



Office of
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The Mysterious Hydrology of Thirlmere Lakes

A report by Thirlmere Lakes Inter-Agency
Working Group



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Contents

- Acknowledgements iv
- 1 Introduction 1
- 2 Geology 4
 - 2.1 Stratigraphy5
 - 2.2 Geological structures and bedrock fracturing7
 - 2.3 Sediment and bedrock hydraulic properties.....9
- 3 Geomorphology 11
 - 3.1 Soil and peat structure11
 - 3.2 Lake bathymetry14
- 4 Water balance..... 15
 - 4.1 Fluxes in 16
 - 4.1.1 Precipitation 16
 - 4.1.2 Runoff, infiltration, interflow 16
 - 4.1.3 Groundwater to surface water connections 17
 - 4.2 Fluxes out 17
 - 4.2.1 Evaporation, evapotranspiration 17
 - 4.2.2 Surface water to groundwater connections..... 19
 - 4.2.3 Creek flow20
- 5 Surveying..... 21
- 6 Research integration 21
- 7 Ecosystems 22
- 8 References 22

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A Thirlmere Lakes Research Workshop, to discuss potential research methods to address identified knowledge gaps, was held on 10 February 2016 in the Goulburn Street Office of the Office of Environment and Heritage. The following attendees are thanked for their contributions to this workshop: Dan Deere, Jonathan Sanders, Damian Gore, Philip Pells, Will Glamore, Martin Andersen, Bryce Kelly, Wendy Timms, Dioni Cendon and Steven Riley

1 Introduction

Thirlmere Lakes, in the Greater Blue Mountains World Heritage Area, is a group of water bodies that comprises Lake Gandangarra, Lake Werri Berri, Lake Couridjah, Lake Baraba and Lake Nerrigorang (Figure 1). These lakes are thought to be about 15 million years old, based on palaeomagnetic studies of regional deformation structures (Bishop et al. 1982; Fanning 1982).



Figure 1: Aerial view of the Thirlmere Lakes and surrounds. Source: Nearmap image taken 1/10/2014

Water levels in Thirlmere Lakes have fluctuated over time, but there has been a recent decline that is of significant concern to the local community. In response to these concerns, the NSW Government appointed a group of four independent scientists and a community representative to evaluate possible causes for the low water levels in the lakes (Independent Committee – Thirlmere Lakes Inquiry, Riley et al. 2012). Their findings were also reviewed by the state's Chief Scientist and Engineer, Professor Mary O'Kane (O'Kane 2013). Both the Independent Committee and the Chief Scientist and Engineer agreed that more research needed to be done to fully understand how the lake system works before there can be a proper understanding of what is affecting water levels.

Recent studies have extended the historical record of estimated lake water levels and investigated correlations with possible drivers of water level variability. Schädler and Kingsford (2016) found that declining water levels coincided with establishment of longwall mining and groundwater extraction from bores, but noted that these effects were difficult to distinguish without a good understanding of connectivity between surface and groundwater systems, which currently does not exist. Pells and Pells (2016) speculated that extraction of

water from nearby mines has impacted lake water levels, based on the inability of their model to adequately simulate water level variability both before and after mining activities nearby. Conclusions drawn from models were clearly dependent on an adequate understanding of the system under investigation, much of which remains uncertain at this point.

There is still much that is unknown about Thirlmere Lakes and their geology, geomorphology, hydrogeology and hydrology and without this information the exact cause of decreasing water levels in the lakes remains a mystery and it is difficult to determine what the primary drivers of surface water loss are. A new monitoring network has recently been established to provide near real-time information on the water levels in each of the five lakes in Thirlmere Lakes National Park, as well as local rainfall (see Figure 2). An inter-agency working group, which includes scientists from the Office of Environment and Heritage (OEH), Office of the Chief Scientist and Engineer (CSE), DPI Water (formerly the NSW Office of Water (NOW)) and WaterNSW (formerly the Sydney Catchment Authority (SCA)), has overseen the establishment of the new monitoring program¹ being funded by OEH (Parks and Wildlife Division) and implemented by WaterNSW (formerly by NOW). The inter-agency working group was also tasked with providing the strategic direction for further research into the hydrology of Thirlmere Lakes.

This report focuses on identifying knowledge gaps to help inform the development of a Thirlmere Lakes Research Prospectus, with the overarching aim of this research program being:

‘to provide a detailed understanding of the hydrological dynamics of Thirlmere Lakes’.

A research prospectus will subsequently be developed that outlines a coherent research program including component research studies to provide high quality fundamental data on the geology, geomorphology, hydrogeology and hydrology of Thirlmere Lakes and their environs. The outcomes of these research studies would then be available to describe and model hydrological and groundwater processes and provide an understanding of how water moves at the surface and within the groundwater systems of the area. One of the most important aims of the research would be to understand the interaction between surface water in the lakes and the underlying groundwater systems.

This research will not only inform an understanding of fluctuating water levels within the Thirlmere Lakes, but can potentially develop methodologies, conceptual and numerical models and knowledge applicable to many different types of wetland systems throughout New South Wales. The importance of this research program will be to combine several scientific disciplines into a broader understanding of the impacts of climate variability on the environment, as well as the sensitivity of ecosystems to external influences.

¹ Near real-time data is available and plots of lake levels can be found on the OEH website at www.environment.nsw.gov.au/water/thirlmere-lakes-water-data.htm. The data can also be downloaded from the DPI Water Real-time data website at www.water.nsw.gov.au/realtime-data.

