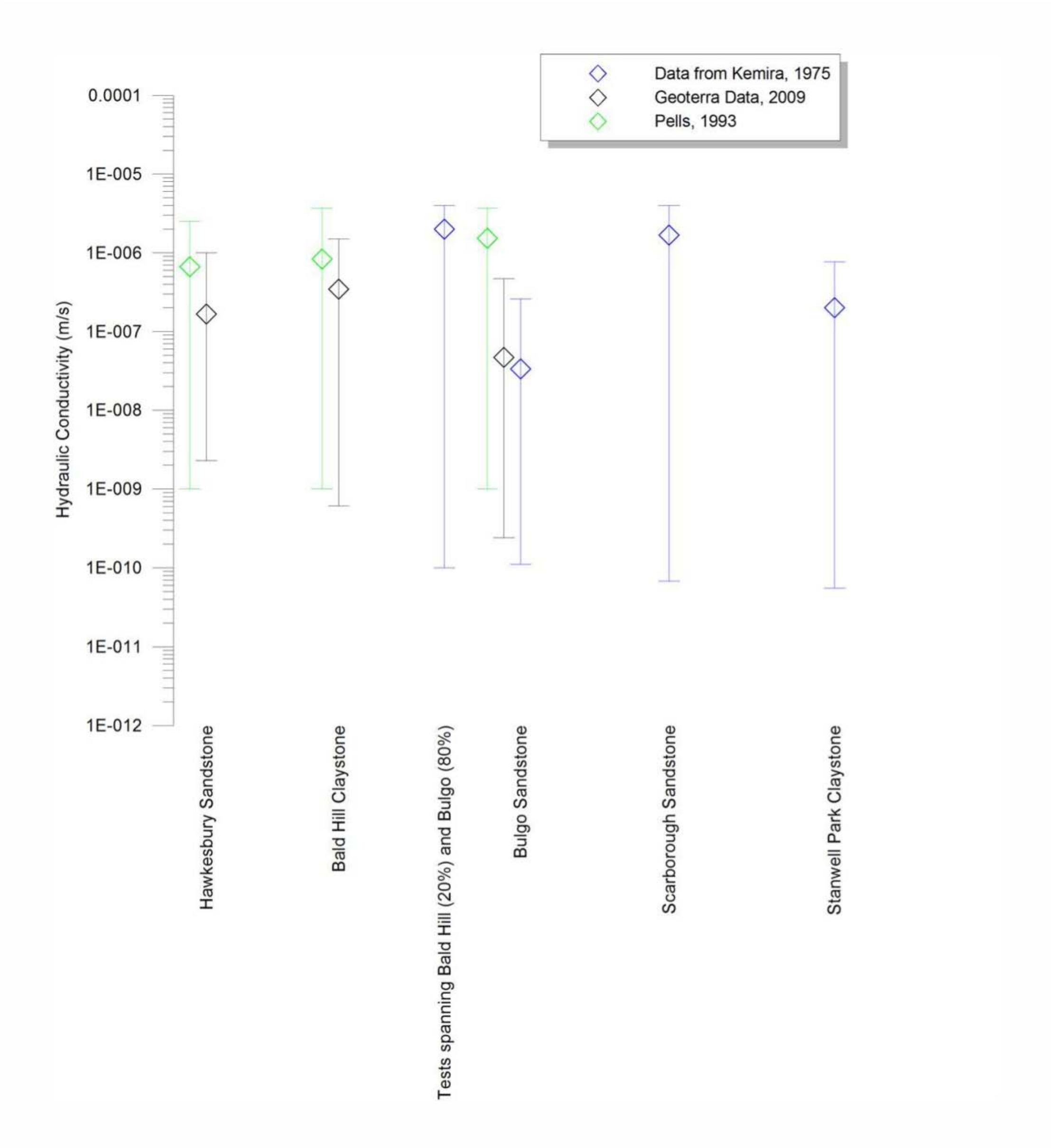


Figure 3.9: Packer test data from the Narrabeen and Hawkesbury.

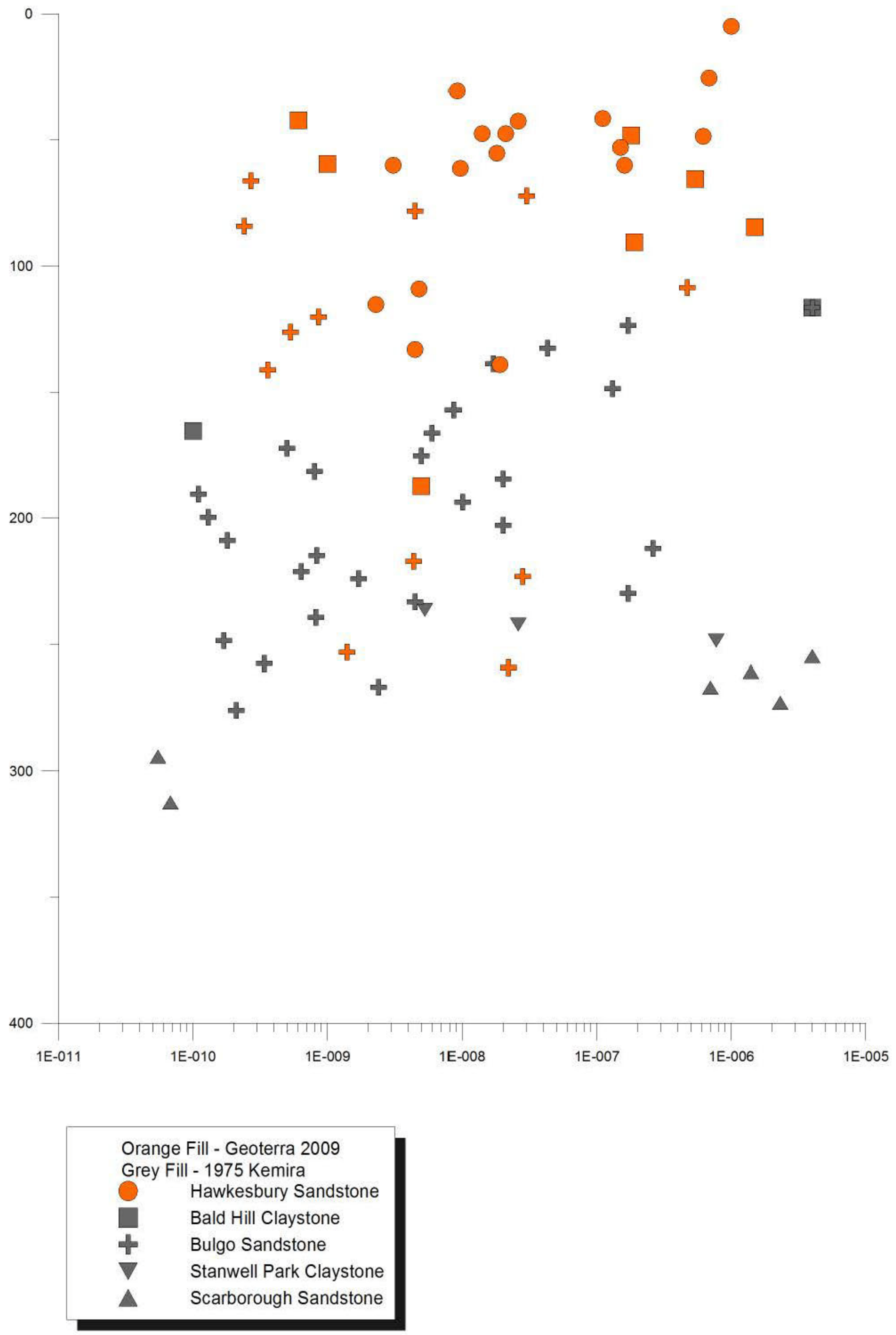


Figure 3.10: Permeability data plotted versus depth.

It can be seen that the measured packer test permeability values for the Bald Hill Claystone fall within the ranges measured in the Hawkesbury Sandstone and the Narrabeen Formation. In assessing these results cognisance must be taken of the fact that where boreholes do not intercept joints, permeability is largely controlled by the near horizontal bedding planes. However, in assessing vertical permeability consideration must be given to the following evidence that the Bald Hill Claystone contains many discontinuities.

The Bald Hill Claystone contains as many as eight soil profiles[25] (ie. eight superimposed palaeosols), is fissured and jointed, and is transgressed (in places) by faults and igneous intrusions (see Figures 3.11 to 3.13).

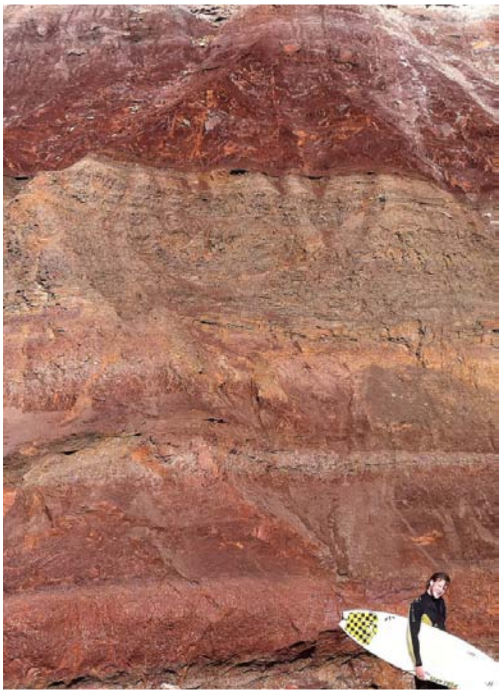


Figure 3.11: Bald Hill Claystone at Long Reef, Sydney

Figure 3.12: Joints in Bald Hill Claystone at Bald Hill

Figure 3.13: Through going joint in the type section at Bald Hill, just north of Stanwell Park.

[25] Herbert (1980) Chapter 2 *A Guide to The Sydney Basin.*

Permeability data, additional to that given above, is presented in Reid, P *Effect of mining on permeability of rock strata in the Southern Coalfield*[26]*.* The following points made by Reid are consistent with our understanding:

> *"The Bald Hill Claystone has a narrower range of both joint spacing and laboratory permeabilities, however the laboratory permeabilities are significantly less than the Lugeon values. This suggests that the permeability of the Bald Hill Claystone is dominated (as one would expect) by secondary permeability.*
>
> *The typical Lugeon permeabilities of the Bald Hill Claystone and the Hawkesbury Sandstone are of a similar order, despite their marked lithological differences. The similarity between the laboratory and Lugeon permeabilities for the Hawkesbury Sandstone suggests that intergranular permeability makes a significant contribution to the overall permeability, in contrast to the Bald Hill Claystone."*

3.4.2 Impact of Longwall Mining on Permeability of the Overlying Rock

The extent to which longwall mining causes rock fracturing, and hence permeability increase, is discussed in detail in Chapter 4 of the Bulli Seam Operations PAC report of July 2010. That report discusses the great uncertainty in respect to the height above longwalls panels in which new fractures will result in a substantial increase in vertical permeability. The Panel concluded, "for the purpose of progressing its assessment that":

"1. When the MSEC model (see Figure 3.14) is applied to conditions similar to the calibration data, it could produce reasonable predictions of the height of fracturing even though it has mechanistic shortcomings for that purpose, with the maximum height being 1.37 times panel width;

2. Based on other studies including Gale (2008), a potentially worst case outcome appears to be fracturing extending up to a height of 1.5 times panel width but with increasing disconnection of fracturing;

3. It is unlikely that the highly connected and freely drainable fractured zone will extend upwards into and beyond the Bald Hill Claystone for longwall panel widths up to 310m. This is suggested by a range of field measurements and observations, the most recent being extensometer measurements conducted over LW32 (310m width) at West Cliff Area 5 where more than 90% of fracture displacements seem to have occurred at or below the claystone."

[26] Symposium on Geology in Longwall Mining, Proc. of Symposium, Uni NSW, 1996.

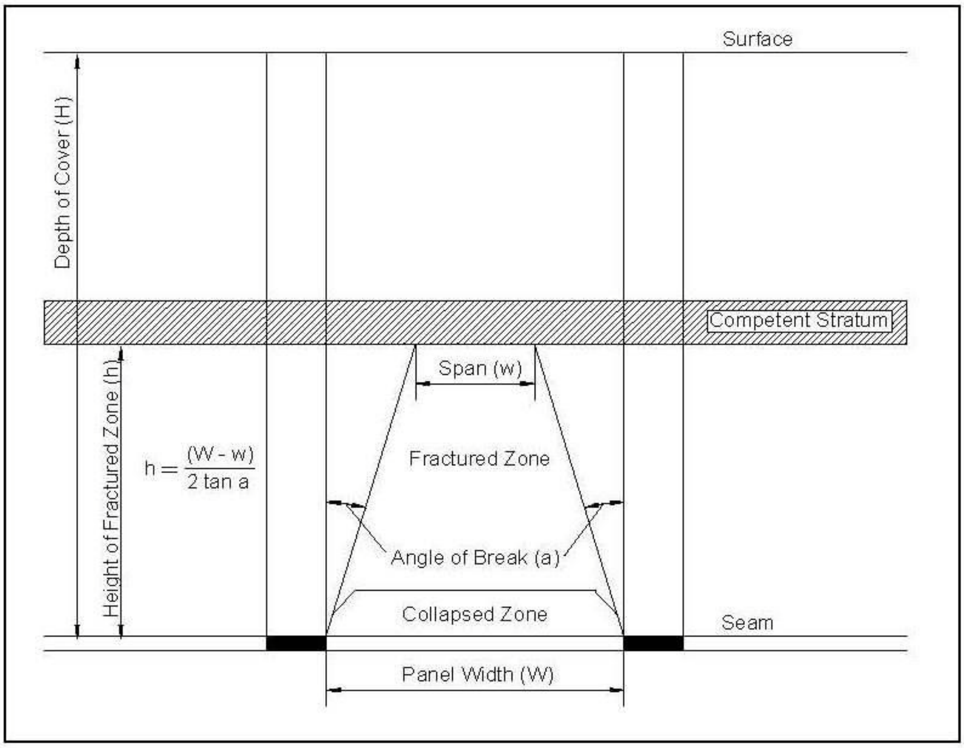


Figure 3.14: MSEC model for extent of fracture zone.

It is our view that the MSEC model infers an extent of fracturing much greater than reality. For the groundwater modelling in the report we have assumed that substantial increase in permeability extends about 60m above the Bull Seam longwalls.

4.1 Layout and Depth

Figure 4.1 shows the layout of the Tahmoor Colliery as of about mid-2010.

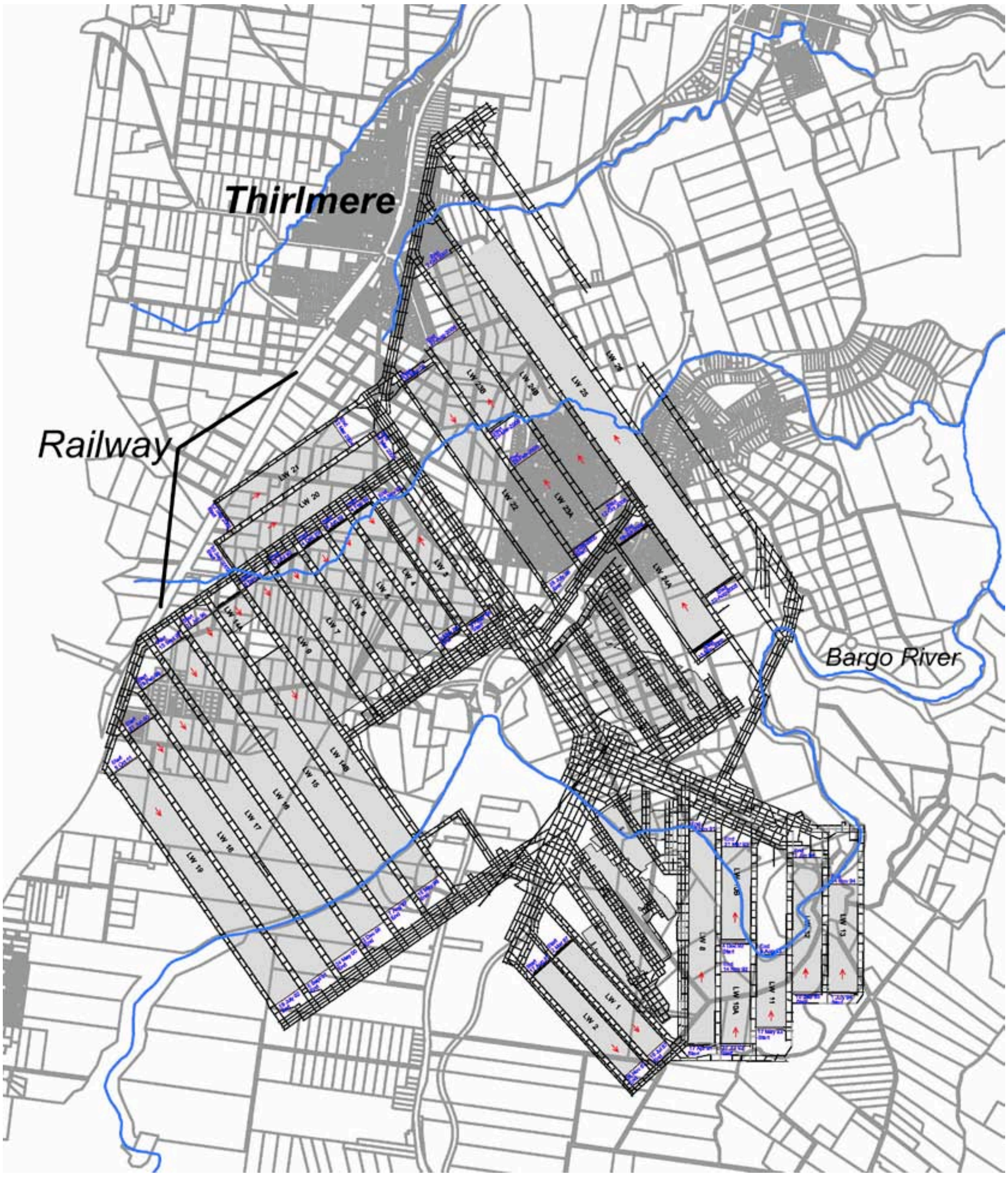


Figure 4.1: Tahmoor Colliery as of about mid 2010.

The longwalls that are closest to the Thirlmere Lakes were mined between about June 1996 and late 2003 (see Figures 4.2 and 4.3). These longwalls are in the Bulli Seam at a depth of about 300m.

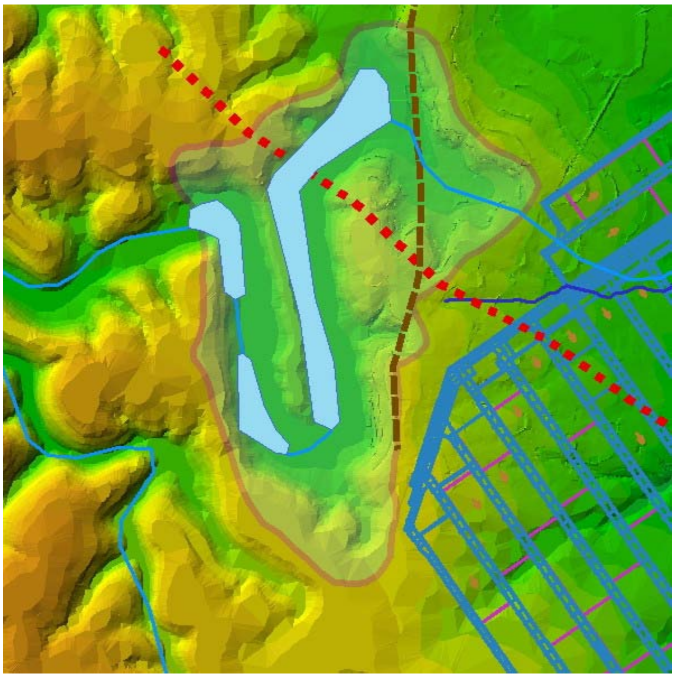


Figure 4.2: Proximity of longwalls to Thirlmere Lakes.

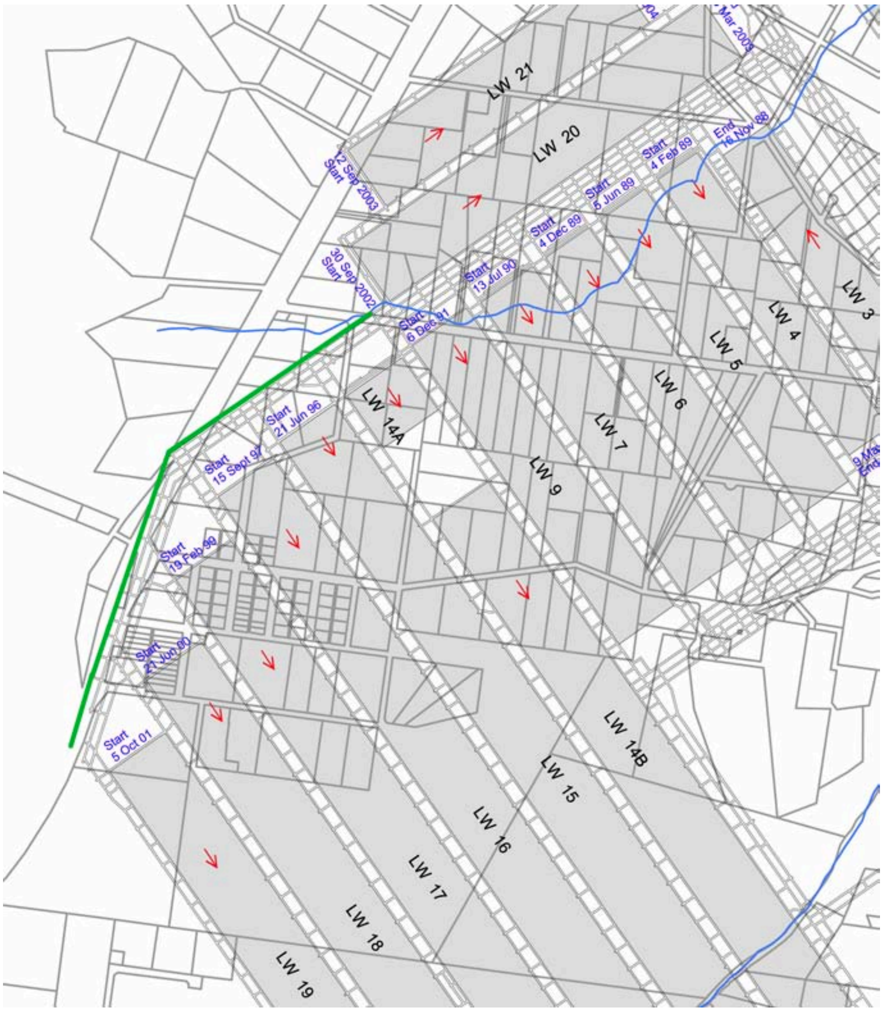


Figure 4.3: Dates of longwalls near Thirlmere Lakes.

As of about 2008 new longwalls at Tahmoor have been to the north east, progressively further from the lakes.

4.2 Very Brief History

Tahmoor Colliery was commenced by Clutha Development Proprietary Limited in early 1976 with the excavation of a decline (drift) and No. 1 shaft[27]. The mine has had a number of owners and we are not party to all the details.

What is known as fact is that since 2004 there are copies of Annual Environmental Management Reports (**AEMR**) on the Internet. They were issued by the following companies:

- 2004 – Austral Coal
- 2005, 2006, 2007 – Centennial Coal
- 2008, 2009, 2010 – Xstrata Coal

Significant inflows were encountered during sinking of the decline and shafts 1 and 2. These flows came from fracture zones (probably faults) within the Hawkesbury Sandstone, and are detailed in the paper by Fawcett and Rose, and are not repeated here. Because significant quantities of grout were pumped into the rock around the decline and shafts, it is not possible to compute mass natural permeability values from the inflow data. However, Fawcett and Rose do given transmissivity data from a separate pumping borehole that was installed near the drift. They quote a range of values from 3.7 to 9.9 cm^2/sec. It is worth noting that when this separate dewatering borehole had to be turned off, at one stage, inflows into the drift increased to 11.3 litres per second. This is a very high inflow compared with typical experience in the Hawkesbury Sandstone.

Records of water pumped from the mine are summarised in the Annual Environmental Management Reports. The plot reproduced as Figure 4.4 was sourced from the Internet.

[27] Fawcett and Rose (1978) loc cit.

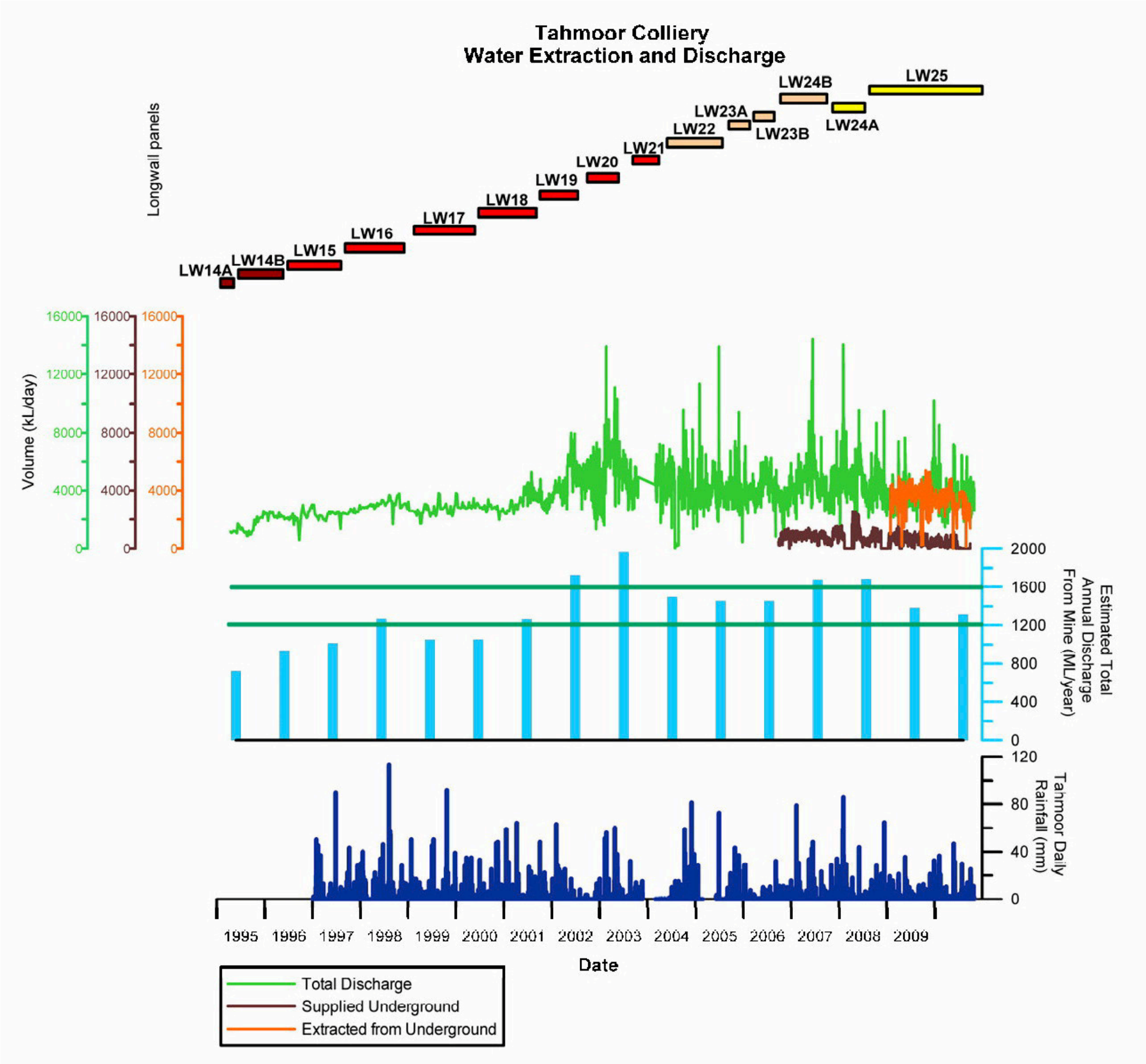


Figure 4.4: Record of mine pumping.

Figure 4.5 reproduces the drawing of piezometer and stream monitoring sites from the 2010 AEMR.

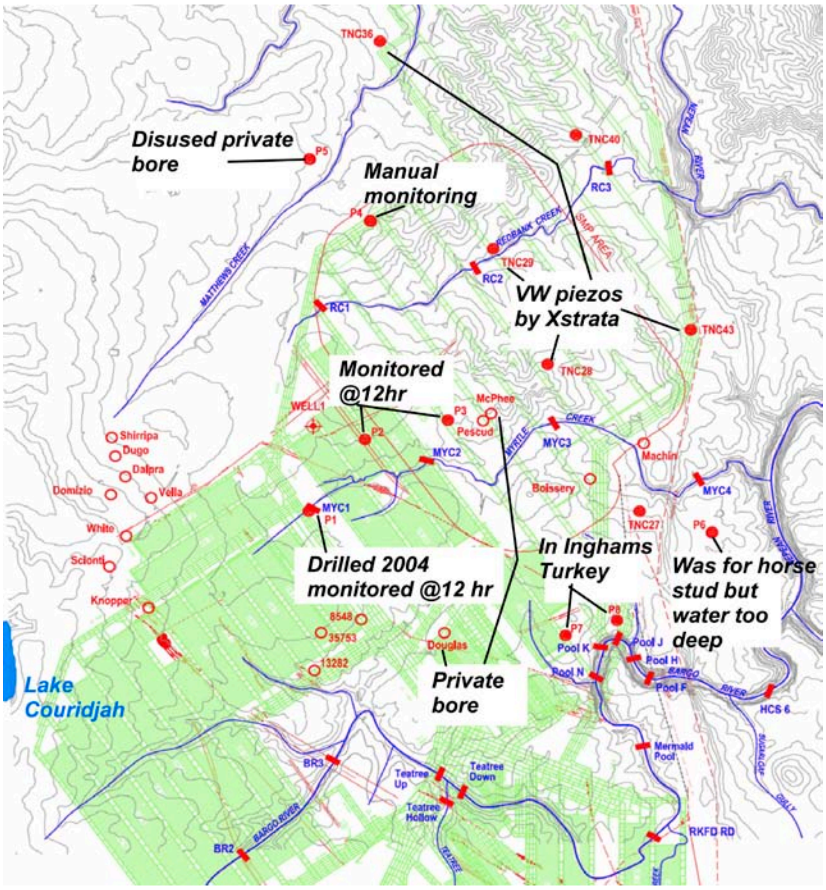


Figure 4.5: Piezometer and stream monitoring locations from 2010 AEMR.

CHAPTER 5. MODELLING OF LAKE FILLING

5.1 Introduction

This chapter examines the historical levels in Thirlmere Lakes from a hydrologic perspective, and comments on whether the recently observed levels can be explained by climatic / hydrological processes alone.

5.2 Available Data

5.2.1 Surface Topography and Lake Bathymetry

A digital elevation model (DEM) of the region was constructed using the following available level data:

- 10 and 5 m contours as supplied to Pells Consulting in CAD format.
- Ground surveys undertaken by Pells Consulting on the 9th May 2011 and the 22nd August 2011.
- Bathymetry data of the lakes from Fanning (1974).

The DEM and the locations of these data are summarised in Figure 5.1.

A long section down the channel thalweg was prepared as shown in Figure 5.2. Also shown on Figure 5.2 are three selected cross sections. The observed surface slopes of either side of the valley were projected downwards to approximate the depth of the valley, and hence the extent of alluvial/colluvial fill which underlies the swamps. It was noted that (with exception to Lake Gandangarra) slopes of 1V:4H were good approximations of the valley slopes in general.

This process is similar to that adopted by Fanning (1974), which led her to conclude that the recent sediments were at least 50m deep. Boreholes were drilled by Fanning into the sediments to the limit of the drilling rig, which was about 31m, without encountering bedrock.

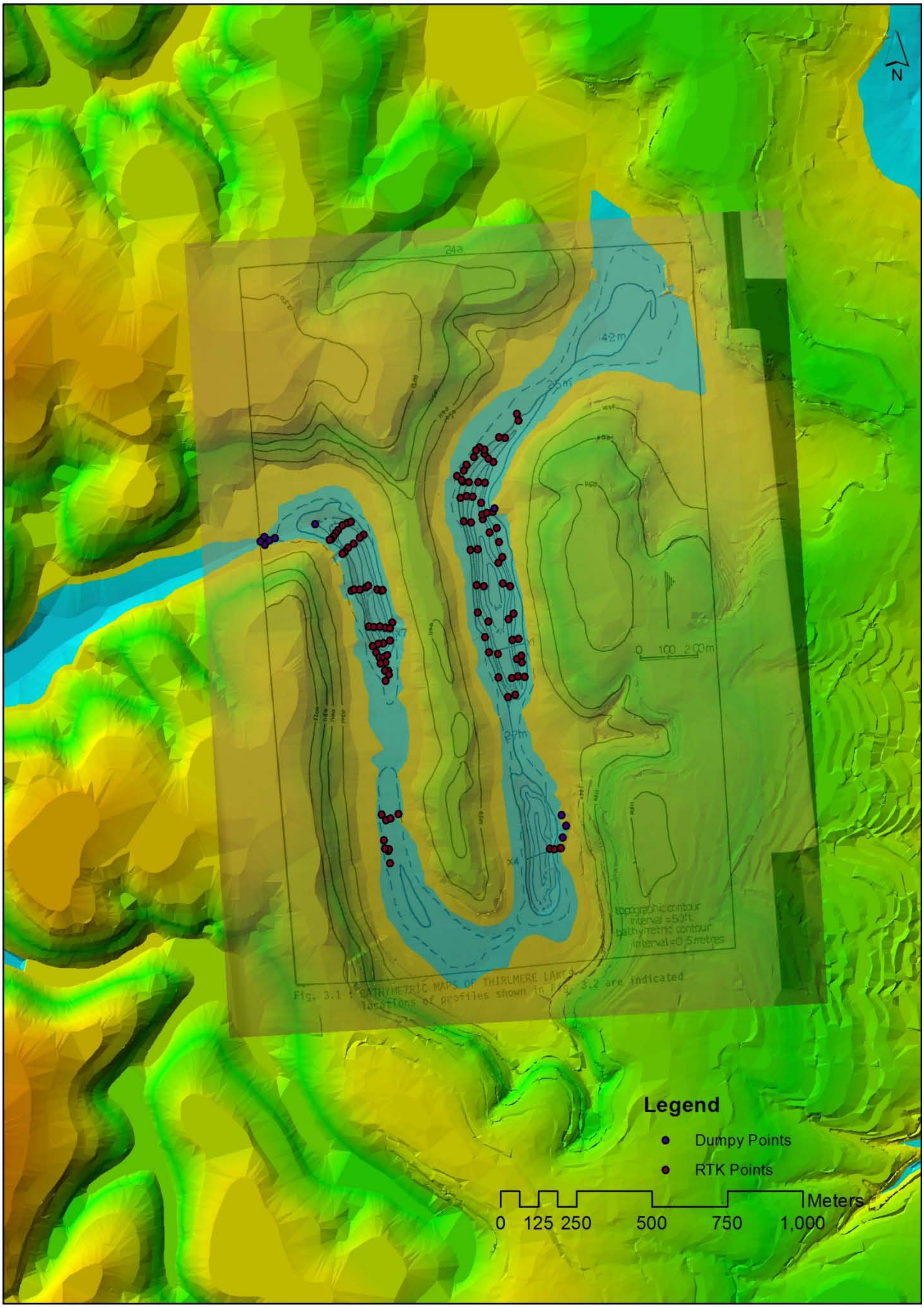
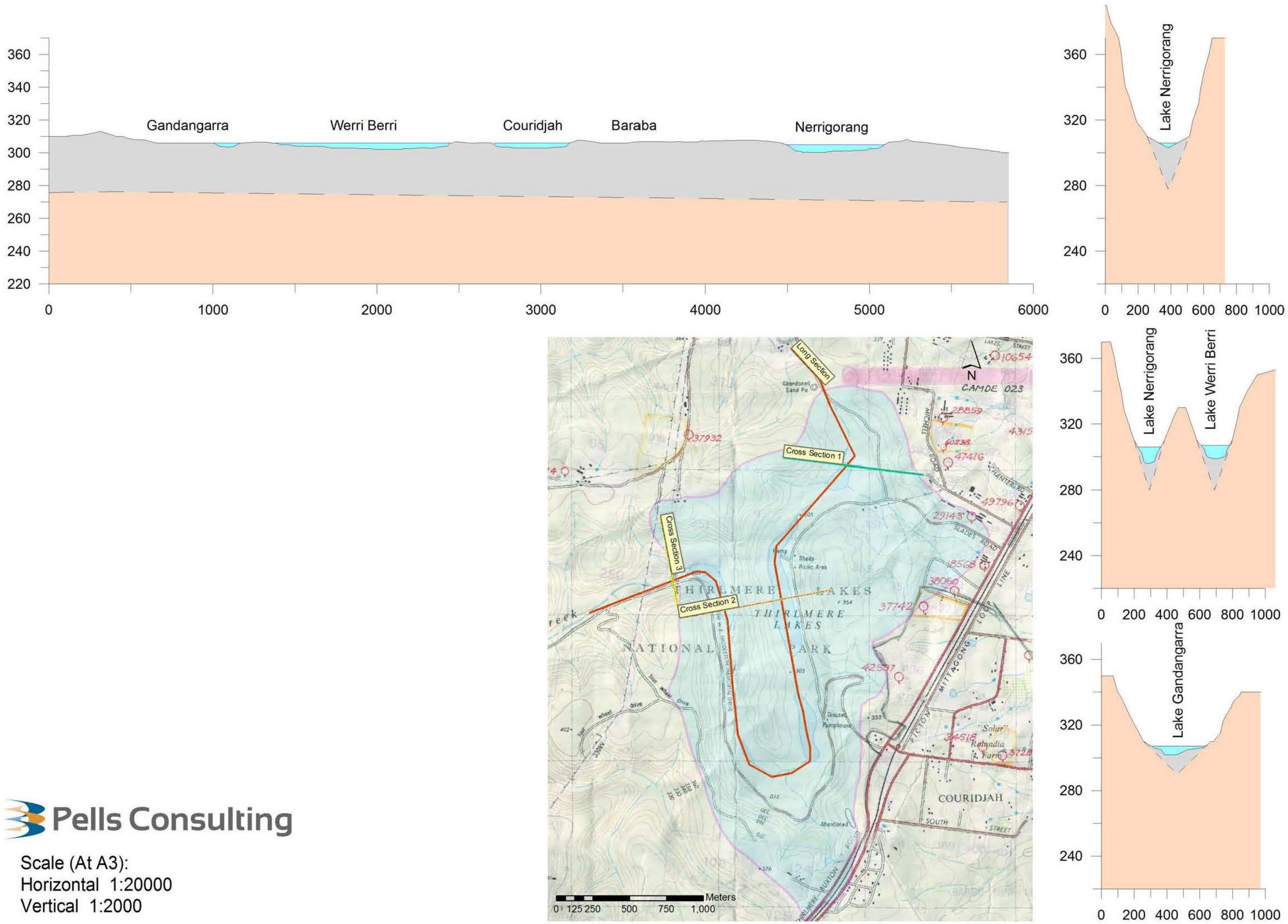


Figure 5.1: Digital elevation model of lakes area.



Scale (At A3):
Horizontal 1:20000
Vertical 1:2000

Figure 5.2: Longitudinal and cross sections.

5.2.2 Catchments

Sub-catchments were drawn for each of the lakes using the DEM, as shown in Figure 5.3.