The Mysterious Hydrology of Thirlmere Lakes

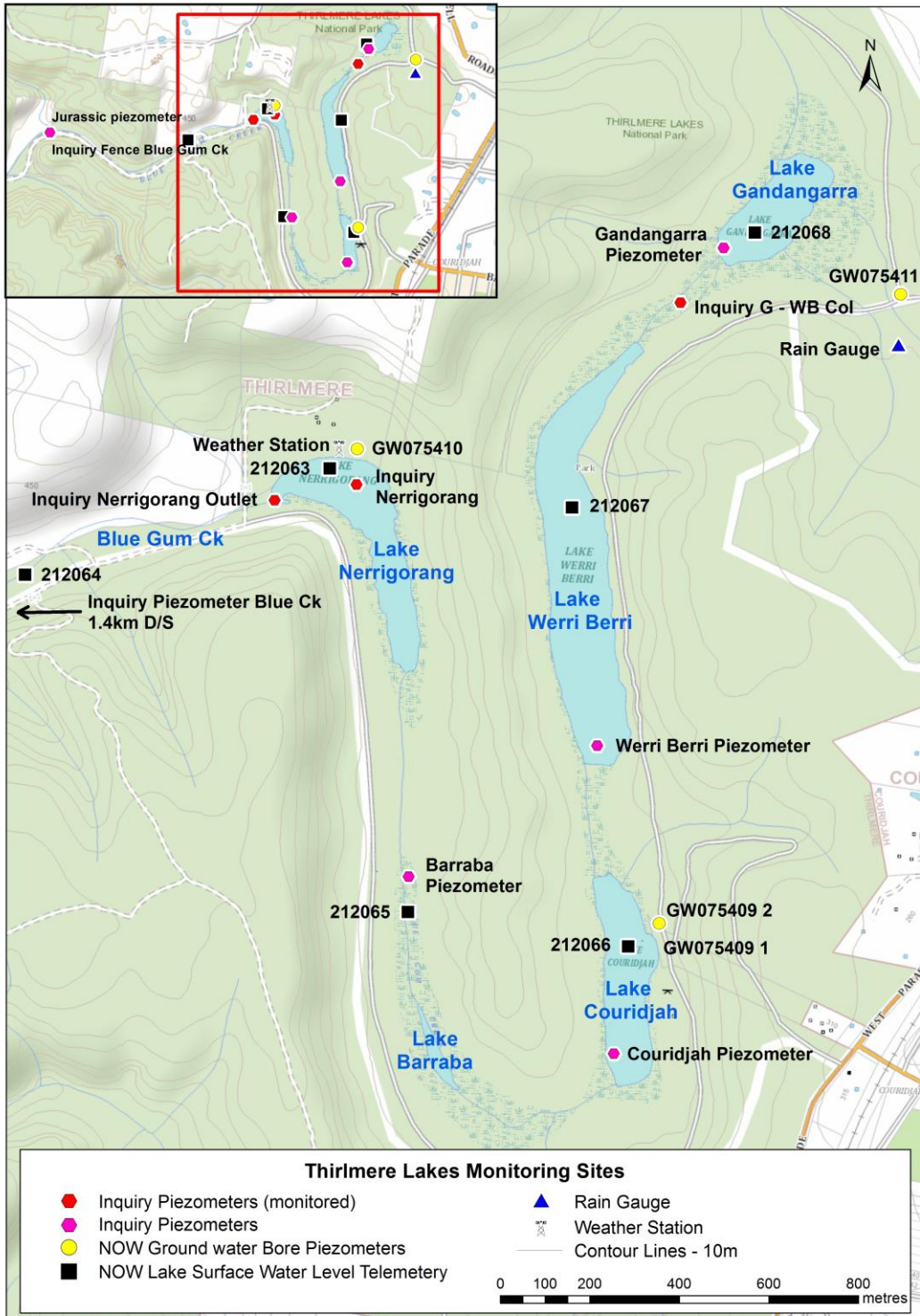


Figure 2: Monitoring locations at Thirlmere Lakes and surrounds

2 Geology

The conceptual geological model for the lakes environment comprises a late Cretaceous to early Tertiary alluvium (clayey quartz sand) overlying Triassic Hawkesbury Sandstone (quartz sandstone having a clay matrix and sideritic cement) – see Figures 3 and 4. The deposition of the Hawkesbury Sandstone occurred after the uplift of the Lachlan Fold Belt tilted the Sydney Basin. The uplift event led to the deposition of the deltaic sand (i.e. Hawkesbury Sandstone), which is believed to be derived from the Upper Devonian quartzites of the Lachlan Fold Belt (Herbert 1980). The deposition of the Hawkesbury Sandstone is alluvial in origin, and formed from a high energy braided stream system in a deltaic/alluvial environment. Shale lenses found within the main Hawkesbury Sandstone are believed to be from abandoned channels within the rapidly shifting braided channel environment.

Beneath the Hawkesbury Sandstone the stratigraphy continues to be representative of the regional southern Sydney Basin sequence: Permo-Triassic Narrabeen Group (shale, shaly sandstone, quartz-lithic sandstone and clay siltstone) overlying Permian Illawarra Coal Measures (lithic sandstone, shale, siltstone, claystone, coal seams and carbonaceous shale), and then at depth the Permian Shoalhaven Group (lithic sandstone and micaceous siltstone). Within the sedimentary sequence several low permeability layers are considered to act as aquitards, the most important of which is considered to be the Bald Hill Claystone. There are significant knowledge gaps regarding the Bald Hill Claystone, including its horizontal extent beneath the park, its thickness and its continuity in the immediate area of the lakes.

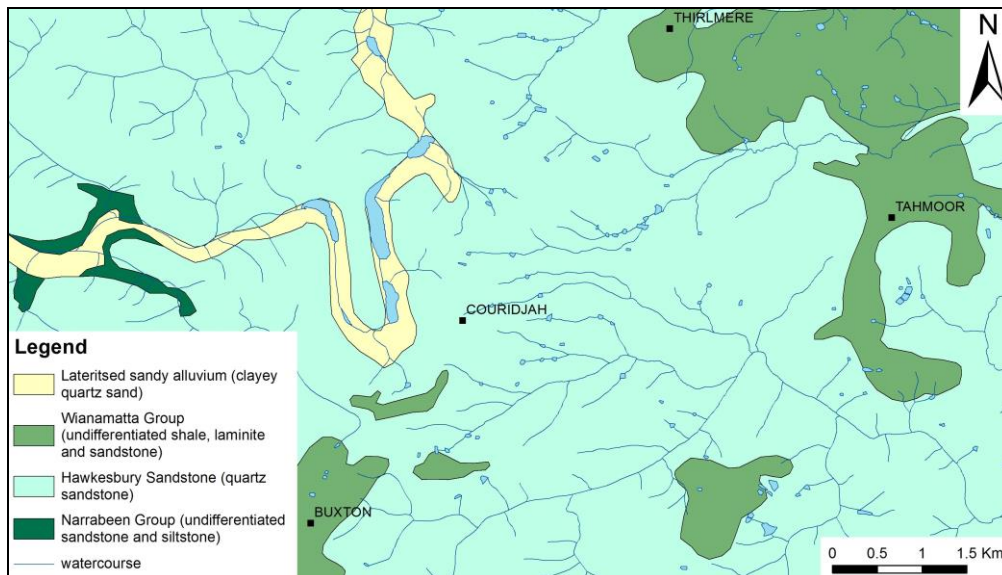


Figure 3: Geology of the Thirlmere Lakes region (modified from Stroud et. al. 1985)

Properly understood, the physical setting (including geomorphology, stratigraphy and structural geology such as faults and bedrock fracturing) is an important determinant of the water balance for the lakes in that it controls both shallow and deep groundwater flow and recharge/discharge relationships. The shallow environment behaviour may also be

influenced by the presence of a substantial thickness of alluvial soils which could provide a subsurface storage component to the water balance. Further, any alluvium present could act as a conduit between other components of the water balance (this component is addressed further under the *Soil and peat structure* and *Water balance* sections).

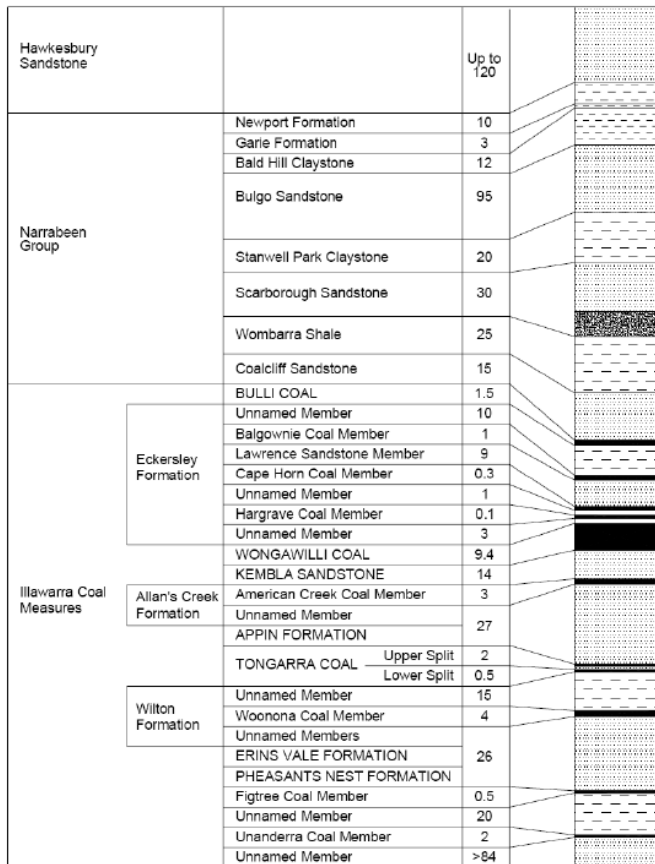


Figure 4: Stratigraphic section of the Southern Coalfield below the Wianamatta Group and Mittagong Formation, showing thickness of each unit (from Fig.4, p.21, NSW Dept of Planning, 2008; © State of New South Wales through the Department of Planning).

2.1 Stratigraphy

Why we need this research

A knowledge of the geological stratigraphy around and underneath Thirlmere Lakes is fundamental to understanding subsurface hydrology including groundwater catchment boundaries, flow pathways (particularly the direction and slope) and surface water interactions with the underlying groundwater systems (see Figure 5). There are very few boreholes within 1km of Thirlmere Lakes that provide detailed information suitable for the analysis of geological stratigraphy for the lakes themselves. A comprehensive appreciation of the stratigraphic setting beneath the lakes is critical in understanding the elements of the water balance on which this influential factor has an effect.

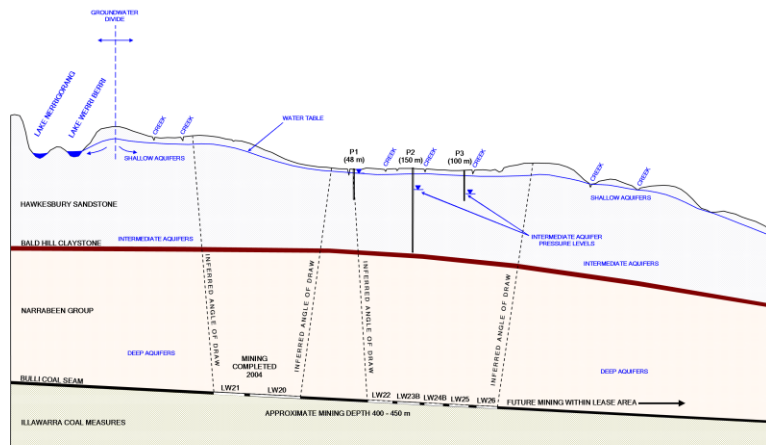


Figure 5: Original conceptual geological and groundwater model for Thirlmere Lakes (Russell et al. 2010)

What we know already

In May and June 2011, the then NSW Office of Water Groundwater Drilling Unit drilled and constructed four monitoring bores in the vicinity of three of the five lakes in the Thirlmere Lakes National Park. The report for the drilling program (Russell 2012) documented that three of the bores were drilled to shallow depths (GW075409/1 to 15m below ground level; GW075410 to 18m below ground level; GW075411 to 28m below ground level) using a mud coring technique; these were intended to monitor groundwater levels in the alluvium. The fourth monitoring bore (GW075409/2) was drilled using air rotary techniques to a depth of 100m to establish a water level record for the underlying Hawkesbury Sandstone groundwater system. The deep monitoring bore was constructed to monitor a significant water bearing zone between 73 and 76m depth below the ground surface. This water bearing interval was considered to be representative of the more regional groundwater system within the sandstone. It is noted that the 100m deep bore did not penetrate to the depth of the Bald Hill Claystone at that location.

What we don't know yet

The knowledge of the bedrock stratigraphy near and underneath the Thirlmere Lakes is incomplete and insufficient to reliably define the connection between shallow (local) and deep (intermediate to regional) groundwater systems (see Figure 6 for an illustration of part of the core from Lake Couridjah). Added to this is the complexity in determining a definitive boundary between the shallow alluvium or colluvium surrounding and potentially underlying the lakes, and the variably weathered Hawkesbury Sandstone beneath it.