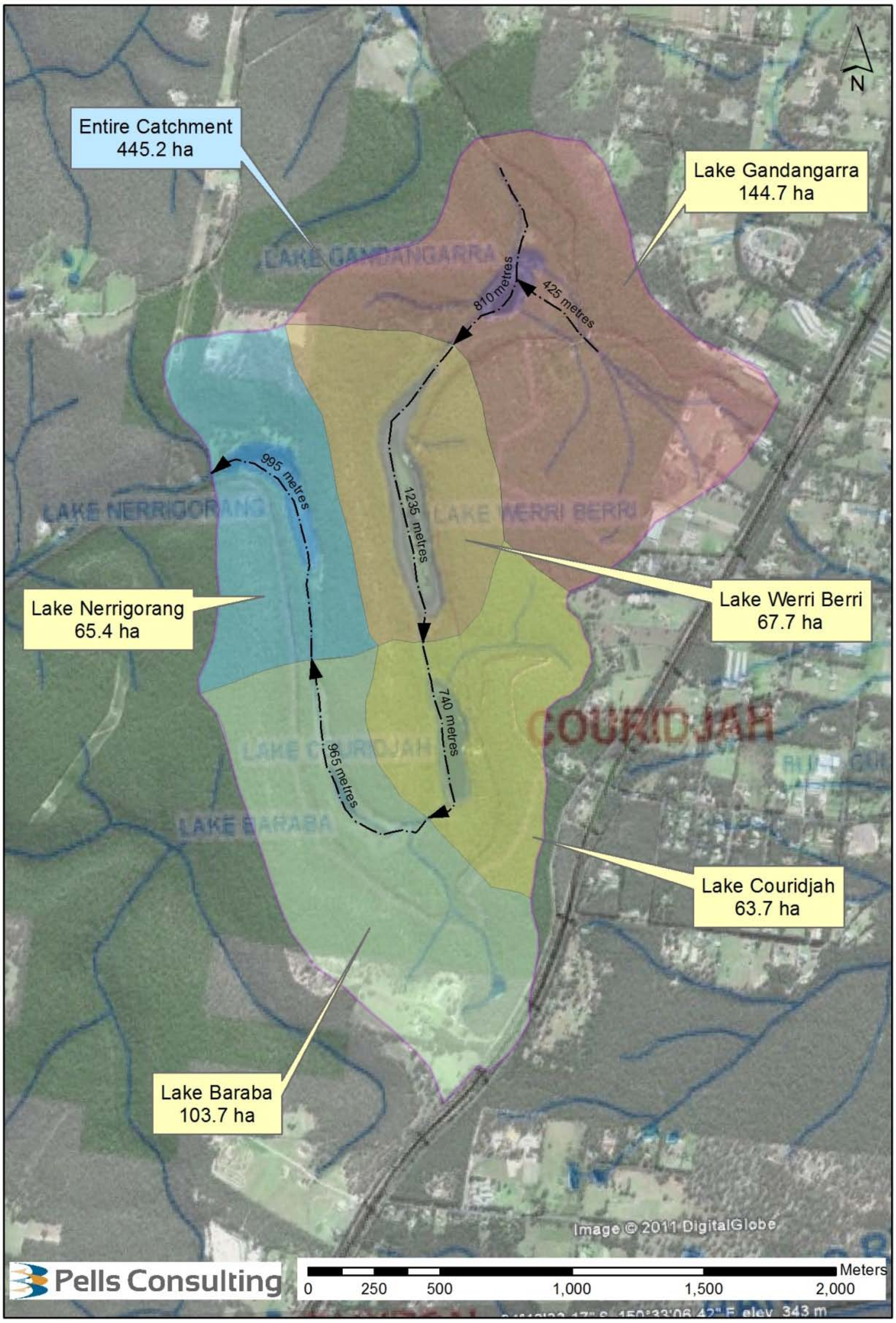


Figure 5.3: Catchment areas.

5.2.3 Stage – Surface Area and Stage – Storage Characteristics

Stage - v- Surface Area and Stage -v - Storage characteristics for each of the lakes were estimated by estimation of surface areas for each lake at 1m contour intervals up to the 313 m contour.

In order to establish hydrologic models which track the assessed water levels in the alluvium, it is noted that an alluvium mass defined by bedrock slopes of 1V to 4H will have a wetted cross sectional area “A”, and water-table surface width according to the relationships shown in Figure 5.4.

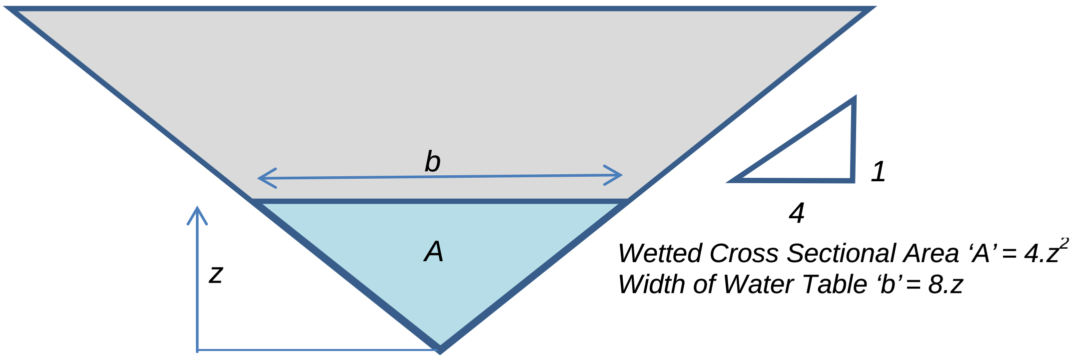


Figure 5.4: Paleochannel alluvium storage.

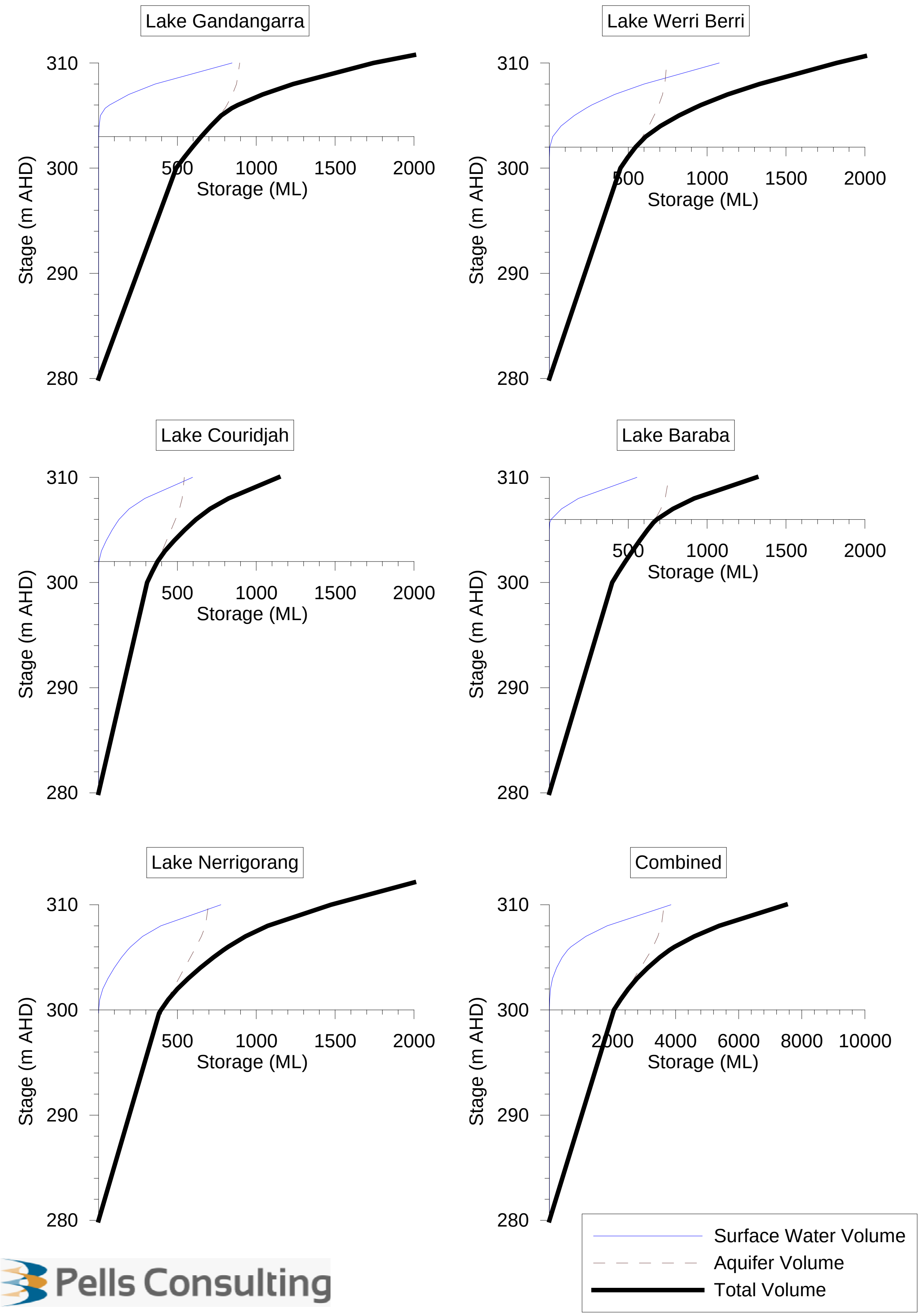
The valley width at the 310 m contour is typically 120 metres, giving an approximated depth of alluvium of 30 metres, having a base at approximately RL 280 m AHD.

Choosing a porosity of 0.25 to represent the alluvium, the volume of water in the alluvium can be estimated at a particular RL, for each channel reach as

$$\forall = l.z^2 \qquad (1)$$

Where $\forall$ = volume of water in the aquifer (m^3)
l = length of channel reach in m (from Figure 5.1)
z = depth of water table above base of alluvium

Plots of Stage – Storage characteristics presented in Figure 5.5 include this representation of the storage of water in such an assumed paleochannel.



Pells Consulting

Figure 5.5: Stage (depth) – versus – Storage volume curves.

5.2.4 Seepage

There are two components of groundwater movement that are of interest.

First is the movement of groundwater down the valley, within the alluvium. From Figure 5.4, it can be seen that the channel thalweg has a gradient of approximately 1V:1000H. Assuming that this is representative of the gradient of the water in the aquifer, and continuing with the assumed geometry of the alluvium (Section 5.2.3), an estimate of the down-valley flow can be given using Darcy's law, as:

$$Q_A \quad = k.i.4z^2 \qquad (2)$$

Where Q = discharge ($L^3.t^{-1}$)
k = hydraulic conductivity of the alluvium ($L^3.t^{-1}$)
i = hydraulic gradient
z = depth of water table above base of alluvium

The errors in the assumed geometry and gradient are expected to be small in comparison with the uncertainty in hydraulic conductivity estimates.

Secondly, the occurrence of baseflow from the surrounding sandstone formations and towards the lake is of interest. This can be estimated with Dupuit's formula as shown in Figure 5.6 and Equation 3.

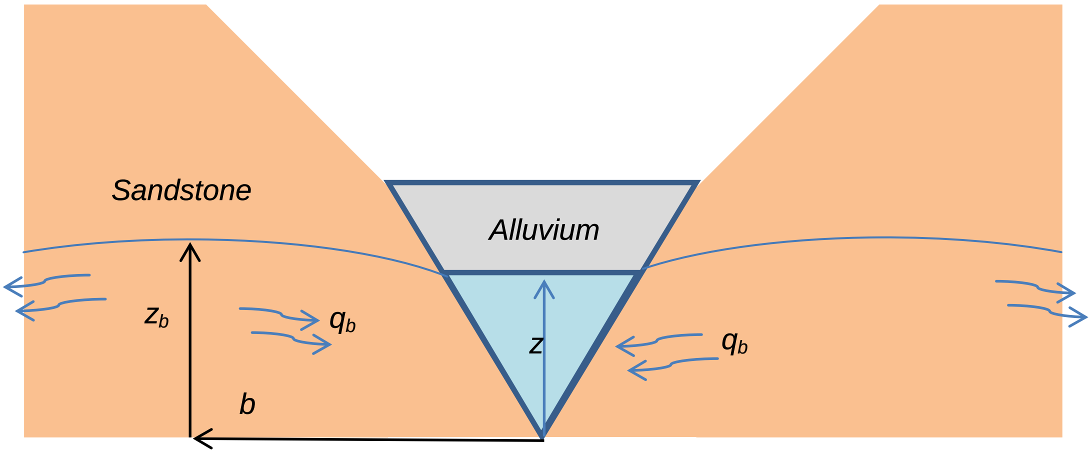


Figure 5.6: Groundwater seepage.

$$q_b \quad = \frac{k}{2b}.(z_b^2 - z^2) \qquad (3)$$

Where q_b = discharge per side of channel per unit length of channel ($L^2.t^{-1}$)
k = hydraulic conductivity of the sandstone ($L^3.t^{-1}$)
b = distance from channel to groundwater divide (L)
z = depth of water table above base of alluvium

For the Thirlmere Lakes, assuming that the groundwater divide corresponds with the catchment divide, the length of 'b' can be characterised as being typically 300 m. The uncertainty in geometry is small in comparison to the uncertainty in hydraulic conductivity estimates.

5.2.5 Lake Levels and Lake Pumping

Assessment of historical lake levels is given in Chapter 2 and summarised in Figure 2.10.

Water supplies have been harvested from the Thirlmere Lakes in the past.

A pumphouse was built in about 1870 at Lake Couridjah and fed to water columns at the nearby Couridjah Railway Station for servicing steam locomotives and for water supply to the settlement of Couridjah. The sandstone pump-house is still in existence adjacent to the Lakes. The standpipes, too, remain near the station, but have been disused since 1964.

Water was drawn from Lake Couridjah and used for replenishing steam locomotives after their haul up the steep grade from Picton. After the new rail line through Tahmoor was opened in 1919, water consumption for steam trains was reduced significantly but still continued until about 1964 while steam trains continued (approximately 4 per week).

A settlement was established in 1925 for sufferers of tuberculosis at Picton Lakes Village at Couridjah. Water for the village was supplied from Lake Couridjah.

At the time of writing of this report, no records indicating the pumping volumes were obtained. For the purposes of this study, the following pumping values were assumed:

1. Prior to 1940, pumping of 10 to 12 ML/month[28]
2. Between 1940 and 1960, pumping of 0.6 to 3 ML/month

These pumping rates are important to this study as they impact on the simulation of the 1940's drought, against which current water levels are compared. Further discussion is given below.

5.2.6 Climate Data

A Patched Point Dataset from the Queensland Enhanced meteorological Datasets (www.longpaddock.qld.gov.au/silo) for BoM station 68052 – Picton Council Depot was purchased. The Patched Point Dataset uses original Bureau of Meteorology measurements for a particular meteorological station, but with interpolated data used to fill ("patch") any gaps in the observation record, creating a continuous data set from 1 Jan 1889 to 26 April 2011. The dataset provides daily rainfall and a range of daily pan evaporation readings and evapotranspiration estimates. The monthly average rainfall and evaporation data and evapotranspiration estimates from the Patch Point Dataset from BoM station 68052 – Picton Council Depot is shown in Figure 5.7.

In Australia, ET_{ACTUAL} typically accounts for over 90% of rainfall (Ladson, 2008). It is apparent that the estimated Actual Evapotranspiration exceeds recorded rainfall. This is likely to reflect inaccuracies in the estimates, but it is suffice to say that it evapotranspiration is likely to account for a large proportion (i.e. over 95%) of the rainfall at this location.

In addition, a 'data drill' was undertaken (from the same source), for the co-ordinates 34 12's and 150 33'E. The data drill provides a synthetic timeseries which could be selected at a location closer to the lakes (~ 3.5 km). Rainfall data relevant to this location was extended to 1858 by Pells Consulting. The location of each dataset is shown in Figure 5.8 and rainfall data from both stations are summarised further in Figures 5.9 and 5.10 alongside historical lake level data.

[28] 10ML (megalitres) equals 2.6 million gallons. This is equal to 6 steam engines per day taking about 15,000 gallons each. The TB village may have taken about 2,000 gallons per day, which is equivalent to about 0.2ML/month.

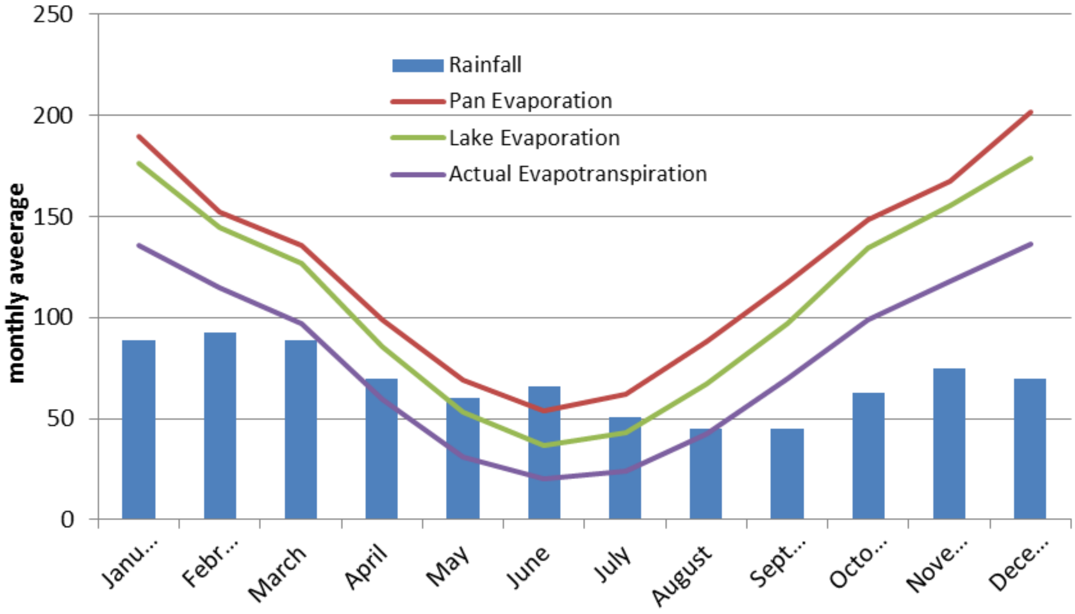


Figure 5.7: Average monthly rainfall and evaporation.

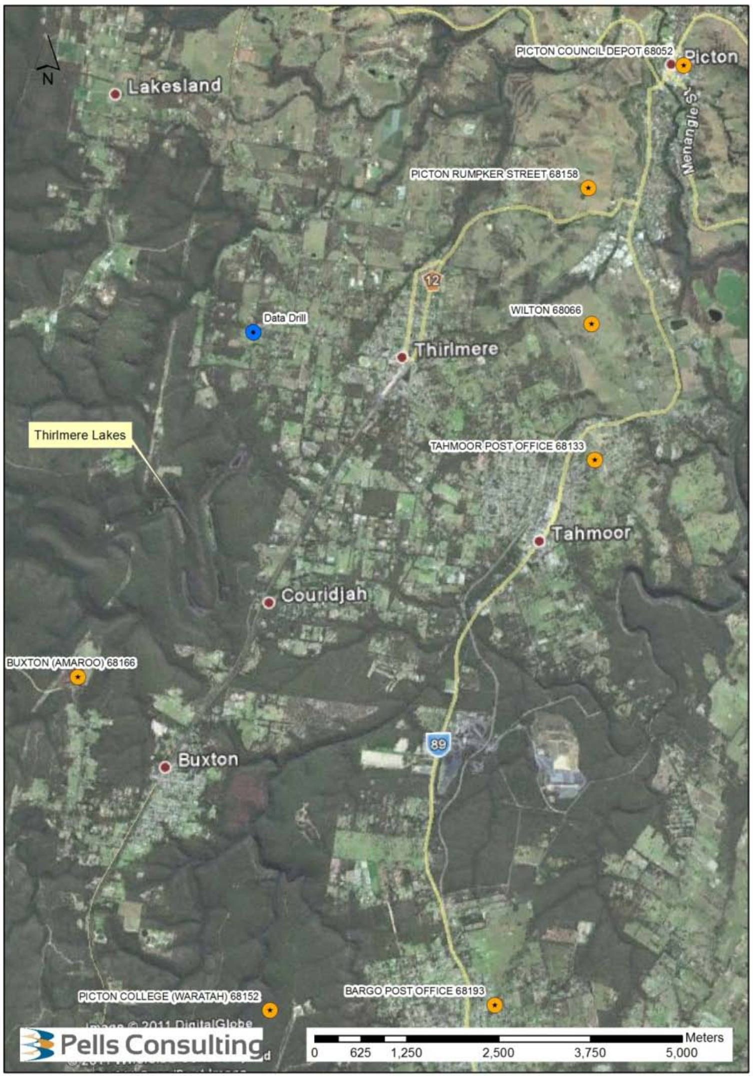


Figure 5.8: Rainfall stations.