More comprehensive information about the Bald Hill Claystone is required, as well as other low permeability layers in the sequence. It has been suggested that the Bald Hill Claystone has a relatively uniform dip to the east and was approximately 70m below Lake Nerrigorang and 90m below Lake Werri Berri (Pells & Pells 2011). Further drilling is required to validate exactly where the Bald Hill Claystone occurs relative to the lakes. Additional drilling has also been suggested to better define the stratigraphy beneath the valley that contains the Thirlmere Lakes system.

Potential measurement techniques: bore drilling, borehole logging, high resolution imaging tools, surface seismic surveys, electromagnetic/resistivity surveys



Figure 6: Core from Lake Couridjah (Source: NOW Drilling Report – Russell 2012)

2.2 Geological structures and bedrock fracturing

A knowledge of the geological structures (faults and dyke intrusion zones) near and underneath Thirlmere Lakes is fundamental to understanding groundwater flow pathways within the underlying strata. Geological structures and bedrock fracturing in the vicinity of the lakes can provide conduits for fracture flow through otherwise low permeability strata or formation boundaries. There are very few boreholes within 1km of Thirlmere Lakes that provide a detailed analysis of geological structures and fracture networks.

Why we need this research

In order to formulate a comprehensive geological conceptual model it is necessary to develop an understanding of the fracturing within the strata underlying the lakes, including

the existence of any interconnected networks both vertically and horizontally and the geometry of any major openings. From there it may be possible to assess whether or not such fractures and bedding planes provide avenues for water losses from surface or shallow systems to deeper groundwater environments.

Elsewhere in the Sydney region, deeply incised valleys cut into Hawkesbury Sandstone typically develop unique unloading features (valley bulging and heaving) due to the stress relief effects associated with the erosional removal of overburden. It is unclear if the lakes are positioned above an ancient, deeply incised palaeochannel and therefore it is not known if such fracturing is present at intermediate depths beneath the unconsolidated sediments that are assumed to be infilling the valley. If present, this type of fracturing could provide for interaction between alluvial and shallow sandstone groundwater systems over a significant area of the catchment.

Anthropogenic disturbances, such as far field displacements from the nearby longwall mining, have also had the potential to initiate fracturing in various geological units; however, the nature and extent of these induced fractures is not well understood, if they are present at all.

What we know already

Previous work has identified that the formation of the lakes could be contemporaneous with the development of the Lapstone Monocline, the regionally extensive deformation feature dividing southern and western plateaux from the central Sydney Basin depression (the Cumberland Plain). Tentatively, this dates the lake system as forming at around 15 million years² before present (Fanning 1982). More locally, the lakes are positioned between the Thirlmere Monocline to the east and the Mount Tomah Monocline to the south west, both of which have been identified within regional coalfield geological mapping published by the Geological Survey of NSW (Moffitt 1999). It is expected that the deformation along these extensive fold axes would trigger fracturing of strata across extents and in directions determined by those structures and by the regional stress orientations.

What we don't know yet

There are several knowledge gaps which need to be addressed before any conceptual geological and/or numerical groundwater models can be developed:

- If the sandstone bedrock is dipping to the east as has been postulated elsewhere, the lakes may be isolated from the regional groundwater system and missing discharge from the deeper parts of the formation (as the flow path would be underneath the lakes). An accurate appreciation of the configuration of the Hawkesbury Sandstone is needed to improve the conceptual model.
- It is unclear if the dip of the strata is affected by discontinuities such as faults, lineaments, etc.

It is important to understand the possible fracture distribution in the vicinity of the lakes since such features on local to regional scales could provide conduits for fracture flow through strata. It is apparent from the results of recent drilling and subsequent monitoring that the deep groundwater system in the Hawkesbury Sandstone has not been significantly dewatered, as there remains a substantial hydraulic pressure that would be expected to have

² But note the Inquiry Committee suggestion that the Thirlmere Lakes valley may be a structurally-controlled headwater reach of Blue Gum Creek, where the Hawkesbury Sandstone has not been breached by incision and hence still controls the geometry of the catchment.

declined if deeper drainage was active. However, it is not certain that such conditions persist beneath each of the lakes as there is only the one deep monitoring point currently installed within the national park in close proximity to Lake Couridjah.

Potential measurement techniques: magnetic resonance tools, borehole logging, surface seismic surveys, electromagnetic/resistivity surveys, optical cable methods

2.3 Sediment and bedrock hydraulic properties

Porosity and permeability are two of the primary factors that control the storage and movement of fluids in rocks and sediments. Porosity is the ratio of the volume of the void space to the total volume of material and is usually expressed as a percentage (%). The effective porosity lacks a single or straightforward definition; however, it is most commonly considered to represent the porosity of a rock or sediment available to contribute to fluid flow through the rock or sediment. The term permeability or hydraulic conductivity as defined by Darcy's law (and used in groundwater flow assessment) is a measure of the capacity of a rock to transmit water.

The hydraulic conductivity of a rock is a function of hydraulic conductivities of the matrix (the rock material itself) and defects (open joints and separated bedding planes) resulting from stresses applied to the rock. Hydraulic conductivity can be measured in the field or in the laboratory. Field measurements using packer tests refers to the total (matrix and defect) hydraulic conductivity, while the laboratory permeability tests using rock cores measure matrix permeability.

Storativity or the storage coefficient, is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. Storativity is a dimensionless quantity, and ranges between zero and the effective porosity of the aquifer.

Why we need this research

Assessment of hydraulic properties of lake sediments and underlying bedrock is essential for a more general understanding of groundwater flow, connectivity between alluvial and bedrock groundwater systems and for the development of numerical groundwater models.

What we know already

The Hawkesbury Sandstone was deposited in the Middle Triassic period, and is the principal regional sandstone unit across the southern Sydney Basin. It outcrops over many places in the Illawarra area and forms cliffs along the Illawarra escarpment. It varies in thickness from 160m in the Mittagong area to approximately 250m in the Sydney region (Lee 2000).

The Hawkesbury Sandstone is predominantly quartzose sandstone (approximately 90%), with siltstone/fine-sandstone laminate, and siltstone and claystone interbeds making up the remaining 10% (Moffitt 1999). Hawkesbury Sandstone is quartz sandstone with a grain size generally within the medium to coarse range, but often varying from fine grained through to very coarse. The sandstone grains are typically subrounded to subangular, and the overall appearance is generally considered to be moderate to poorly sorted (Bembrick et al. 1987).

X-ray diffraction (XRD) shows that the compositions of the sandstone matrix (which comprise up to 20% of sandstone) and mudrock of the Hawkesbury Sandstone are similar, with 70% illite or degraded illite and 30% kaolinite (Bowman 1974). Secondary silica, siderite and

calcite are present as cementing materials. Graphite, rutile, zircon and tourmaline are the common heavy minerals forming about 0.1% of the Hawkesbury Sandstone. XRD analyses previously performed on core samples from shallow (<20m depth) Hawkesbury Sandstone in the Waratah Rivulet showed that the sandstone is predominantly a quartzose sandstone averaging 85% (up to 93% quartz), with minor illite/mica around 9%, kaolinite about 1.2% (up to 18%), siderite around 4.4% (up to 9%) and minor calcite and pyrite (J Jankowski unpublished data)

Shale layers commonly occur within the Hawkesbury Sandstone and can be 6–12m in thickness. These layers contain siderite and illite/mica as dominant minerals.

The mineralogy of the underlying rocks has the ability to significantly affect the permeability, porosity and storativity of a hard rock aquifer. The relationship between mineralogy and matrix porosity and permeability of the Hawkesbury Sandstone and underlying stratigraphic formations is discussed in Al gahani (2012) and Zaid and Al gahani (2015).

Numerous studies of aquifer hydraulic conductivity of the Hawkesbury Sandstone and underlying formations have been undertaken in the Southern Coalfield for coal and petroleum exploration. Comparison of laboratory (matrix conductivity) and field measurements (bulk rock conductivity estimated from packer testing) indicates that as depth increases fracture hydraulic conductivity approaches the matrix conductivity. Therefore, groundwater flow at shallow depths (up to approximately 200m below ground surface) is dominated by flow through fractures, while at greater depths groundwater flow is controlled mainly by the porosity of the rock matrix (Commonwealth of Australia 2014).

The Bald Hill Claystone is considered to be a significant low permeability formation separating Hawkesbury Sandstone from the deeper groundwater systems. The matrix permeability of the Bald Hill Claystone appears to be significantly lower when compared to hydraulic conductivities measured for sandstone formations. However, field packer test results indicate that the hydraulic conductivity of the Bald Hill Claystone is actually quite similar to other strata (Reid 1996; Pells & Pells 2011). This was interpreted to mean that flow in defects was the dominant flow process in the claystone in the tested areas (Commonwealth of Australia 2014).

What we don't know yet

The permeability, porosity and storativity of unconsolidated sediments and geological strata beneath the lakes is not currently known. Such knowledge is needed to establish rates of infiltration into the groundwater system through the lake sediments (i.e. when there are positive or negative fluxes of fluid through lake sediments) and the potential connections between surface water and groundwater. Variation in infiltration rates due to differences in permeability, porosity and storativity may help explain why the lakes appear to be drying up at different rates. Characterisation of hydraulic properties of unconsolidated sediments and bedrock strata is essential for development of mathematical models of groundwater recharge and flows.

Potential measurement techniques: magnetic resonance tools, geochemical logging tools, dipole shear array tools, packer tests, drill core analyses

3 Geomorphology

A number of hypotheses exist concerning the geomorphology and evolution of Thirlmere Lakes. An account of the hypotheses prior to 1974 was presented in Vorst (1974). The most widely accepted hypothesis was that the lakes were formed in an abandoned Tertiary-age valley of a westward flowing stream whose headwaters were truncated. This truncation was proposed to have occurred with the tectonic activity that gave rise to the faults and monoclines to the south and east. The current estimate of the age of the valley is 15 million years, based on the age of the Lapstone Monocline, following the work of Bishop et al. (1982) and Pickett and Bishop (1992).

More recently, the Independent Committee presented an alternative hypothesis that the Thirlmere Lakes valley is a structurally-controlled headwater reach of Blue Gum Creek, where the Hawkesbury Sandstone has not been breached by incision and hence still controls the geometry of the catchment in both cross section and planform (see Figure 7 for the relative elevations of individual lakes).

Why we need this research

Identifying the bedrock base of the valley is fundamental to understanding the geomorphology of Thirlmere Lakes. Knowledge of the location of the bedrock base near to and underneath Thirlmere Lakes is also fundamental for understanding sediment (soil and peat) volumes. The nature and extent of the sediments has implications for the storage and movement of groundwater, as well as the maintenance of surface water in storage. Significant differences in the hypothesised geomorphology of Thirlmere Lakes still require a resolution.

3.1 Soil and peat structure

What we know already

While Hawkesbury Sandstone dominates the landforms and soils occurring in the area, there are shale outcrops on some of the ridges. Rose and Martin (2007) suggested that this may be either the Ashfield Shale (lower member of the Wianamatta Group) or a shale lens in the Hawkesbury Sandstone. The soils developed on the sandstone are uniform sandy loams with some organic staining in the upper horizons. They are acidic, of low nutrient status and low water retaining capacity and vary in depth and drainage depending on topography (Rose & Martin 2007). Various studies on the location and depth of sediment near the lakes were summarised by Riley et al. (2012; see Figure 7).

Vorst (1974) found that the bedrock cliffs on either side of the valley reclined at angles between 45° and 70° from the vertical (see Figure 8). Boreholes manually augered at short distances from the contact between the sandstone and alluvium suggested that the bedrock continued at approximately the same angle beneath the overlying valley fill. However, interference with the sound waves because of the narrowness of the valley during her seismic survey prevented the bedrock base from being defined; its depth was calculated to be somewhere beyond 50–60m. Pells and Pells (2011) reported that the deep holes (29–33m) dug by Vorst (1974) did not reach bedrock. The bedrock valley was suggested by those authors as being very deep and filled with unconsolidated sediment. In contrast, for the NOW groundwater bores, the depth to the weathered sandstone was reportedly from 6–15m (Russell 2012).