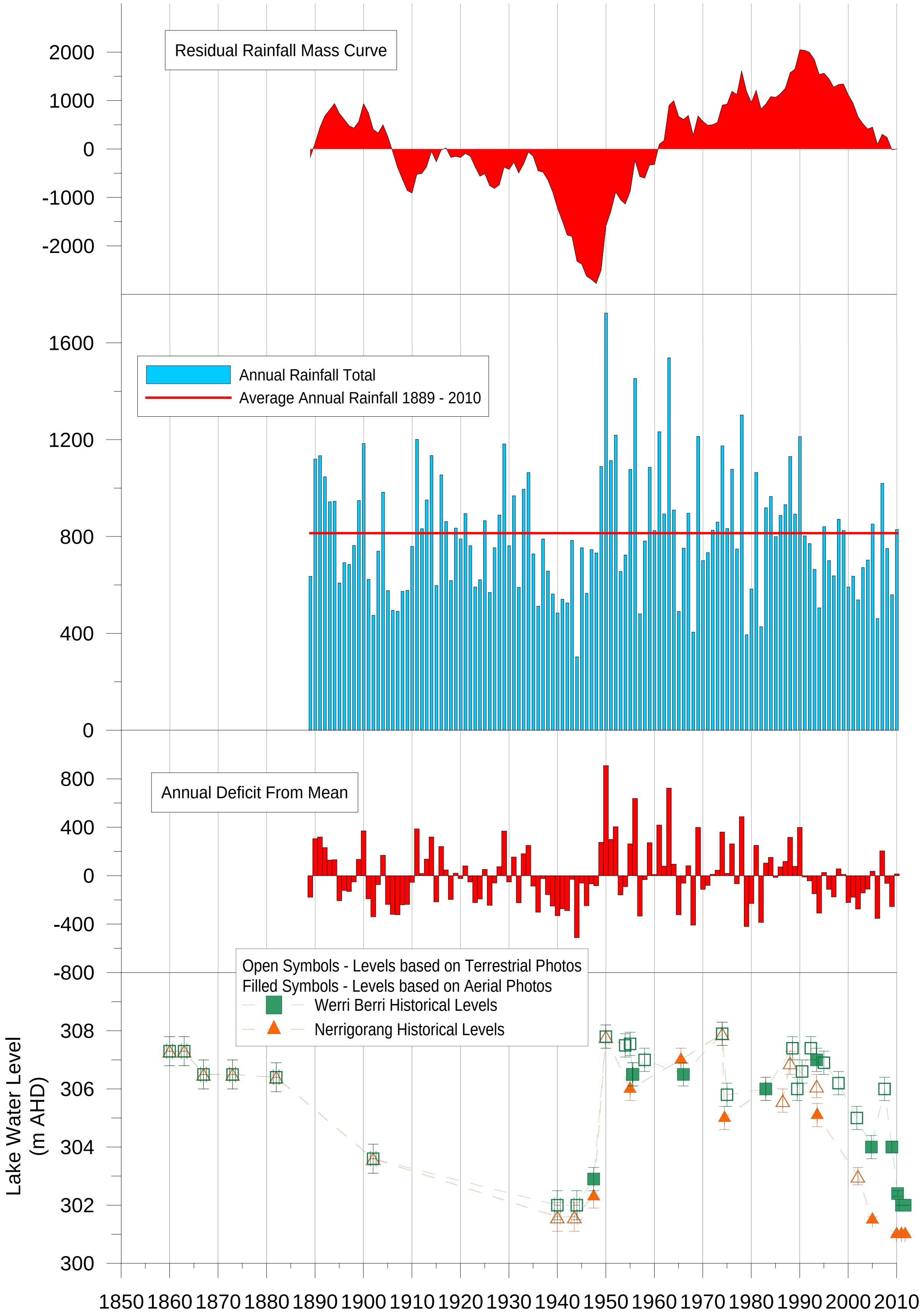


Figure 5.9: Rainfall summary using Picton PPD data.

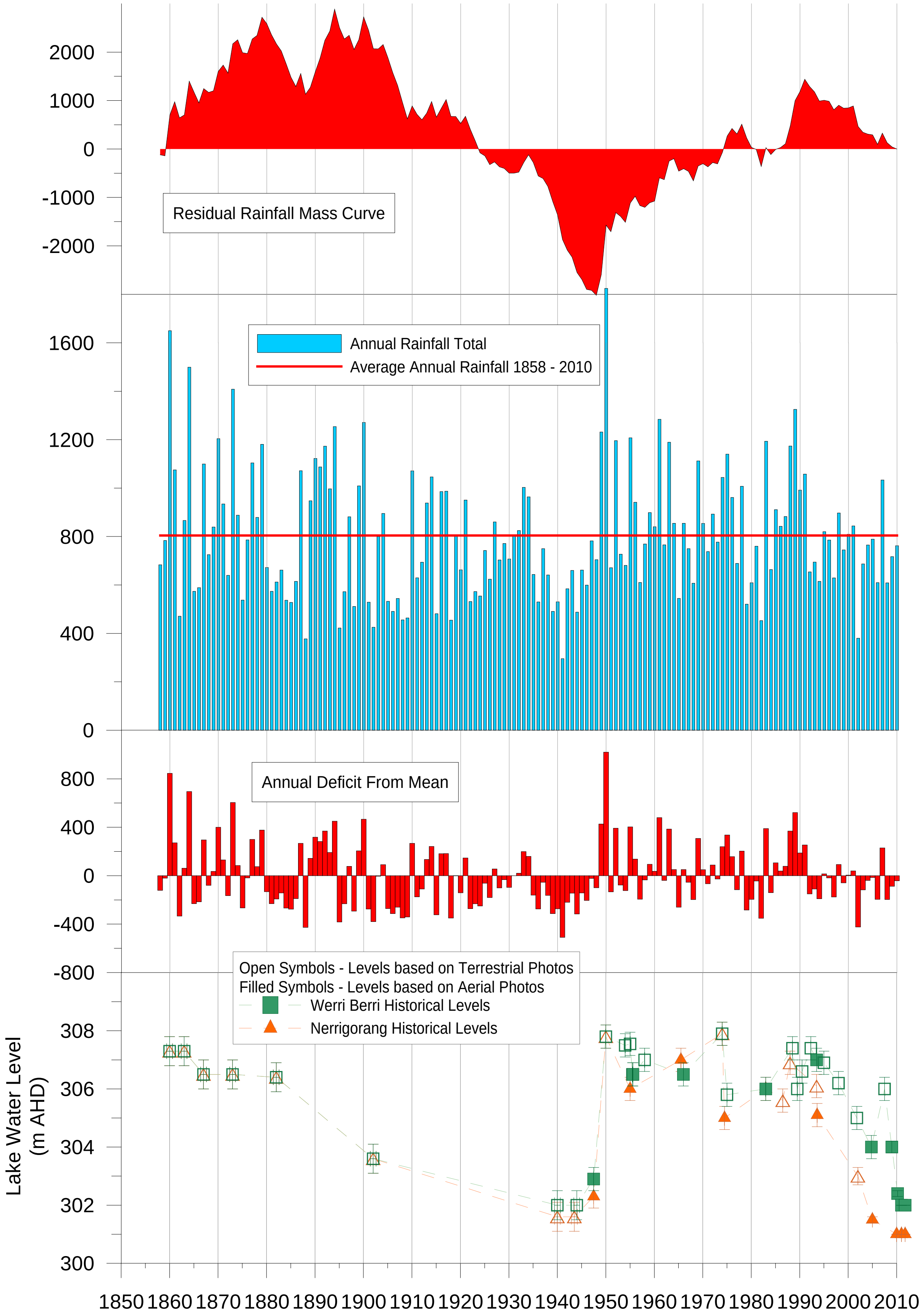


Figure 5.10: Rainfall summary using extended Drill Data for Thirlmere location.

5.3 Surface Water Modelling

5.3.1 Overview of Volumes

A conceptual water balance of the lakes hydrologic system is depicted in Figure 5.11.

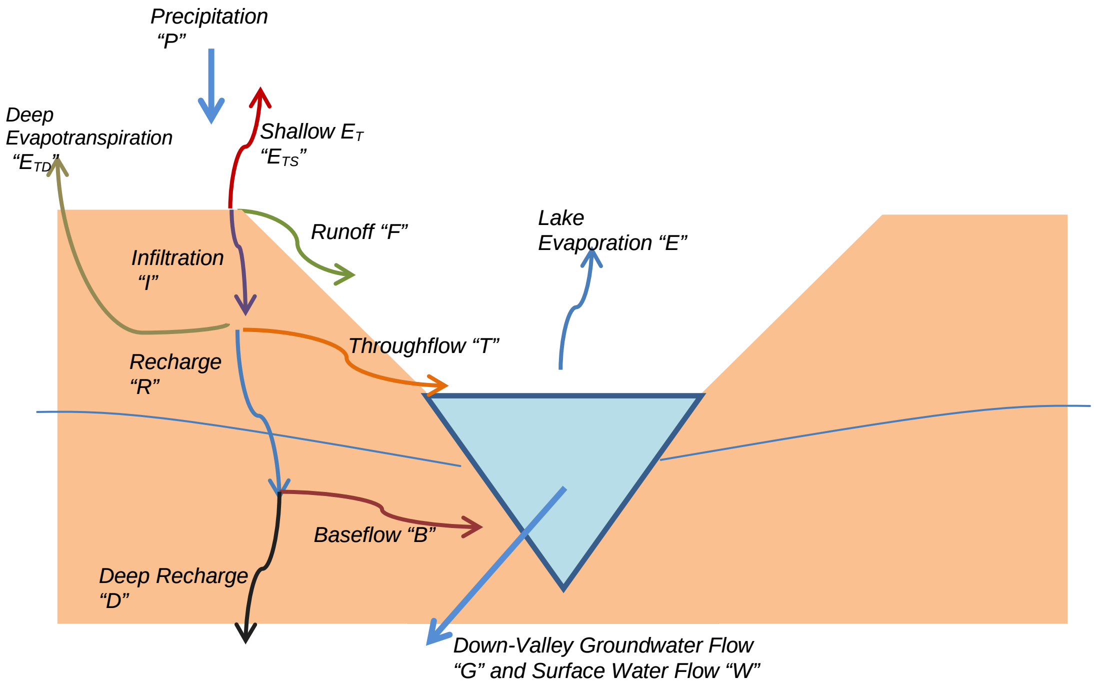


Figure 5.11: Components of the water balance.

Actual evapotranspiration (ET_{ACTUAL}) includes "evaporation from streams and lakes … transpiration from plants and transfer of water vapour directly from the surface" (Ladson, 2008). As such, we can write:

$$ET_{ACTUAL} = E_{TD} + E_{TS} + E \qquad (4)$$

The balance of external inflows and outflow to this system can be expressed as:

$$P = ET_{ACTUAL} + G + W + D + \Delta S_L + \Delta S_A \qquad (5)$$

The following mass-balance relationships are applicable to the internal flow components (fluxes are considered positive in the directions shown in Figure 4.13):

Runoff Balance

$$F = P - E_{TS} - I \qquad (6)$$

Infiltration Balance

$$I = R + T + E_{TD} \qquad (7)$$

Recharge Balance

$$R = B + D + \Delta S_A \qquad (8)$$

Lake Balance

$$F + T + B = E + G + W + \Delta S_L \qquad (9)$$

These values are indeterminate as there are more unknowns than equations. However, a broad examination of the quantities can be found by using the equations in a parametric study. Such an analysis was undertaken to estimate the general magnitude and sensitivity of each parameter for an assumed steady state condition[29] using the available climate data and Equations (1) to (9). The methodology and range of assessed values are summarised in Table 5.1.

TABLE 5.1
SUMMARY OF WATER BALANCE

Variable	Description	Source / Explanation	Range	
			mm/a	ML/a
P	Precipitation	From SILO rainfall patched dataset, Picton	800	3560
ET_{actual}	Actual Evapotranspiration	Taken as fraction of precipitation (various), ranging from 90% to 99%	720 to 792	3200 to 3525
E	Lake Evaporation	From SILO Lake evaporation data using derived stage-surface area relationships.	80 to 100	350 to 450
E_{TD}	Deep ET	Taken as a fraction of (E_{TD} + E_{TS}), $E_{TD} = \alpha.(E_{TA} - E)$. α ranges from 0.3 to 0.7	185 to 500	820 to 2225
E_{TS}	Shallow ET	Equation (4)	185 to 500	820 to 2225
F	Runoff	Ranging from 2% to 10% of precipitation	16 to 80	70 to 350
I	Infiltration	Equation (6)	215 to 600	950 to 2650
T	Throughflow	Equation (7)	-40 to 105	-180 to 470
R	Shallow Recharge	Equation (8)	-20 to 120	-90 to 530
B	Baseflow	Equation (3)	1 to 40	5 to 180
G	Down-Valley Groundwater Flow	Equation (2)	0.2 to 22	1 to 100
D	Deep Recharge	Equation (5)	-20 to 80	-90 to 360

* Equation (9) was used as a check

Despite the wide range of values used, the net quantity of water entering the lakes (ie F + T + B) remains relatively constant, ranging from a minimum of 80 mm/a to a maximum of 120 mm/a – i.e. 10 to 15% of rainfall. The value of F+T ranges from 40 to 120 mm/a.

The SILO patched point climate data (Picton) provides estimates of ET_{ACTUAL} that are over 100% of rainfall. This is probably in error, but it is accepted that ET_{ACTUAL} is large, probably over 95% of annual precipitation. This would indicate, for example, that less than 40 mm/a would be typically available to account for deep recharge “D” and down-valley groundwater flow “G”.

5.3.2 Lumped Model, SimHyd

The rainfall-runoff model *SimHyd* was used to estimate daily runoff volumes into the lakes for the period 1 January 1889 to 4 October 2011. This model provided runoff estimations using daily rainfall and potential evapotranspiration which were representative of the sum of: surface runoff (“F”); Throughflow (“T”) and Baseflow (“B”). Further information about *SimHyd* can be found in Podger (2004).

[29] It was assumed that during average climate conditions the net change in storage is zero (ie. $\Delta S_L = \Delta S_A = 0$) and the lakes do not overflow into Blue Gum Creek (i.e. “W” = 0)

For this model, the total catchment size for the entire Thirlmere Lakes system was used. Hence, model outputs were representations of the net daily runoff into all of the lakes. The outputs from SimHyd were exported into a spreadsheet where a simulation of the overall lake water levels was undertaken through application of Equation (9) and the Surface Area –v- Stage and Storage – v- Stage relationships representative of the sum of all lakes.

Iterations of the combined SimHyd and spreadsheet model were undertaken to examine the response of the catchment (and lake levels) to historical rainfall. Care was taken to ensure that values used in the model, and the balance of water, were reasonable and appropriate for the catchment (as per Section 5.3.1 above).

The aim of the study was to attempt to establish a model which simulated the complete sequence of historical water levels.

In the first instance, no representation of pumping was including in the model. It was found that, regardless of the parameters chosen (within the bound of 'reasonableness'), models which simulated low levels in the 1940's and recent times significantly under predicted the higher levels between 1950 and 2000. Similarly, models which approximated the higher levels between 1950 and 2000 would not acceptably simulate the lower levels of recent times and the 1940's. Significant effort was expended, with numerous iterations undertaken, to verify this finding.

Given this finding, the model was adjusted so that the representation of the well established 1950's to 2000's levels was achieved as well as possible, and the pumping of the lakes was included (with cognisance of reasonable representation of known pumping activities) so that the 1940's drought was well represented. This provided the best representation of historical levels.

The results for two selected simulations are shown in Figure 5.12 below. The water balances implied for each simulation are shown in Table 5.2.

TABLE 5.2
WATER BALANCE, SIMHYD MODELS

Item	Tag	Simulation 1		Simulation 2	
		mm/a	%	mm/a	%
Precipitation	P	826	100%	826	100%
Actual Evapotranspiration and Aquifer Changes	$E_{TA} + \Delta S_A$	809	98%	804	97%
Deep Recharge	D	0	0%	0	0%
Runoff, Throughflow and Baseflow	F + T + B	93	11%	107	13%
Lake Evaporation	E_{Lake}	75	9%	85	10%
Outflows	W	3	0.3%	4	0.5%
Groundwater Flow	G	1	0.2%	1	0.2%
Pumping	-	12	2%	15	2%
Change in Lake Storage 1/1/1889 - 4/10/2011	ΔS_L	0.8	0.1%	1.3	0.2%

The following observations are made:

- The models provided reasonable simulations of historical water levels.
- The values for runoff and evaporation are sensible and are consistent with water balance estimates undertaken above.
- Due to the long period of simulation prior to 1900, the representation of post 1900 levels were insensitive to the initial lake water level chosen.
- The models were relatively insensitive to values for down valley groundwater (G) and surface water flow (W), when those values were within the bounds discussed above.
- The representation of 1940's low levels was sensitive to pumping values chosen in the late 1930's and early 1940's. It was insensitive to pumping values in other times.
-

The models predict higher post-2000 lake levels than those observed.

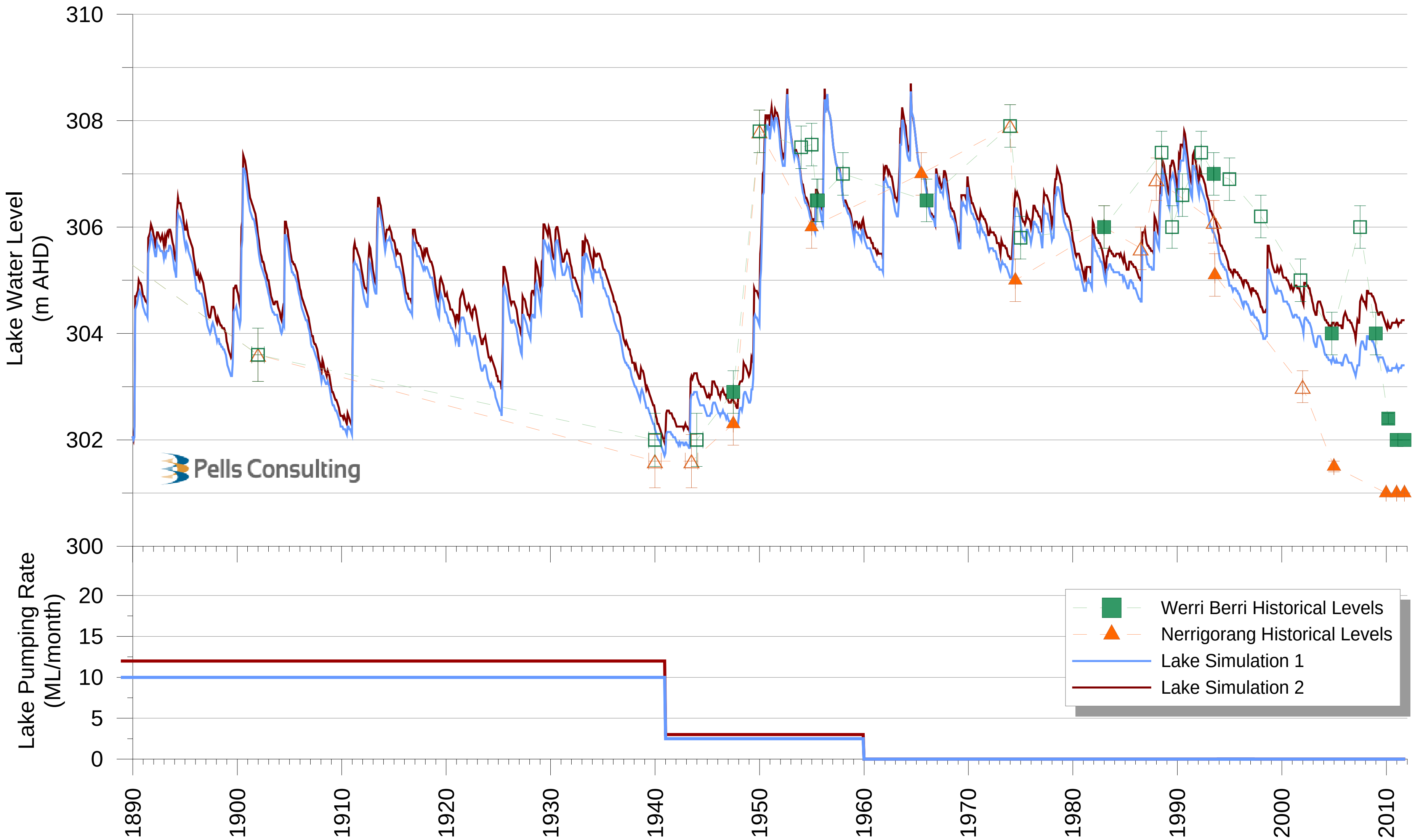


Figure 5.12: SimHyd Simulations.