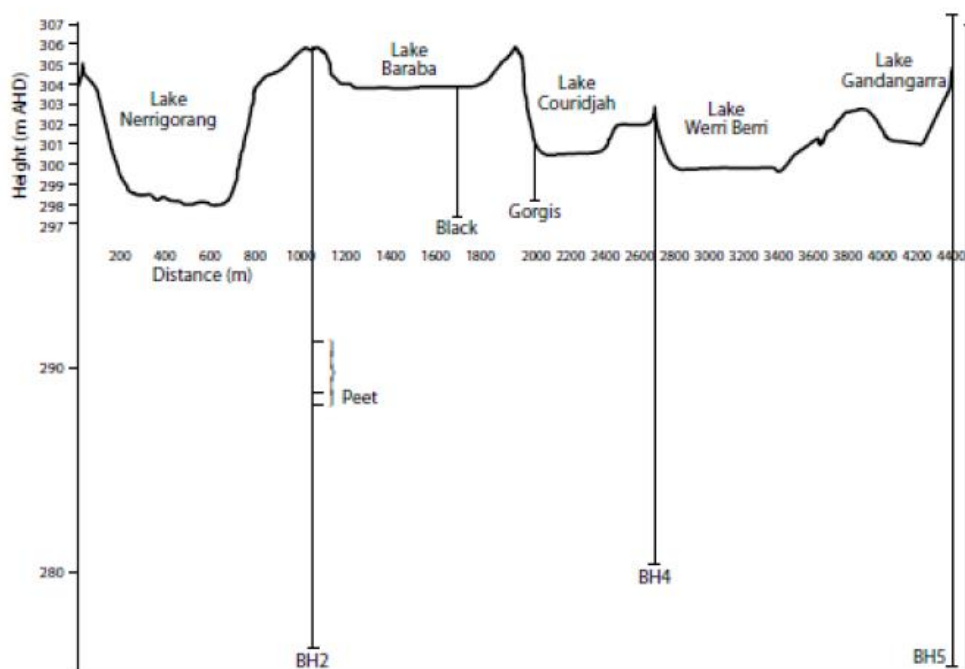


Figure 7: Location and depth of cores studying sedimentology. Source: Thirlmere Lakes Inquiry – Riley et al. (2012)

Sediment cores have also been extracted from Lake Baraba to a depth of 6.35m and dated using both conventional radiocarbon dating and atomic mass spectrometry (AMS) methods (Black et al. 2006; see Figure 9). The age at the base of the sedimentary sequence at Lake Baraba was reported to date from over 43,000 years. At Lake Baraba, peat was found above 0.172m (0–172cm), a transitional layer of peat and clay between 0.172 and 0.41m (172–410cm), which became more clayey with depth, and clay below 0.41m (>410cm). The sedimentation rate of the clays at Lake Baraba was found to be relatively lower (i.e. 0.04mm/yr) than within the peat (~0.67mm/yr).

Dry Lake, which is to the north west (upstream) of Lake Gandangarra, is located in the Cedar Creek catchment which drains to the north east. Dry Lake is outside of Thirlmere Lakes National Park but there is a strong suggestion that its geomorphic history is linked with Thirlmere Lakes (Riley et al. 2012). Dry Lake sediments have previously been examined (Rose & Martin 2007; see Figure 10). It was reported in that study that sediment coring was limited to a depth of 1.5m because of heavy clay, with a basal date of ~9000–10,000 years being determined. In that location peat was also deposited most rapidly (~0.22mm/yr). There appeared to be a hiatus in the Dry Lake sediments representing a period of zero or minimal deposition or a period of erosion between 2000 and 5000 years before present, coinciding with a layer of diatomaceous earth. The alternation of fine clay, peat and coarse sediments on the lake margin was suggested to reflect the advance and retreat of the littoral zone in response to fluctuating water levels (Rose & Martin 2007).

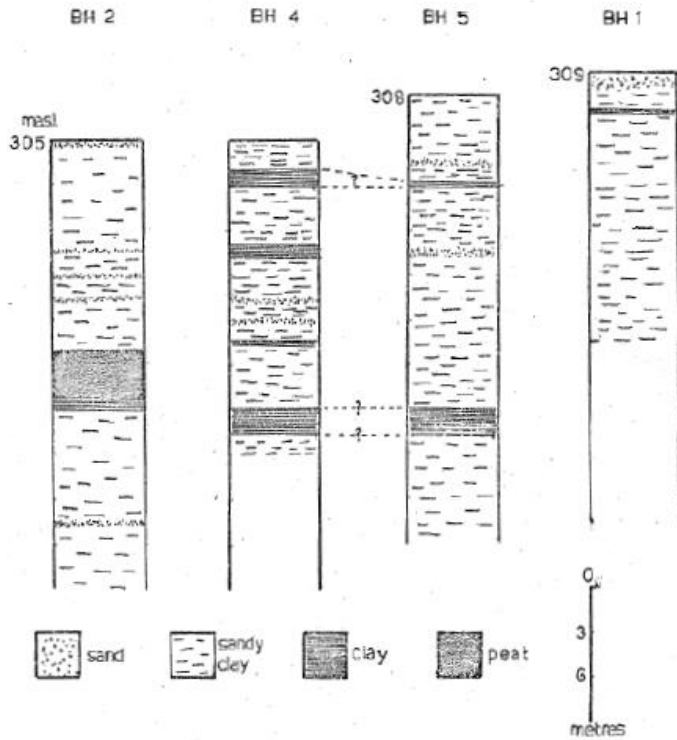


Figure 8: Stratigraphic logs from Vorst (1974). Source: Vorst (1974)