5.3.3 Sub-Catchment Model, SWMM

A second simulation was undertaken using the hydrologic / hydraulic model *SWMM 5*. This model has the capability for simulation of rainfall-runoff processes as well as simulation of flow hydraulics, including flow into and out of lakes or reservoirs. As such, simulations undertaken in SWMM 5 could predict lake levels directly (ie. without the need to the secondary spread sheet stage used in the SimHyd simulations).

The SWMM 5 model is developed and maintained by the United States Environmental Protection Agency. Further details about the SWMM 5 model can be found at the USEPA website at http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/.

The SWMM model was established to represent runoff from each of the 5 catchments (Figure 5.3). This runoff was routed to three reservoir systems representing the lakes:

- "Upper Lakes" representing the combined storage of Lakes Gandangarra, Lake Werri Berri and Lake Couridjah;
- Lake Baraba; and
- Lake Nerrigorang.

Flow between these lakes, and from Lake Nerrigorang to Blue Gum Creek, were simulated with weirs, choosing dimensions representative of the surveyed elevations. An overview of the SWMM 5 model is shown in Figure 5.13.

The reservoirs in SWMM were assigned with storage and surface area characteristics representative of a combination of their respective lakes. Evaporation was applied to the reservoir surface in accordance with the surface area for the relevant water level, and daily pan evaporation data factored at 0.85 (which concurs with the Silo Lake Evaporation data provided).

The 'aquifer' routine in SWMM was invoked in the model with 5 aquifers used, 1 for each catchment. This provided a means to simulate the internal quantities of "B", "R", "T" and "E_{TD}" (as shown in Figure 5.11).

The model was run using daily climate data for the period 1st January 1889 to 4th October 2011.

As for the SimHyd model presented above, the aim was to establish a model which simulated the complete sequence of historical water levels. Iterations of the model were undertaken with different parameters until a model was found that provided both a sensible balance of quantities, and a good representation of historical lake levels. In undertaking these iterations, the following findings were made:

- Using the SWMM model, it was possible to reasonably simulate levels prior to 2000 (including the 1940's low levels) without the inclusion of pumping of water from the lake. However, these models over-predicted recent levels.
- Models that were established to fit recent (post 2000) levels underestimated historical levels significantly.
- When pumping was included, a model that provided the best fit was found. Such a model simulated the timeseries up to approximately 2007 well, but still over predicted the currently observed low levels.

A plot of simulated versus historical levels from the chosen model is shown in Figure 5.14. The model mass-balances and quantities are summarised in Table 5.3.

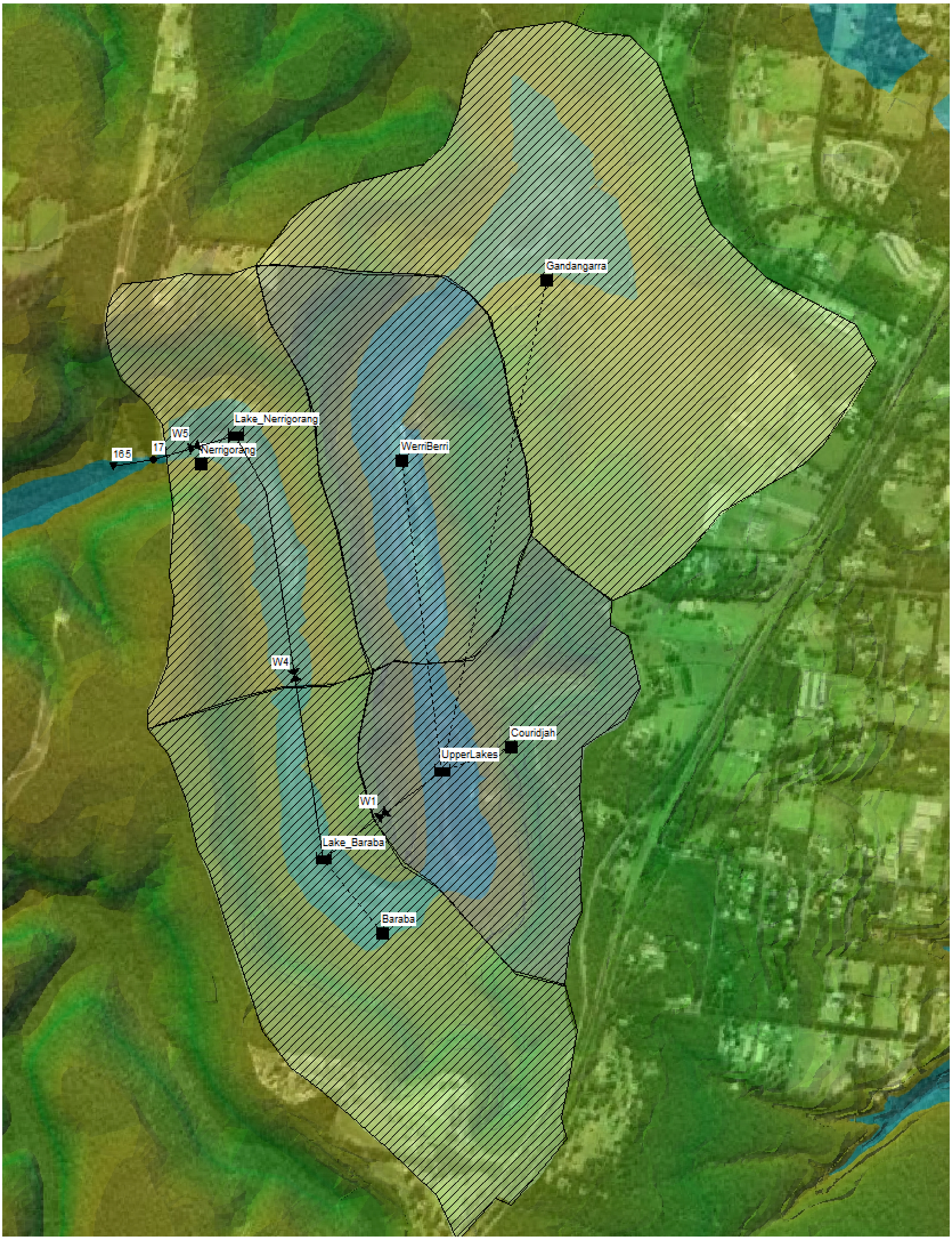


Figure 5.13: Overview of SWMM Model.

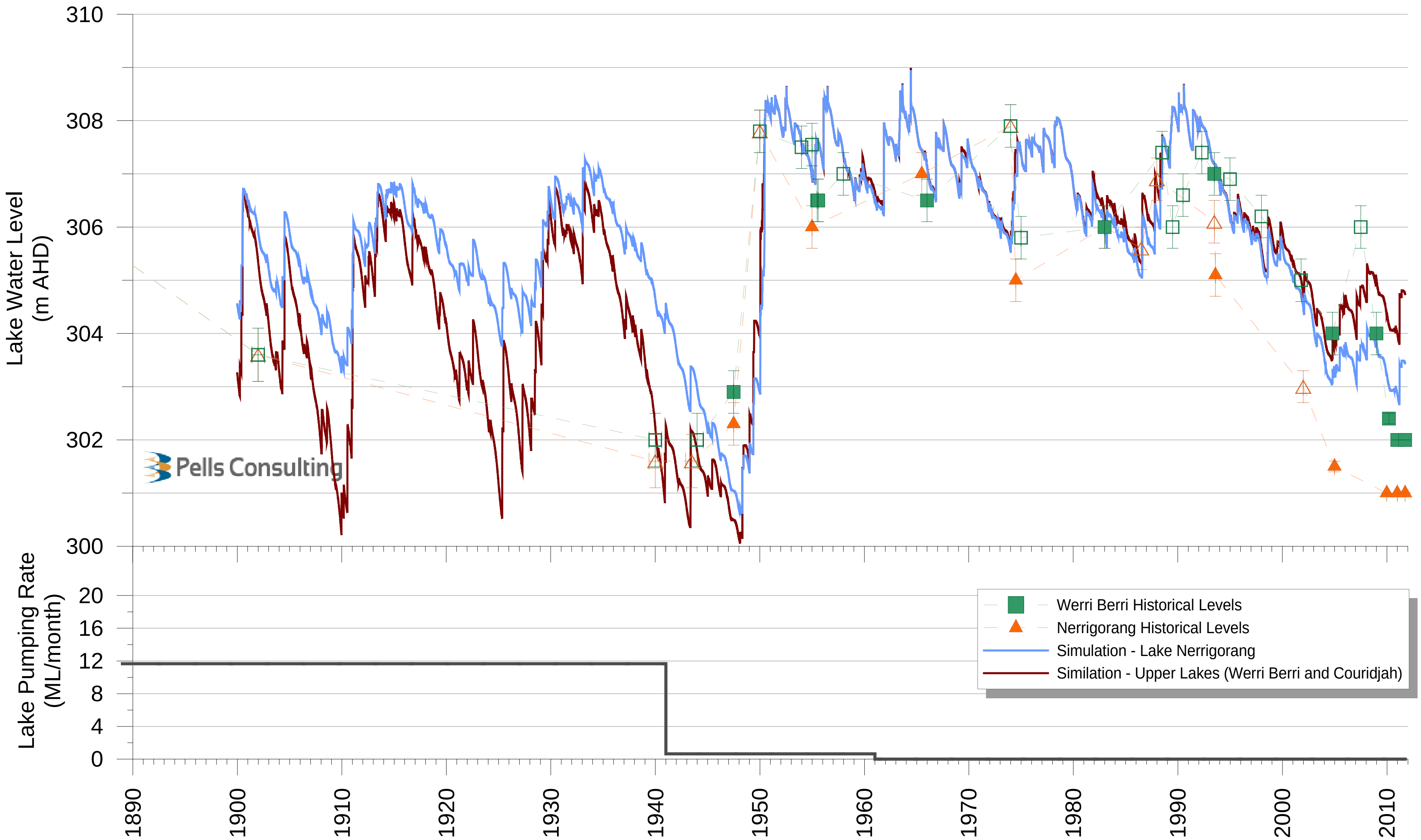


Figure 5.14: SWMM Simulation.

TABLE 5.3
MASS BALANCE OF SWMM MODEL

Item	Tag	Average Annual Volume (mm/a)	% of Total Rainfall
Precipitation	P	814	100%
Actual Evapotranspiration	E_{TA}	781	96%
Shallow Evapotranspiration	E_{TS}	26	3%
Deep Evapotranspiration	E_{TD}	652	80%
Lake Evaporation	E	103	13%
Deep Recharge	D	4	1%
Infiltration	I	666	82%
Runoff and Throughflow	F + T	122	15%
Baseflow	B	2	0%
Recharge	R	14	2%
Surface Water Flow	W	13	2%
Down-Valley Groundwater Flow	G	0	0%
Pumping	-	9	1%
Change in Lake Storage 1/1/1889 - 4/10/2011	ΔS_L	-0.703	-0.1%
Change in Aquifer Storage 1/1/1889 - 4/10/2011	ΔS_A	7	1%

5.4 Discussion

5.4.1 Limitations of Modelling

There are always limitations in the accuracy of data available for hydrologic modelling. The key hydrological parameters, being: the catchment size and shape; historical rainfall, and; evaporation data are known with reasonable confidence, although evaporation data are estimates only, based on pan evaporation measurements at Picton. There is further uncertainty in simulation of runoff to represent historical water levels of the Thirlmere Lakes due to uncertainty in data sources, such as:

- The timeseries of historical lake levels are intermittent and are assessed to have an accuracy of up to +/- 0.5 metres (as indicated with error bars on Figures).
- The stage-storage and stage-surface area representations of the Thirlmere lakes are based on limited ground survey data are hence approximations.
- The geometry, extent and characteristics of the alluvial aquifer underneath the lakes is not well known.
- Representations of groundwater seepages are based on estimates of hydraulic conductivity.

- The model response to drought is calibrated against one key event, being the 1940's. However, it is known that pumping occurred from lakes at this time. Historical records of pumping were not found for the study, and the simulated levels in the 1940s are found to be sensitive to the degree of pumping.

It is important to note that the solutions to runoff and evaporation balances presented above are non-unique. That is, there are many hydrological parameters used, and the simulated lake level timeseries could be approximated by a numerous combinations of alternative parameters.

Nonetheless, the water balance summaries presented with the modelling results are sensible, and are consistent with known or established understanding of hydrological processes. While the modelling is not deterministic, it presents a broad, yet rational, representation of the catchment processes.

5.5 Findings

Historically, the water levels in Thirlmere Lakes have been very low at times. These low levels have occurred prior to mining and have resulted from climatic processes *and* pumping of water from the lakes. The fall in water levels since 1990 have been accompanied by net deficit in rainfall in this period. It is clear that climatic forces go some way to explaining the current low water levels.

However, the hydrologic modelling presented in this chapter suggests that climatic variables do not fully explain the current low water levels. Notwithstanding the uncertainty in modelling, and subsequent to undertaking of numerous iterations using various parameters, it was evident that:

- Models which reasonably approximated historical levels do not predict recent levels well. The current water levels in the lakes are lower than predicted by such models.

- Models tweaked so that they match current levels under-predict historical levels significantly.

- Since the onset of mining, Lake Nerrigorang has exhibited lower levels relative to other lakes. These lower levels are not represented in the SWMM modelling of Lake Nerrigorang.

- The lakes are currently 1.5 to 2.5 m lower in level than predicted by the models presented which are considered to be the most robust.

Therefore, the models indicate that the historical water balance at the lakes that applied between 1900 and 1990 prior to mining of longwalls 3 and onwards, does not give a reasonable simulation of recent levels – the inference is of loss of additional water from the balance for current water levels to occur.

5.6 Postulations

An impact to the hydrological balance that could be expected from longwall mining is an increase in 'deep recharge' (D), as water is drawn downwards to replace that removed from mine dewatering. From Figure 5.11 above, it is evident that this would impact on the supply of baseflow interactions with the lakes. It is a rational that increases to "D" following mining would explain the recent changes in water balance of the lakes as suggested by hydrologic modelling.

Significant water level decline in Lake Nerrigorang commenced in 1991, about 4 years before significant decline commenced in Lake Werri Berri and Couridjah. Lake Nerrigorang was empty by late 2009, and there is robust anecdotal evidence it was not empty in WW2. We hypothesize that the paleovalley beneath Nerrigorang is eroded through the Bald Hill Claystone (see Figure 3.3) and this has allowed a greater increase in "deep recharge" (D) compared with the other lakes.

It is important to note that such an increase in "deep charge" (D) would <u>not</u> impact on the immediate infiltration and runoff processes that occur during large rainfall events. An impact of mining through the change in "D" does not preclude Thirlmere Lakes refilling under large rainfall events. However, the changes to "D" would impact subtly on the duration and persistence of lake water levels, such as how long higher water levels in the lakes would persist after refilling.

6.1 Introduction

This chapter deals with the groundwater regime in the area from the Thirlmere Lakes to about the town of Tahmoor (See Figure 6.1).

Figure 6.1: Area considered for groundwater assessment.

The assessment given herein are based on:

- information from monitoring by Tahmoor Colliery;
- information from private, registered, bores in the area, most of which were installed prior to the commencement of Tahmoor Colliery;
- data from monitoring bores installed, in mid-2011, at three locations around the lakes by NSW Office of Water (see Figure 6.2);
- data from some regional boreholes given in the NSW Office of Water report of December 2010;
- hydrogeological data given in Chapter 3; and
- mine layout information given in Chapter 4.

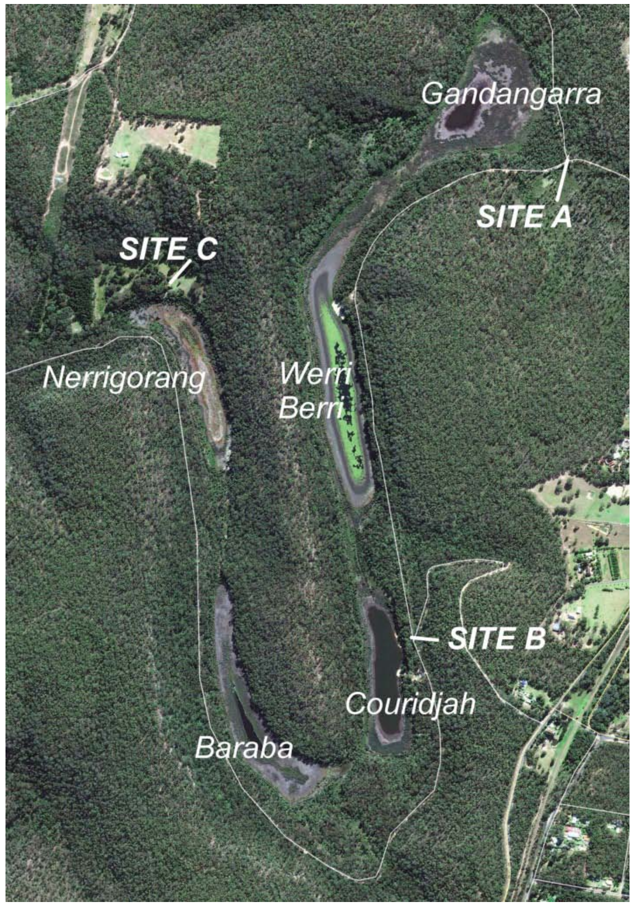


Figure 6.2: Locations of NSW Office of Water Monitoring Piezometers.

In addition computer-based groundwater modelling has been undertaken to gain an understanding as to how flow directions and groundwater pressures may have changed as a result of the underground mining.

It must be appreciated that a comprehensive study of the groundwater regime, and changes to that regime, around the lakes, would be a multi-million dollar study, and even with such investment, uncertainties would remain. Extensive borehole drilling, ground permeability testing, fault investigations, and flow and pressure measurements, extending over several years, would be necessary to gain a detailed understanding of the present groundwater regime. But even then we would not know details of the regime as it existed prior to mining.

Thus we do not presume that this chapter provides all that can be known about the groundwater regime. However, we think that the facts documented herein, and the relatively simple hydrogeological analyses, give a reasonable understanding of changes that have probably occurred, in the vicinity of the lakes, during the time period of the operation of Tahmoor Colliery.

Three important points must be made at the outset.

Firstly, it is very important, when considering groundwater systems, to separate flow quantities from changes in the pressure regime. This is a difficult concept for many people and is best illustrated by an example.

> There are areas of coal mining in the southern and northern coalfields that are directly beneath lakes and reservoirs. In several of these locations there is incontrovertible evidence that seepage is downwards towards the mine workings, creating significant pressure changes that affect water levels in monitoring bores. Yet the amount of water entering the mine workings is often so low that the workings are dry and dusty.

Just because flow directions may be altered to being towards underground workings, does not mean that substantial quantities of water are flowing to those workings. This may occur, but does not follow automatically. It is a function of the permeability of the ground.

Secondly, because of the typically low permeability of the Sydney Basin rocks, it can take a very long time for a new equilibrium state to be reached following underground mining. This period may be 10s of years or even 100s of years. So conclusions reached from short term monitoring can be inappropriate.

Thirdly, the concept of aquifer[30] and aquiclude[31], as widely used in the groundwater profession, can be misleading. Our issue is with the term 'aquiclude'. No layer of rock between the Bulli Seam and the Thirlmere Lakes is impervious. To be so, the layer would have to be like a thick sheet of plastic. There are layers that have very low permeability, but this is still finite and cannot be ignored. These layers are not aquicludes.

6.2 Tahmoor Colliery Data

We do not have access to all the data collected at Tahmoor Colliery over the past three decades. The information we have obtained is from the Annual Environmental Management Reports (2004 to 2010) and from a report titled "Xstrata Coal – Tahmoor Colliery, End of Longwall 25, Streams, Dams and Groundwater Monitoring Report" of 15 June 2011.