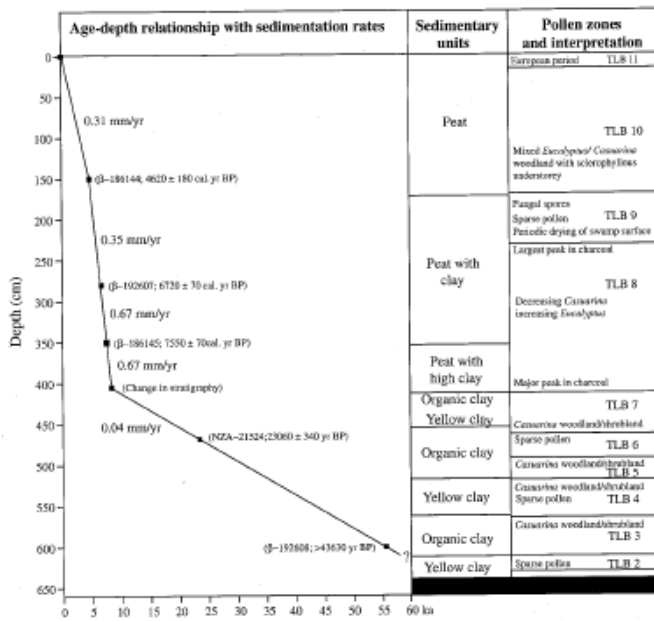


Figure 9: Stratigraphic logs from Lake Baraba. Source: Black et al. (2006)

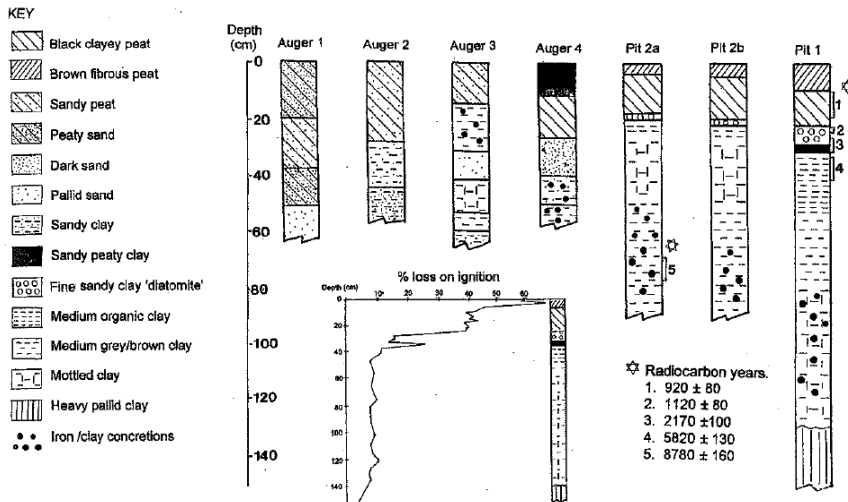


Figure 10: Stratigraphic logs from Dry Lake. Source: Rose and Martin (2007)

3.2 Lake bathymetry

What we know already

There are a number of studies which have attempted to describe the bathymetric form of the lakes but it is noted that the spatial resolution for any one lake appears to be limited. Pells and Pells (2011) constructed a digital elevation model (DEM) for the region to define surface topography and lake bathymetry. This was based on:

- 10 and 5m contour data supplied to Pells Consulting in CAD format
- ground surveys undertaken by Pells Consulting on 9 May 2011 and 22 August 2011
- bathymetry data of the lakes from earlier investigations (Vorst 1974).

Vorst (1974) obtained spot depths of the lakes using a leadweight on the end of a calibrated line, and bottom profiling undertaken using a Furuno FG200 Echosounder³. The bathymetric maps and bottom profiles obtained by Vorst (1974) showed that the lakes had relatively steep sides and flat bottoms, except for a bench at a depth of 4.3–4.71m in Lake I (Werri Berri⁴) and Lake II (Couridjah), and 5.4–6.0m in Lake IV (Nerrigorang). The feature may be related to either a low lake level shoreline or the channel of a former river course.

What we don't know yet

The location of the bedrock base adjacent to and underneath the lakes remains largely unknown. The deepest bore reported by Vorst (1974) reached 33m but did not reach

³ Vorst (1974) suggested that error inherent in the echosounding could have been as much as 10%, so a repeat bathymetric survey for the lakes as they are now may be worthwhile, especially if it is linked to a DEM for the area identifying the current boundary of the surface water.

⁴ Vorst (1974) included Lake Werri Berri and Lake Gandangarra as part of the same Lake (Lake I), but noted that Lake IA (Gandangarra) was 'merely a northern extension of Lake I which has become separated from it since about 1960'.

bedrock. Weathered sandstone was encountered on the eastern edges of the lakes at 6–15m and at about 10m near Lake Nerrigorang (Russell 2012). While peat has been sampled down to 6.35m at Lake Baraba, there is limited understanding of the total depth and volume of peat or alluvial sediments underlying each of the lakes. There are also limited measurements on the exact depth of the lakes where they continue to hold water. As a result, the volume of the sediments (soil and peat) and the volume of water contained within the lakes is poorly described. This is a fundamental knowledge gap if a detailed water balance is to be constructed for the lake system.

Potential measurement techniques: LiDAR, Real-Time Kinematic (RTK) survey, ground penetrating radar, surface seismic (refraction) surveys, resistivity studies, geoprobe studies

4 Water balance

The movement of groundwater is generally controlled by elevation with the potentiometric surface typically mirroring topography (Parkin 2002). A preliminary conceptual model for the Thirlmere Lakes can be illustrated by a schematic water balance based on recent observations and the experiences of recent lake behaviour (Figure 11). Whilst the diagram illustrates some of the apparent interrelationships between contributing factors, not all components are known, nor can they be accurately quantified (hence all connecting arrows are of approximately the same size).