This latter report "provides a compilation of physical and geochemical groundwater, upland plateau stream and Bargo River stream monitoring…. since 2004". The important point is that this work covers the area of longwalls 22 to 25, which are well away (5km to 8km) from the Thirlmere Lakes. The report deals mainly with creek flows (Myrtle Creek, Redbank Creek and Bargo River) that we consider to be substantially separate from the issue of the Thirlmere Lakes. It should also be noted that Myrtle and Redbank Creeks are directly undermined, so that cracking observed in Myrtle Creek cannot be transposed to indicate that there could have been cracking of the strata beneath the Thirlmere Lakes.

[30] An 'aquifer' is simply 'a layer of rock which holds water and allows water to percolate through it" (Macquarie Dictionary).
[31] An 'aquiclude' is impervious to the flow of water (Huisman, *Groundwater Recovery*, 1972).

Figure 6.3 is Drawing 1 from the 15 June 2011 report, and is said to show the Tahmoor Colliery piezometer and stream monitoring sites. It shows the locations of some of the private bores discussed in Section 6.3, below, but the document itself gives no information in regard to those bores. What the report does say is summarised below, using material extracted from the report.

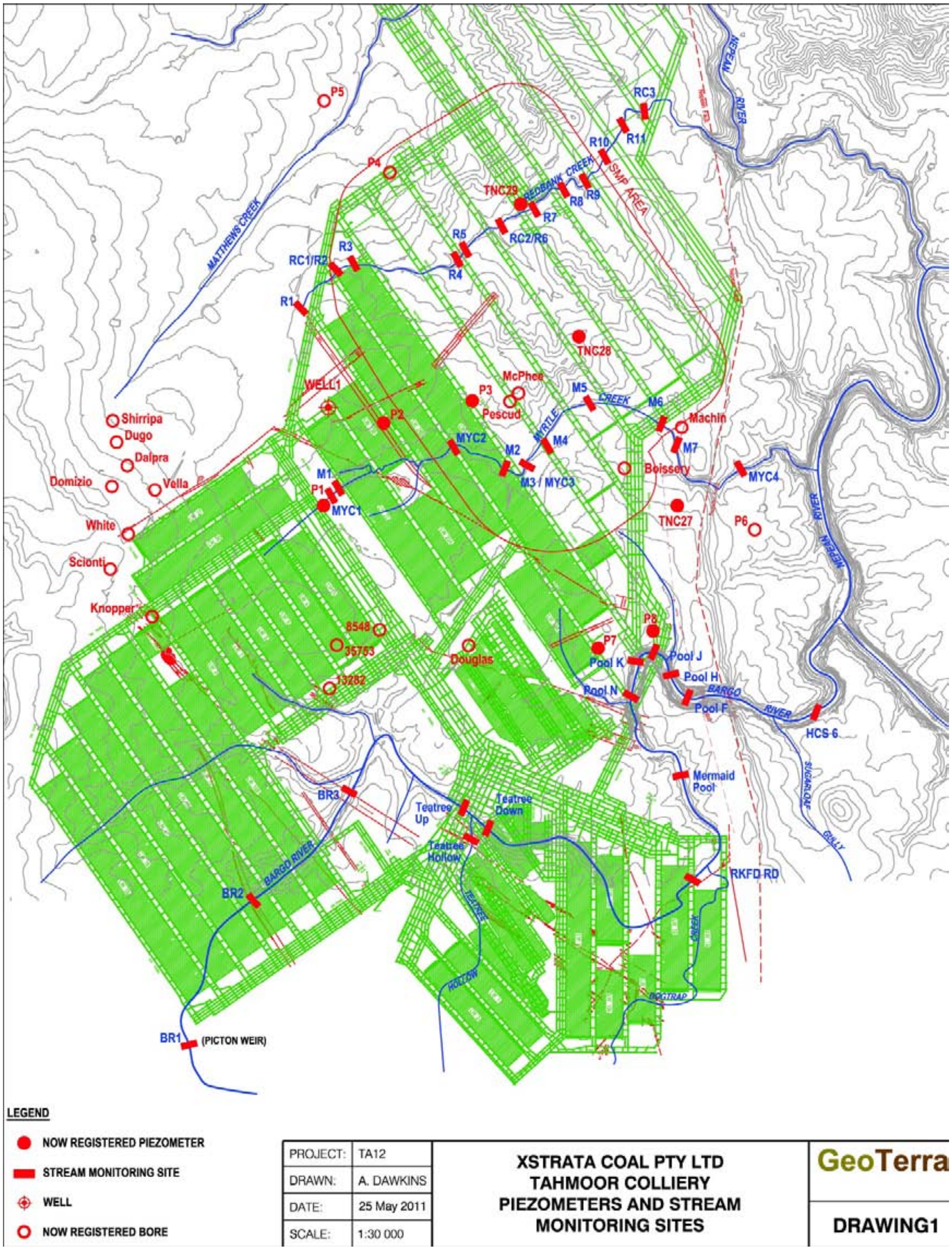


Figure 6.3: Drawing 1 from GeoTerra report of 15 June 2011.

5.9 Groundwater

5.9.1 Groundwater Levels Over Longwalls 22 and 23

Regular manual and data logger based standing water level monitoring began in June 2004 with the drilling of P1 by the colliery, which is located 450m south west of Panel 22.

Between August 2004 and June 2007, P1 depressurised by approximately 5.6m and then recovered by approximately 1.8m up to August 2008 during the extraction of Longwalls 22 to 24. Since Longwall 25 began in late August 2008, P1 has depressurised then recovered by approximately 0.9m.

Piezometer P2 is within a remnant coal exploration bores over Panel 23B. Depressurisation and subsequent recovery occurred over the northern end of Longwall 23B in piezometer P2 in three stages between January 2005 and April 2008, for a total maximum drawdown of approximately 8.4m. The bore recovered marginally above its original (pre December 2004) water level between April 2008 and July 2009. Since Longwall 25 started, P2 has depressurised by approximately 2.4m.

5.9.3 Groundwater Levels Outside the SMP Area

Piezometer P4 is a manually monitored bore in an undeveloped, unsecured block of land, 300m northeast of Panel 26.

P5 is a disused private bore 950m north-west of Panel 26 that was used for general domestic / irrigation water. Monitoring ceased in P5 in August 2010 due to a request from the property tenant.

P6 is a manually monitored private bore, which has never been used, located 1.1km east of Panel 26.

During the extraction period of Longwalls 22 to 25, P4, P5 and P6 have had relatively stable water levels.

Private bores GW109010 (Pescud) and GW105254 (McPhee) are sealed bores and their water levels are not monitored.

(GeoTerra Table 15) Groundwater Level Variations
Bore Monitoring

Bore	Monitoring Start Water Level (mbgl)	Minimum Water Level (mbgl)	May 2011 Water Level (mbgl)	Comment
P1	7.47	12.950	11.44	Subsidence affected within LW22 20mm subsidence area
P2	40.33	48.44	43.31	Subsidence affected within LW23B 20mm subsidence area
P3	50.70	50.42	33.71	No subsidence affect, bore located over LW 25 / 26 chain pillar
P4	37.05	37.04	37.32	No subsidence affect, bore located over western end of LW 27
P5	24.85	24.85	25.10	No subsidence affect, bore outside of LW 22 to 26 20mm subsidence area
P6	94.23	94.76	94.13	No subsidence affect, bore outside LW22 to 26 20mm subsidence area

Bore	Monitoring Start Water Level (mbgl)	Minimum Water Level (mbgl)	May 2011 Water Level (mbgl)	Comment
P7	55.14	55.14	48.89	No subsidence affect, bore located between east end of LW25 and the Bargo Gorge
P8	84.63	84.63	82.53	No subsidence affect, bore located between east end of LW26 and the Bargo Gorge

This report also discusses some vibrating wire piezometers. These were installed in late 2008, are far from the Thirlmere Lakes, and the data, at this time, is considered to be of no significant relevance.

It is apparent that Tahmoor Colliery has information regarding groundwater conditions, particularly in relation to private bores (see Figure 6.3) which is unavailable to us.

Our assessment of the available colliery data, summarised above, is that most of it covers the post-2004 area of the mine, which is 5km or further from the lakes than longwalls 3 to 9, 14 to 19, and 20 and 21. Therefore the data are not directly relevant to the matters covered by this report. However, the data have general relevance as they indicate that, while the monitoring piezometers show lowering of groundwater pressures in association with undermining, or nearby mining, and downward flow gradients, there is not complete depressurisation of the strata above the longwalls. The data also seem to suggest that changes to the groundwater regime are not uniform, and are probably controlled by major geological structures (fault and intrusive dykes).

6.3 Private Bores

Figure 6.4 shows the locations of private bores recorded on the NSW government database.

On 22 September and 4 October 2011, visits were made by personnel from Pells Consulting to speak to the owners of most of the bores shown on Figure 6.4. The owners could not be contacted at the following sites: 18568, 34518, 37289, 10584, 60238 and 34518.

Notes have been kept on our files in respect to what the other owners told us. However, because of potential legal implications we do give those notes in this report. What we can say is that it is reported that water levels, or yields, from the following bores have been affected since the time that longwall mining occurred beneath or within about 1km of those particular bores.

- 49796
- 42537
- 11200
- 37860

Two other bores on properties known to owners of the above bores were said to have lost their yield.

The impacts have been substantial. Bores of 60m to 120m depth, with registered yields of up to 3 litres per second are reported to have lost all or most of the yield in the periods corresponding with longwall mining beneath, or near, to the bore locations.

Equally well, the following bores are considered by their owners as having not been affected: 29143 and 11299, although the latter owner had only owned the property subsequent of it being undermined.

Figure 6.4: Locations of registered bores.

Some issues with private bores are alluded to in the available AEMR reports, as set out below.

<u>2008, 2009, 2010 Reports (same words)</u>

*"**4.5.1 Private Bores***

Near surface ground water levels may be affected by mine subsidence. Any property owner that has a registered borehole affected by mine subsidence is provided with water until the area stabilises and the bore is re-established. Each bore owner is contacted and 'Subsidence Management Plans' developed where there are identified risks.

4.5.1.1 <u>During Reporting Period</u>

During the 2007 to 2008 reporting period a poultry farmer reported problems with iron oxide particles hampering his facility by blocking fine mist sprays. In the interim, the colliery is supplying water to the poultry farmer."

<u>2007 Report</u>

*"**4.4.1 Bores***

a. <u>During Reporting Period</u>

Water bore owners affected by Longwall 21 have had all repairs done as necessary. During the last reporting period the poultry farmer reported problems with iron oxide particles hampering his facility by blocking fine mist sprays."

<u>2006 Report</u>

*"**4.4.1 Bores***

a. <u>During Reporting Period</u>

Water bore owners affected by Longwall 21 have had all repairs done as necessary, excluding one final installation of a pump. During the last reporting period the colliery undertook to the installation of one new bore and pump at the poultry farmer property, and one new pump for a neighbouring property. The market gardener property is still one mains supply.

b. <u>Next 12 months</u>

One final property is will have a new pump installed in July 2006. All repairs will then have been completed and mains supply disconnected.

No bores have been identified within the zone of influence for longwalls 22 and 23. A Surface Safety and Serviceability Management Plan (SSSMP) has been prepared by Geoterra for bores located within the Mining Application Area for Longwalls Panels 24 to 26."

2004 and 2005 Reports

"4.4.1 Bores

a. Preceding 12 months

2 bore owners, a Poultry farmer and Market gardener were identified as low risk of bore water loss due to their location in respect of longwall 21. Due to the potential business risk and volume of water required by the Poultry farmer, a Subsidence Management Plan was prepared. As part of the SMP a water main was installed as a back-up for these owners. The mains water was turned on in early November 2003. The bore has not recovered by the end of the Review period."

If, as we think, the poultry farmer referred to repeatedly in the AEMR reports, is the owner of 49796 then we note the following.

That 61m bore, installed in 1980, is reported as having lost all water at the time of longwalls 15,16 and 17. The owner was then connected to the town water supply, and some time later a new, ~ 120m deep bore, was installed. The owner reports that the new bore produced water with such high iron content that it blocked the misting system in his poultry shed. This new bore, is not used, and he is still using town water.

Our conclusions from the available data on private bores, east of the lakes, and near or above longwall panels, are:

1. There have been substantial decreases in groundwater head (water level, in lay terms), and yield, at certain bores having depths ranging from 60m to 120m.

2. Other bores, some quite near to affected bores, have not shown comparable decreases, and therefore we conclude that major geological structures (near vertical faults and dykes) are playing an important note in the post-mining groundwater regime.

6.4 NSW Office of Water Monitoring Plan

In mid-2011, NSW Water installed four groundwater level monitoring boreholes (piezometers) in the lakes area, one at the north end of Lake Nerrigorang, two near the old Lake Couridjah pump station, and one within the area of Lake Gandangarra.

Figure 6.5 shows the locations of the piezometers and Tables 6.1 and 6.2 give relevant data as supplied by NSW Water. Ground level at the two piezometers at Lake Couridjah was measured, by ourselves, on 22 August 2011, using a combination of GPS (RTK mode) and optical levelling, as 309.1m[32].

[32] This should not be taken as the official collar level.

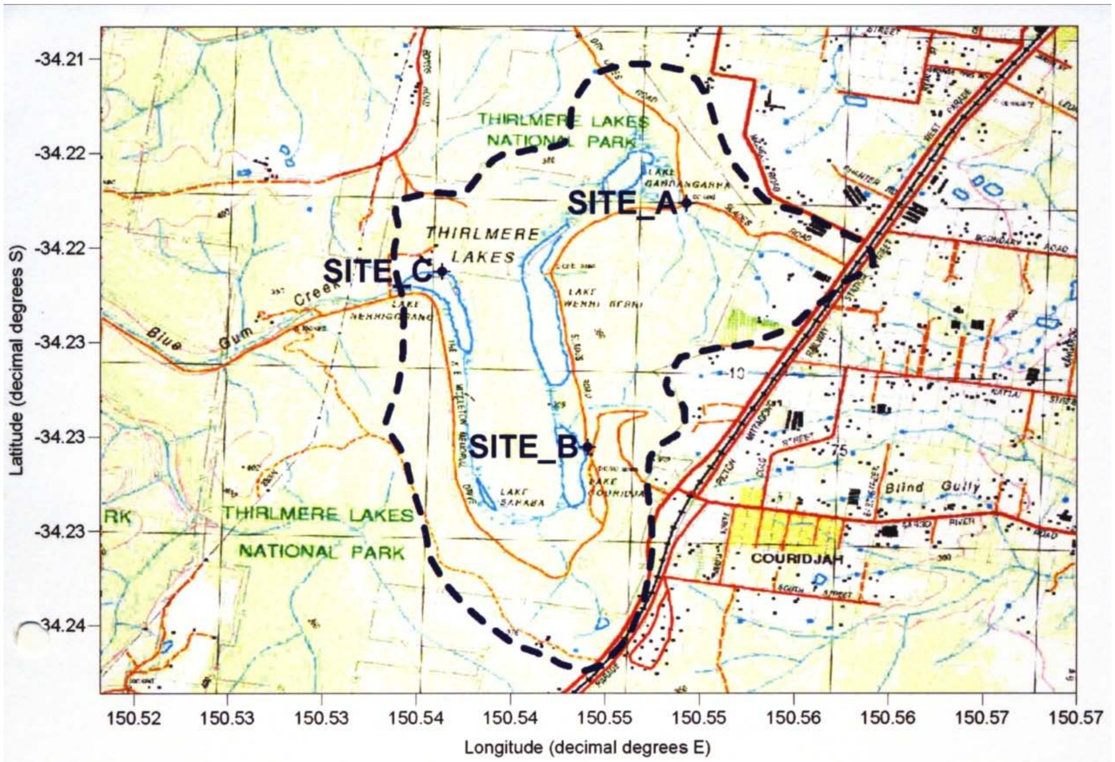


Figure 6.5: Locations of NSW Water piezometers.

TABLE 6.1
SUMMARY DRILLING DETAILS FOR THIRLMERE LAKES NATIONAL PARK MONITORING BORES

Site	Site identifier	Hole identifier	Depth drilled (m)	Method	Depth completed (m)
Lake Gandangarra	A	GW075411	28	HQ core/ Rotary mud	28
Lake Couridjah	B	GW075409/2 GW075409/1	100 24	TUBEX/ Rotary air HQ core/ Rotary mud	100 15
Lake Nerrigorang	C	GW075410	18	HQ core/ Rotary mud	17.5

TABLE 6.2
SUMMARY STANDING WATER LEVELS FOR THIRLMERE LAKES NATIONAL PARK

Site	Hole identifier	Standing water level (mbgl)	Time	Date
A	GW075411	12.74	12:46	28-JUN-2011
		12.82	16:00	17-AUG-2011
		12.885	15:20	22-SEP-2011
		12.96	10:40	13-OCT-2011
B	GW075409/1	8.35	13:09	28-JUN-2011
		8.45	15:40	17-AUG-2011
		8.532	14:15	22-SEP-2011
		8.64	11:06	13-OCT-2011
	GW075409/2	16.99	13:13	28-JUN-2011
		17.12	15:25	17-AUG-2011
		17.215	14:08	22-SEP-2011
		17.19	11:09	13-OCT-2011
C	GW075410	9.19	13:32	28-JUN-2011
		N/A	N/A	17-AUG-2011
		9.355	14:45	22-SEP-2011
		10.41	11:30	13-OCT-2011

We consider that the two piezometers at Lake Couridjah are of most significance. These indicate that the water level in the shallow borehole (15m deep) is about 8m higher than that in the Hawkesbury Sandstone at a depth of about 100m. this indicates a significant downward seepage gradient. Alternatively it may be thought of as a perched water table in the Recent colluvium, controlled by Couridjah lake level, and a much lower groundwater pressure in the Hawkesbury Sandstone, one that can reasonably be ascribed to a downwards flow direction.

6.5 Department of Water Regional Bores

The following information is quoted from the NSW Office of Water report of December 2010.

The NSW Office of Water maintains a series of seven groundwater monitoring bores at five sites throughout the Southern Highlands, centred around Moss Vale. The nearest bore is located near Mittagong approximately 15 km to the southeast of Thirlmere Lakes. Groundwater levels are being monitored in order to assess aquifer dynamics such as recharge processes and observing extraction impacts. The installation and construction of these bores in 1998 was undertaken to establish monitoring in an area of significant groundwater extraction. This area was subsequently embargoed in 2004.

Table 2 NSW Government Southern Highlands monitoring bore summary (modified from Willing 1998)

Bore no Site Depth (m bgl) Slotted interval (m bgl) WBZ* depth (m bgl) WBZ* elevation (m AHD)

Bore no	Site	Depth (m bgl)	Slotted interval (m bgl)	WBZ* depth (m bgl)	WBZ* elevation (m AHD)	Estimated yield (L/s)	SWL at completion (m bgl)	SWL at completion (m AHD)
GW075032/1	Berrima STP	31	24-29	24	654	0.35	15.5	662.78
GW075032/2	Berrima STP	91	73-88	73	605	1.5	25.5	652.68
GW075033/1	Burrawang Pumping Station	36	30-35	30	662	0.8	20.2	672.80
GW075033/2	Burrawang Pumping Station	101	89-99	89	603	2.0	19.8	672.70
GW075034	Bong Bong Reserve	101	90-100	90	570	1.5	24.6	635.41
GW075035	Boxvale Walking Track car park	91	74-89	74	574	1.4	25.8	622.45
GW075036	Cunningham Park	85	73-83	70	590	1.1	43.6	616.68

Whilst these bores are several kilometres removed from the Thirlmere Lakes, they are useful in defining the regional groundwater behaviour that has occurred as a result of the prolonged drought.

Two NSW Office of Water groundwater hydrographs, rainfall and residual mass are shown in Figure 24 and Figure 25 (herein Figures 6.6 and 6.7) at Berrima (GW075032/1 and GW075032/2) and near Mittagong (GW075035) respectively.

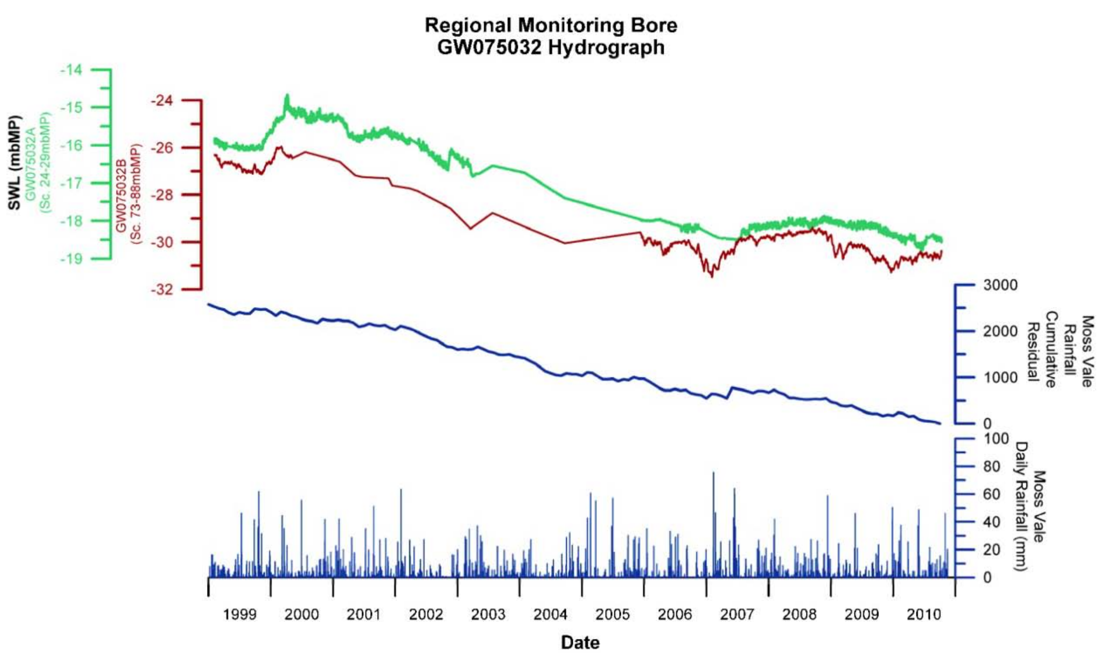


Figure 6.6: Hydrographs of groundwater levels from NSW Government monitoring bores GW075032/1 and GW075032/2 in the Southern Highlands.

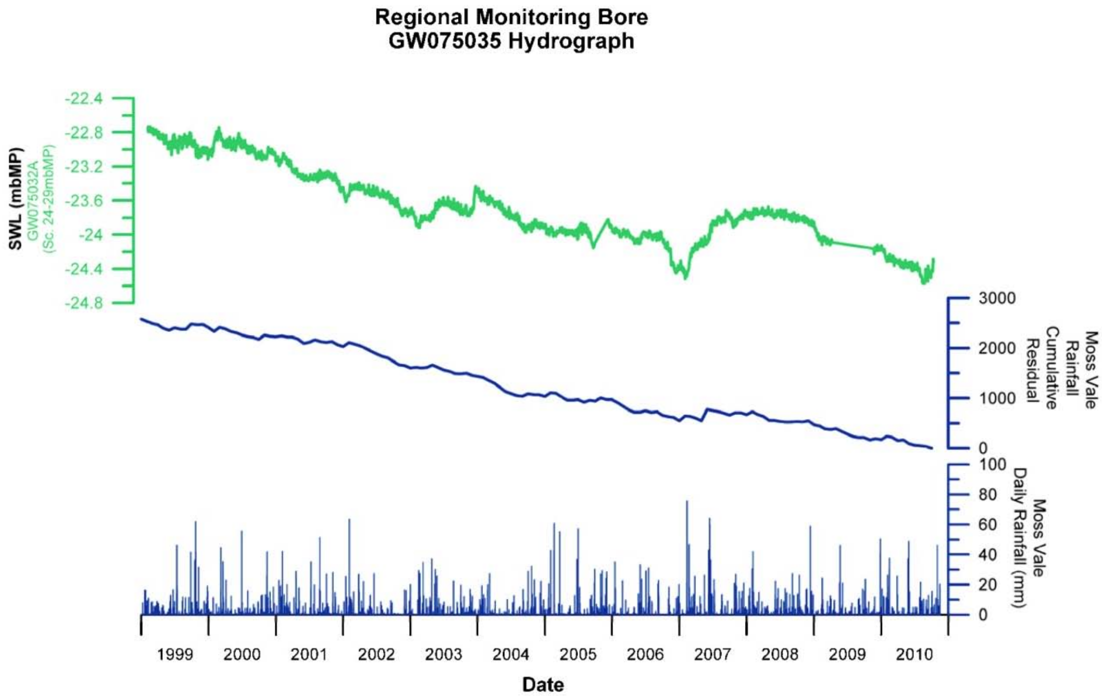


Figure 6.7: Hydrograph of groundwater levels from NSW Government monitoring bore GW075035 in the Southern Highlands.

The hydrographs at Berrima show typically natural conditions in the water table. There has been a decline in the water levels of around 4 m for the shallow aquifer (around 25 m below ground level) and 5 m in the deep aquifer (around 80 m below ground level). This decline is considered natural because the residual mass curve shows there has been a similar trend in rainfall over the period of monitoring for both bores. The hydrograph from the monitoring bore near Mittagong (closest to Thirlmere Lakes) also shows continuing decline in association with reduced rainfall of almost 2 m (deep aquifer at approximately 80 m). Typically the majority of the monitoring bores are showing a similar gradual decline in water levels due to declining rainfall, except were significant extraction is occurring that affects the hydrograph. It is apparent from the hydrographs presented for the NSW Government monitoring bores that rainfall recharge is important in maintaining the range of groundwater levels typically observed. Climatic influences are significant.

We accept the point made from these records that the regional groundwater regime reflects, at a muted scale, long term rainfall trends. However, we have reservations as to the direct relevance of bores some 15km away from Thirlmere. We also note that the decreases in water levels are in the range 2m to 5m. The water level drops in the private bores, mentioned in Section 6.3, are in the range of 20m to 40m.

6.6 Groundwater Modelling

6.6.1 Introduction

The hydrogeology of the site is discussed in Chapter 3. From the information given in that chapter it is apparent that to incorporate the impact of postulated faults and dykes, and to take into account the full geometry and 30 year mining history at Tahmoor would involve a very complex three dimensional groundwater model. Developing and running such a model was considered but put aside for three reasons:

1. It is considered that we have insufficient baseline groundwater data, insufficient knowledge of historical mine inflows, and insufficient data on rock mass and rock structure (faults) permeability, storativity and geometry to warrant a complex 3D model.

2. The primary value in a 3D model would be to estimate seepage flows into the Tahmoor Colliery. These inflows come from sources over an area of more than 100 square kilometres. We are of the view that for the reasons given in point 1, above, and because the Thirlmere Lakes would contribute, probably, a small proportion of the total inflow, it would be inappropriate to expect a numerical model to provide an accurate calculation of the proportion flowing from the lakes prior to, and post, mining.

3. A comprehensive 3D model would probably cost in excess of $100,000 to develop, calibrate and run, a sum considered unreasonable for this self-funded study.

We are of the view that two dimensional finite element seepage analyses can provide appropriate understanding as to how mining could have changed the groundwater seepage regime around the lakes, and the sensitivity of such changes to a key parameter, namely the permeability of the Bald Hill Claystone. Therefore we have performed such analyses.

Largely because the technicalities would be incomprehensible to the lay reader we do not set out all the details of our analyses. They are available in our files, if of value to any party. However, we have sought to give enough technical information for specialists to know what has been done.

6.6.2 Modelling

We have conducted 2D finite element seepage analyses for a West-East section at 6210500mN. Figures 6.8 and 6.9 show portions of the finite element model. The model is based on the stratigraphy explained in Chapter 3. Above the longwalls we have assumed increased permeability to a height of 60m, and no change above that height.

We have run the model for pre-mining conditions, and after mining up to LW21. We have conducted analyses for the following assumptions:

1. Our ‘best guess’ permeability values based on the data given in Chapter 2. These data are summarised in Table 6.3.

2. Vertical permeability of the Bald Hill Claystone 10 times and 100 times lower than the "best guess" values (ie. values of 5 x 10^{-10} m/sec and 5 x 10^{-11} m/sec).

3. Annual infiltration of 20mm or 40mm, and fill lake levels.

In order to avoid complications arising out of desaturation of the ground above the longwalls, we have adopted constant permeability regardless of matric suction.

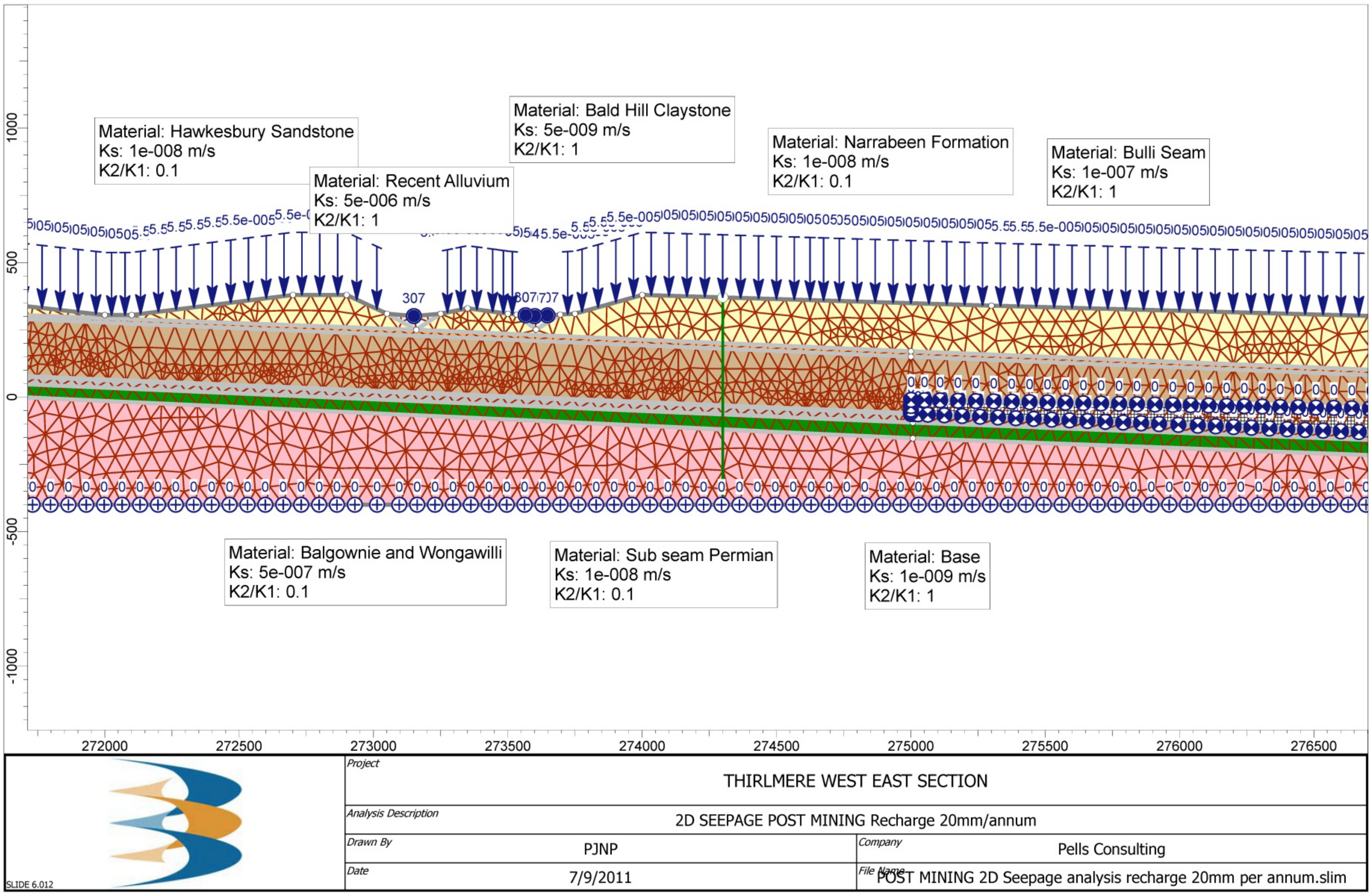


Figure 6.8: Portion of finite elements mesh.

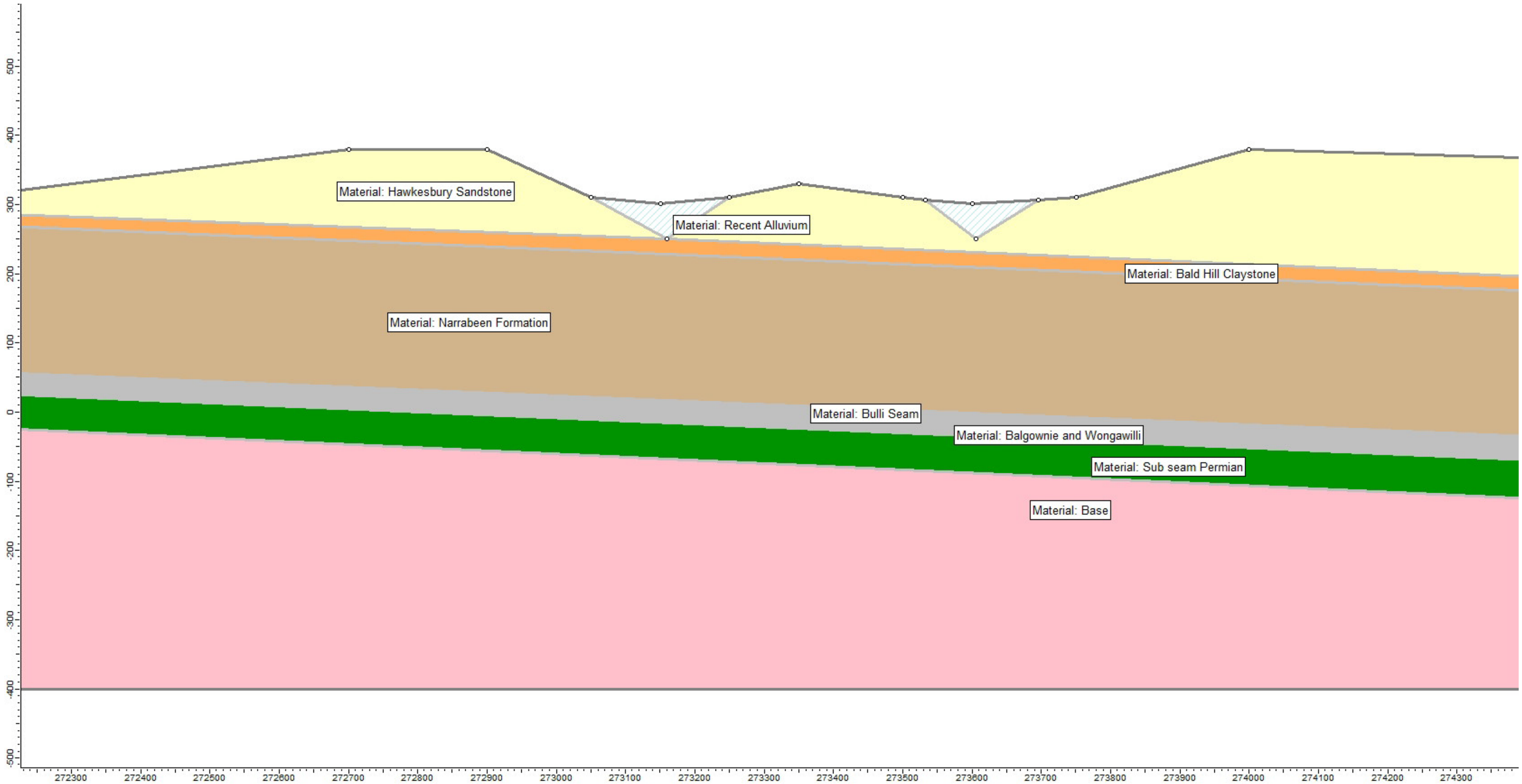


Figure 6.9: Portion of model showing layers.

TABLE 6.3
MATERIAL PROPERTIES

Property	Hawkesbury Sandstone	Bald Hill Claystone	Narrabeen Formation	Bulli Seam	Balgownie and Wongawilli	Sub seam Permian	Base	Bulgo Fault
Color								
Ks [meters/second]	1e-008	5e-009	1e-008	1e-007	5e-007	1e-008	1e-009	1e-006
K2/K1	0.1	1	0.1	1	0.1	0.1	1	1
K Angle [deg]	0	0	0	0	0	0	0	0
Groundwater Model	User Defined	User Defined	User Defined	User Defined	User Defined	User Defined	User Defined	User Defined
GW Model Properties	CONSTANT k 0 .1 Lugeon	Contstant k= 0.05 Lugeon	CONSTANT k 0 .1 Lugeon	Coal k= 1Lugeon	MULTIPLE Coal k= .5 Lugeon	Sub Coal Permian .1 Lugeon	Base k=.01 Lugeon	BARGO FAULT k=10Lugeon

Property	Recent Alluvium	LONGWALLS
Color		
Ks [meters/second]	5e-006	1e-007
K2/K1	1	1
K Angle [deg]	0	0
Groundwater Model	User Defined	Simple
GW Model Properties	Alluvium	Soil Type: General

6.6.3 Results

Figures 6.10 and 6.11 show computed, pre-mining, equipotentials and selected flow lines for the best guess parameters and for 20mm and 40mm annual infiltration.

As expected, from general knowledge of groundwater behaviour, the pre-mining condition involves flow from high ground to valleys, with the Thirlmere Lakes gaining from groundwater seepage, and with seepage east of the lakes flowing to the Nepean River.

We have included a "flow calculation" section line east of the lakes as shown in Figures 6.10 and 6.11. Cognisant of the limitations of the two dimensional model, we note that the pre-mining computed flows are:

20mm/annum recharge – flow $0.004m^3$/day

40mm/annum recharge – flow $0.003m^3$/day

Figures 6.12, 6.13 and 6.14 give the computed, post-mining, equipotentials and selected flow lines, for infiltration of 20mm/annum, and for the Bald Hill Claystone having the following permeability values.

Figure 6.12	$k_h = k_v = 5 \times 10^{-9}$m/sec
Figure 6.13	$k_h = 5 \times 10^{-9}$ $k_v = 5 \times 10^{-10}$m/sec
Figure 6.14	$k_h = 5 \times 10^{-9}$ $k_v = 5 \times 10^{-11}$m/sec

We draw the following understanding from these results:

(i) The presence of the Tahmoor longwalls changes the flow direction from the pre-mining condition, with flow directed downwards to the Bulli Seam and eastwards to the longwalls.

(ii) Because the flow directions change there are significant changes to the groundwater equipotentials, changes that would reflect in water level decrease in bores in the Hawkesbury Sandstone east of the lakes.

(iii) Substantial lowering of the assumed permeability of the Bald Hill Claystone does not change the conclusions in points (i) and (ii).

The computed flows across the measurement section, east of the lakes, are 0.2, 0.19 and $0.15m^3$/day for the models in Figures 6.12, 6.13 and 6.14. This is a fifty fold increase over the pre-mining flows. However, we do not claim that these flows represent an accurate measure of the real, complex, 3D world. They are indicative of the possible long term, steady state change associated with mining. We have not attempted to calculate how long it would take for these steady state conditions to be reached.

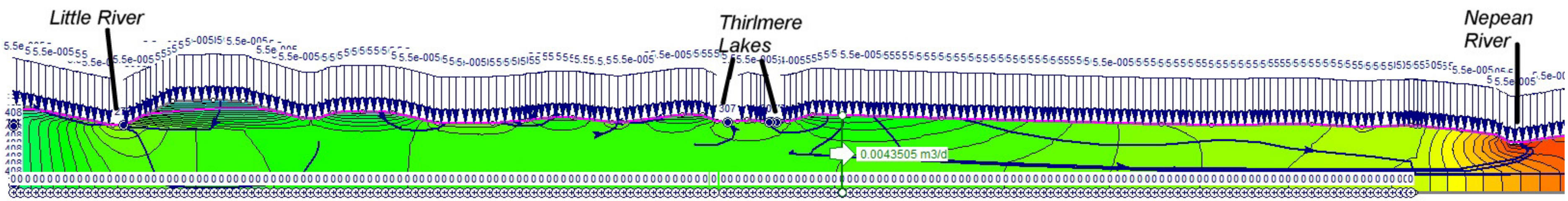


Figure 6.10: Pre-mining, assuming 20mm/annum recharge (equipotentials and selected flow lines).

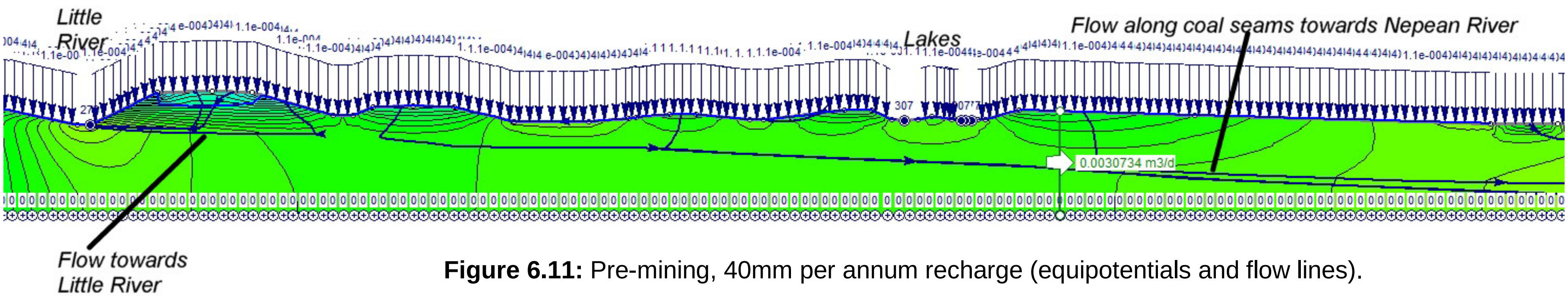
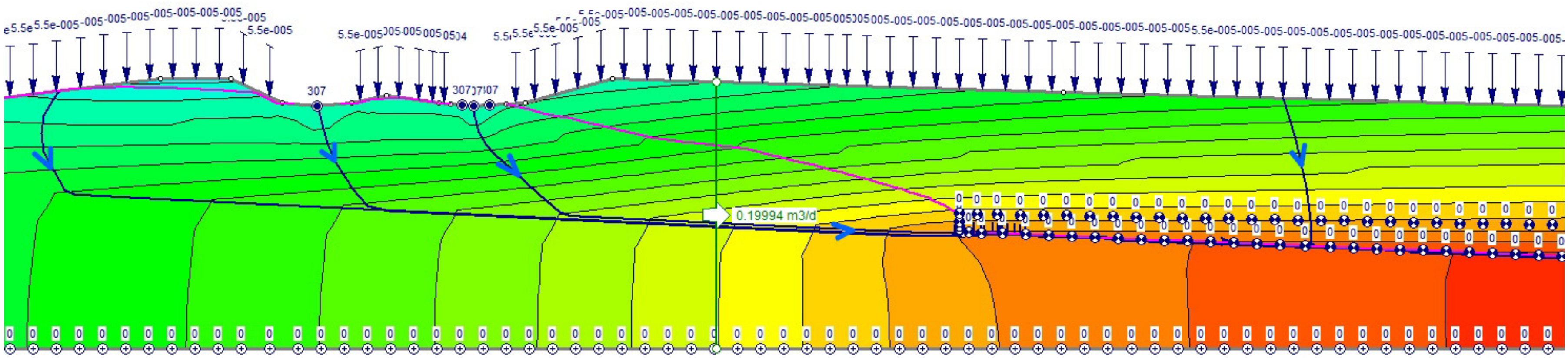


Figure 6.11: Pre-mining, 40mm per annum recharge (equipotentials and flow lines).



POST-MINING 20mm per annum recharge (equipotentials and selected flow lines)

Figure 6.12: Best guess permeability values.

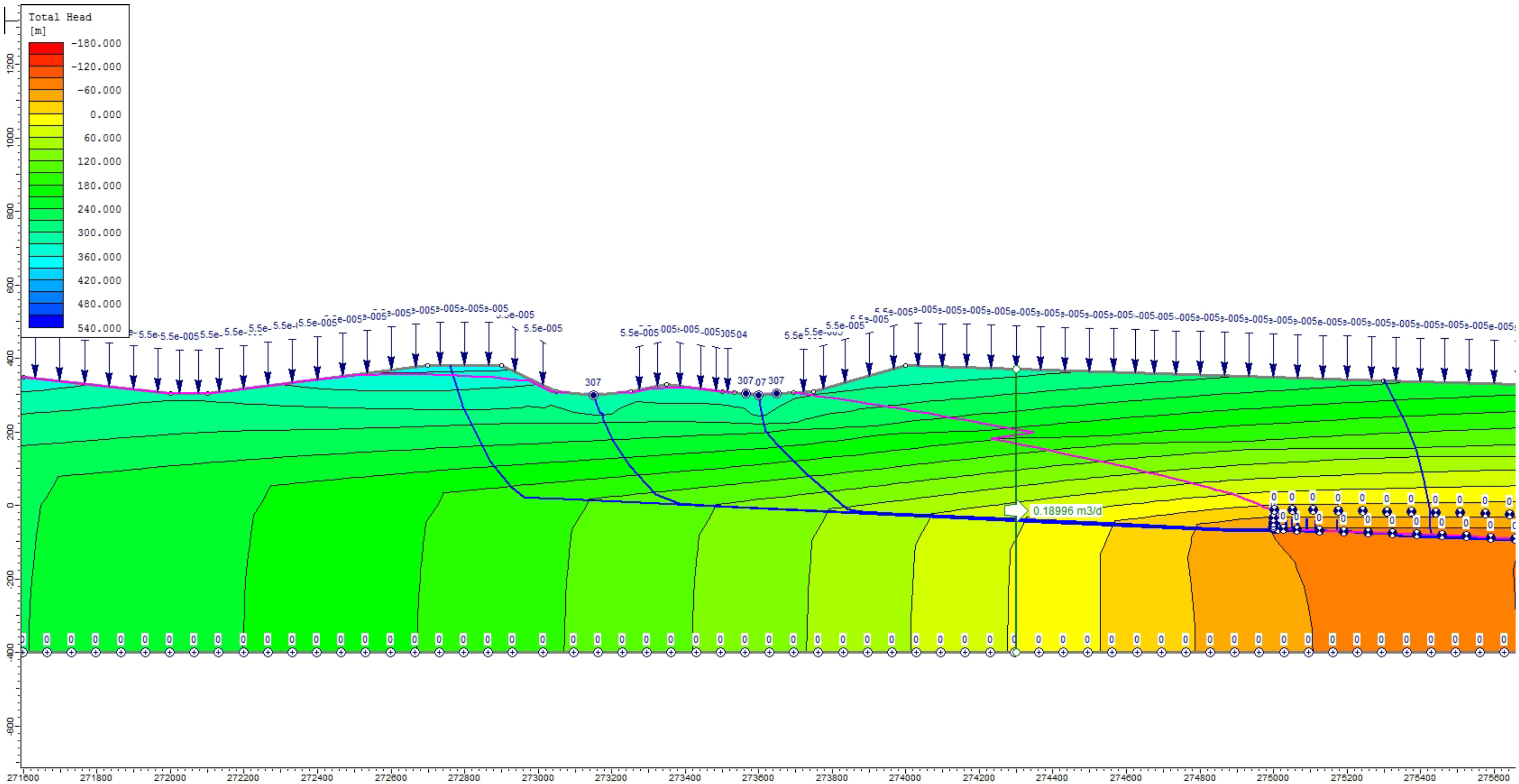


Figure 6.13: Post-mining, Bald Hill Claystone 10 times lower permeability.

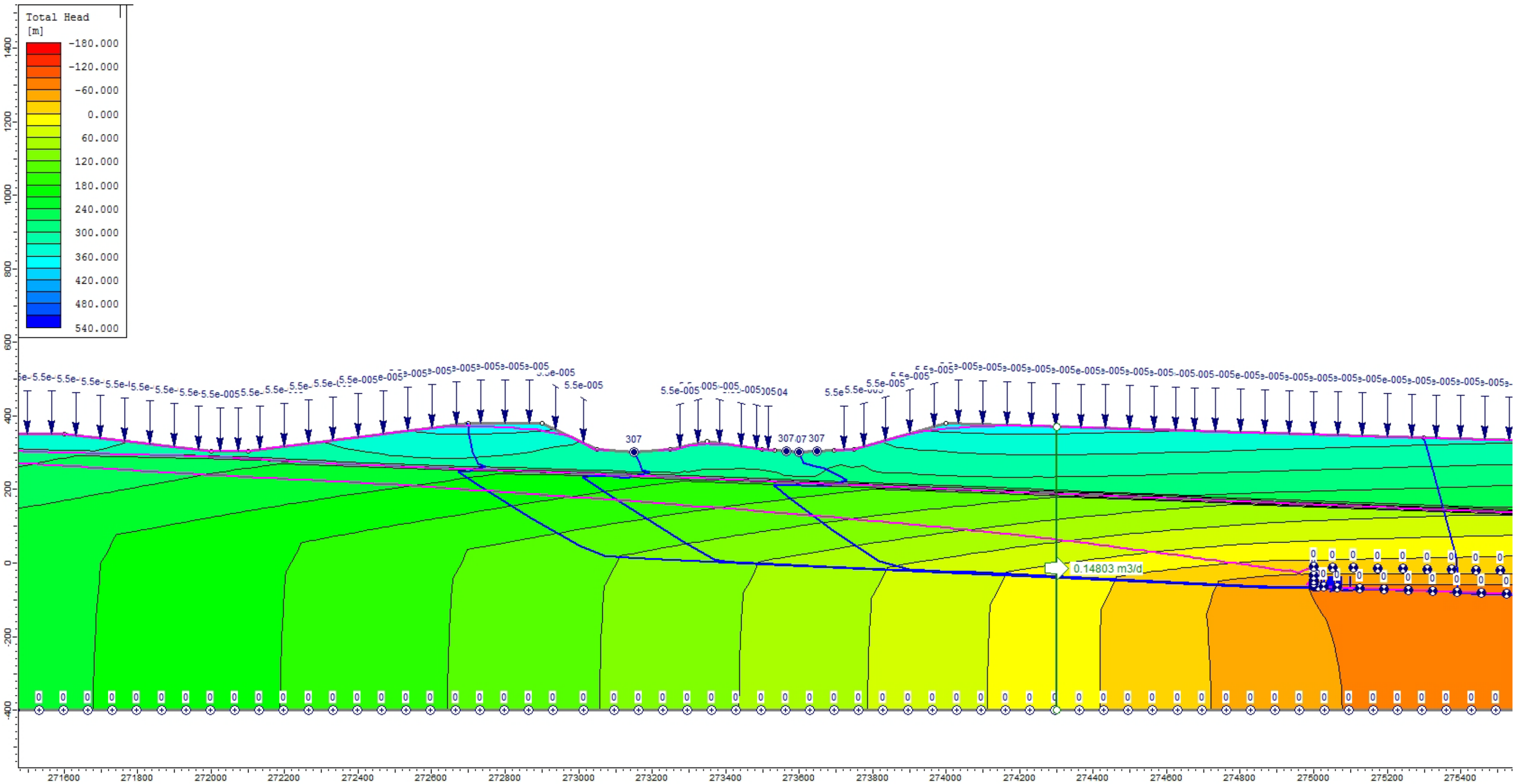


Figure 6.14: Bald Hill Claystone 100 times lower permeability.

CHAPTER 7. SUMMARY OF FINDINGS

7.1 Droughts

(a) The 5-year drought, ending 2006, is the 6th most severe in the records extending back to 1858.

(b) The 3-year drought, ending 2004, is the 8th most severe in the records.

(c) The most severe 5-year drought is the Federation Drought of 1905-1909, but the worst extended drought period (overlapping 5-year periods) is the WW2 period, 1938-1945.

7.2 Lake Levels

(a) The present period, October 2011, is not the first time Lakes Werri Berri and Gandangarra have been dry. There is clear evidence that these two lakes were dry sometime around 1944 as a result of the WW2 drought.

(b) It is recorded that "lake levels" were very low at the time of the Federation Drought (~1909).

(c) The present period is the only time that Lakes Nerrigorang and Couridjah are known to have been dry. There is strong anecdotal evidence that Lake Nerrigorang was not dry during the WW2 drought.

(d) The level of Lake Nerrigorang started falling in about 1992. The levels of Lakes Couridjah, Werri Berri and Gandangarra did not start dropping significantly until about 1996. Lake Nerrigorang was empty by the end of 2009. Lakes Werri Berri and Gandangarra were empty two years later. It has been stated by Paul Rackleyft that this behaviour was inconsistent with the historical knowledge in his family. They had bought the land around Lake Nerrigorang in about 1926.

7.3 Mining

(a) Longwalls 3 to 7, which are between about 2 km and 5 km east of Lake Nerrigorang were mined between 1989 and 1991. Longwalls 14 to 19, which are south of Longwalls 3 to 7, and about 1 km east of Lakes Couridjah and Werri Berri, were mined between 1996 and 2001. Longwalls 20 and 21 which are on the NW side of Longwalls 3 to 7, were mined in 2002 and 2003 (see Figure 7.1).

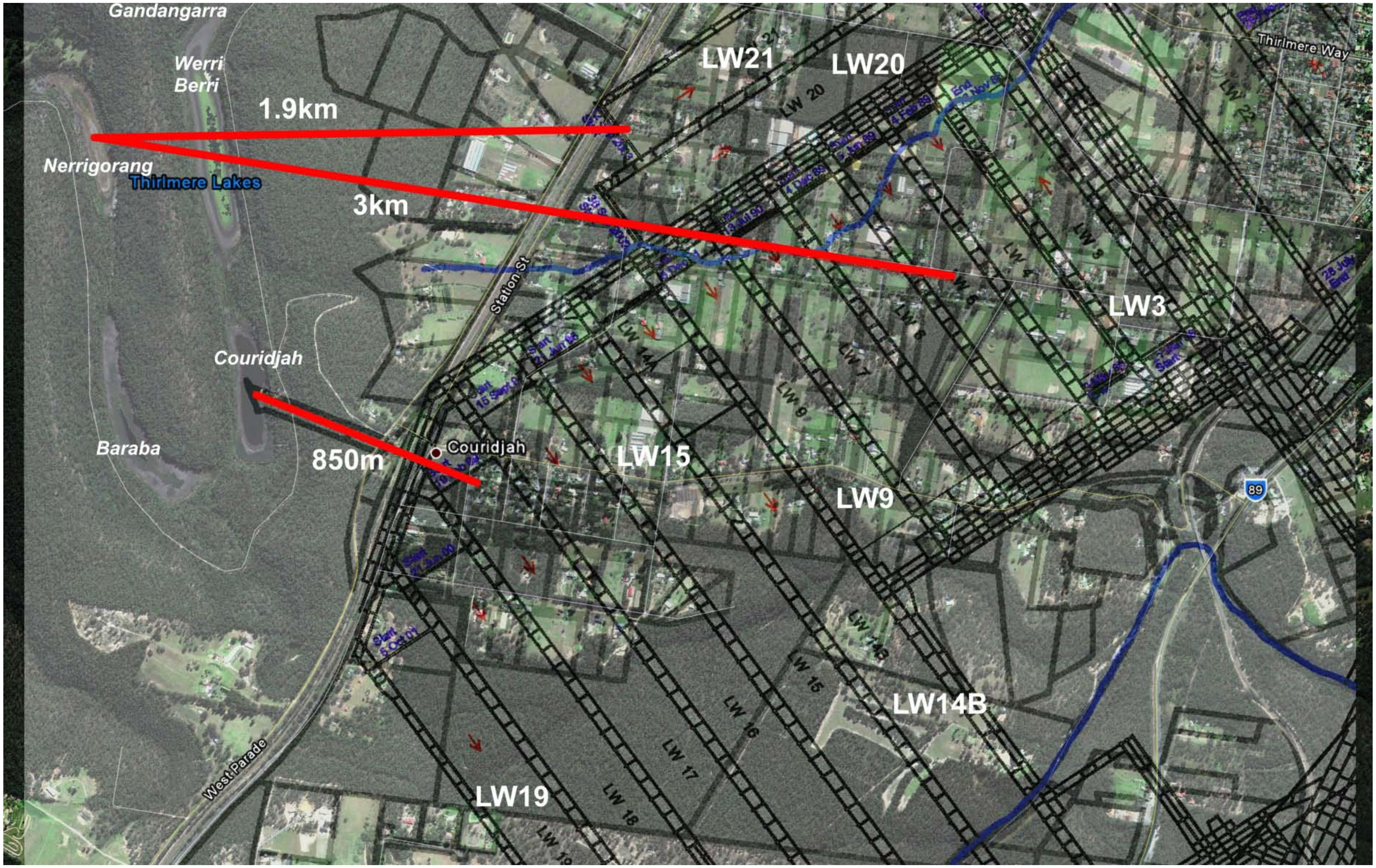


Figure 7.1: Longwall locations in relation to the lakes. Note that due to some distortion the aerial photograph and mine plan are not a perfect fit.

7.4 Geology

(a) While there is not accurate data as to the depth of Recent Alluvium beneath the lakes, all available evidence indicates that the paleovalley eroded into the Hawkesbury Sandstone is about 50m deep. If this is true then it is likely that the floor of the paleovalley beneath Lake Nerrigorang is eroded through the Bald Hill Claystone. This is not the situation at Lakes Couridjah, Werri Berri and Gandangarra.

(b) The Bald Hill Claystone is considered within the groundwater profession as providing a low permeability stratum between surface water and near surface groundwater and the coal seam horizon in the Southern Coalfields.

(c) There is evidence of significant fault and dyke intrusion zones within the area of the longwalls shown in Figure 7.1, and probably extending towards the lakes.

7.5 Groundwater

(a) Tahmoor Colliery pumps approximately 2.5 million litres per day from the mine (Xstrata AEMR, April 2009) but it is not known what proportion of this flow comes from the longwall area to the east of the Thirlmere Lakes as shown in Figure 7.1.

(b) Data from private water bores located between the lakes and Tahmoor Colliery, and above the longwalls of Tahmoor Colliery, indicate that, in places, there has been a reduction in groundwater potentials (groundwater levels, in lay terms). However, the uneven pattern suggests that these reductions are associated with geological structures (faults and intrusive dykes) whose near surface locations are not known. Evidence of such structures is very clear at coal seam level within Tahmoor Colliery. Furthermore, there is substantial documentation of significant groundwater flows emanating from such geological structures, within the Hawkesbury Sandstone, when encountered in the decline and some of the vertical shafts at Tahmoor.

(c) Groundwater modelling indicates that the presence of the mining at Tahmoor Colliery would have changed the natural groundwater flow pattern that would primarily have existed between Little River, to the west of the lakes, and the Nepean River to the east. The computed effect is to change flow directions to being downwards and eastward, via the Bulli Seam to the depressurised area of longwall mining. There is insufficient data for accurate computation of the change in quantity of groundwater flow from the lakes.

(d) The groundwater modelling indicates that even if the permeability of the Bald Hill Claystone were as low as 5×10^{-11} m/sec the conclusions given in 8, above, about flow pattern, and associated change in groundwater equipotentials, remain the same.

7.6 Hydrology Modelling

(a) The models indicate that the historical water balance at the lakes that applied between 1900 and 1990, prior to mining of longwalls 3 and onwards, does not give a reasonable simulation of recent lake levels – loss of additional water has probably occurred.

(b) The lakes are currently 1.5m to 2.5m lower in level than predicted by the most robust models.

7.7 Hypotheses

(a) The 5-year drought ending in 2006 has played a significant role in the current low water levels.

(b) The effect of longwall mining east of the Thirlmere Lakes, up to the boundary of the National Park, has resulted in increased downward seepage from the lakes. This increase in "deep recharge" has impacted on the water balance of the lakes, leading to levels that are lower than would be expected based on climate conditions.

(c) The paleovalley beneath Lake Nerrigorang is eroded through the Bald Hill Claystone. This has allowed a greater increase in "deep recharge" from that lake compared with the others and resulted in water level in that lake dropping earlier and more rapidly than Lakes Gandangarra, Werri Berri and Couridjah.