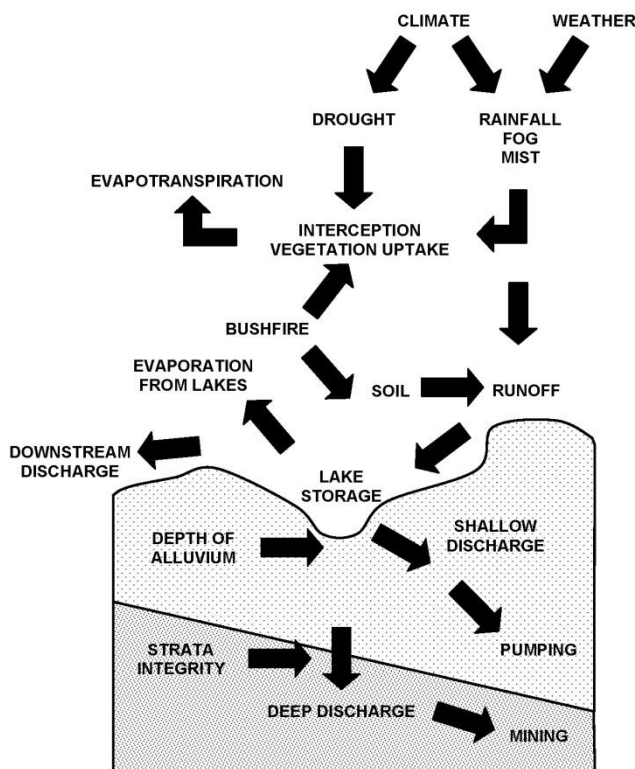


Figure 11: Preliminary conceptual model of lake inputs and outputs

Why we need this research

At a minimum, this preliminary water balance needs to be confirmed by identifying the more dominant causes of water level fluctuations in the lake system. Specific data must be gathered to enable the quantification of the different parts of the water balance, in particular in regard to the input and output fluxes. Beyond that, numerical modelling simulations could be developed once sufficient data has been accumulated to allow predictions of lake behaviour under various climatic regimes. However, given the potential complexity of the lakes environment, there may be linkages between contributing influences that require bridging tools to be developed to facilitate communication between different types of computer programs (e.g. between individual numerical models relating to groundwater, seepage, runoff, climate, etc.).

4.1 Fluxes in

4.1.1 Precipitation

The average annual rainfall of the nearest long-term rainfall gauge at Picton is ~820mm. Rose and Martin (2007) report it as being received in two relatively wet periods from January to March and in June each year (i.e. a bimodal distribution is apparent). The median rainfall for each month is generally greater than 25mm with considerable variation in rainfall from year to year. After long dry spells the Thirlmere Lakes can dry out with known low level stages occurring in 1902, 1929 and 1940 (Rose & Martin 2007; Pells & Pells 2011; Riley et al. 2012) and more recently during the last decade. It is noted that the community uses the term 'dry' even when there is some water in the bed of the lakes. It is more correct to say the lakes were 'substantially dry', which means a large section of the lake bed was exposed and cracked due to desiccation, when referring to the historic and oral records of lake levels (Riley et al. 2012). Riley et al. (2012) provided a detailed analysis of rainfall patterns in the area during the course of the Thirlmere Lakes Inquiry. In response to the Inquiry findings and recommendations, there are now two tipping bucket rain gauges specifically monitoring rainfall immediately adjacent to the lakes (at Lake Nerrigorang and near Lake Gandangarra).

What we don't know yet

While rainfall is now monitored at two locations in the vicinity of Thirlmere Lakes, the relative contribution that rainfall (amount and intensity) makes to water budgets and lake levels still needs to be investigated.

4.1.2 Runoff, infiltration, interflow

Surface runoff (also known as overland flow) is the flow of water that occurs when excess stormwater (or other sources) flows over the ground surface. This might occur because soil is saturated to full capacity, because rain arrives more quickly than soil can absorb it, or because impervious areas send their runoff to surrounding soil that cannot absorb all of it. Surface runoff is a major component of the water cycle.

Infiltration is the process by which water on the ground surface enters the soil.

Interflow is the lateral movement of water in the unsaturated zone, or vadose zone, that first returns to the surface or enters a stream prior to becoming groundwater. Interflow occurs when

water infiltrates into the subsurface, hydraulic conductivity decreases with depth, and lateral flow proceeds downslope. As water accumulates in the subsurface, saturation may occur, and interflow may exfiltrate as return flows, becoming overland flow (Ward & Trimble 2004).

An understanding of surface runoff, infiltration and interflow processes is required to understand the contribution of these components to the overall water budget and, as a consequence, fluctuations in lake levels.

What we don't know yet

Very little is known about surface runoff, infiltration and interflow processes in the vicinity of Thirlmere Lakes.

4.1.3 Groundwater to surface water connections

Exchange of groundwater and surface water occurs in most watersheds and is governed by the difference between water table and surface water elevations (Winter et al. 1998; Healy 2012). If the water table is higher than the stream stage (or lake level), ground water discharges to the stream/lake and the stream/lake is referred to as a *gaining stream/lake*. More detailed modelling of groundwater, lake and stream levels in the area is needed to understand the potential flux of groundwater to the lakes. Preliminary water chemistry results suggest that Lake Nerrigorang in particular may have a significant groundwater input.

The Inquiry report (p.62 and later in the hydrogeology section) states that there is no regional groundwater flow and that flow drains away from the lakes because the lakes are positioned on a topographical high (Riley et al. 2012). This hypothesis suggests that there is only a local groundwater flow system contributing to water levels in the lakes. A question still remains, however, as to whether the lakes are an area for discharge of the local groundwater system or whether through-flow (inflow from one side, outflow from the other side) is also occurring.

What we don't know yet

Very little is known about the connectivity of surface water and groundwater in the vicinity of Thirlmere Lakes.

Potential measurement techniques: optical cable temperature arrays, groundwater characterisation (groundwater–surface water chemistry, tracers, stable isotopes), electromagnetic/resistivity studies

4.2 Fluxes out

4.2.1 Evaporation, evapotranspiration

Evapotranspiration (ET) is the sum of evaporation and plant transpiration from the Earth's land and water surfaces to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception and water bodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. Evapotranspiration is an important part of the water cycle and one of the most difficult quantities to measure.

Evapotranspiration is a significant water loss from drainage basins. Different types of vegetation and land use significantly affect evapotranspiration, and therefore the amount of water leaving a drainage basin. Factors that affect evapotranspiration include the plant's growth stage or level of maturity, percentage of soil cover, solar radiation, humidity, temperature and wind. Isotope measurements indicate transpiration is the larger component of evapotranspiration (Williams et al. 2004; Dinesh Kumar et al. 2014).

Evapotranspiration and the underlying water table are strongly related (William 1994; Devitt et al. 2002; Nachabe et al. 2005), as shallow unsaturated soil and deep saturated groundwater are hydrologically connected through the process of ET (Thompson 2003; Jayakody et al. 2013). The strength of these relationships varies with depth to the water table from the land surface. Roots extract water from the unsaturated zone if the water table is deeper than the root zone, and the unsaturated soil zone is then replenished from the water table below (Jury et al. 1991).

Pan evaporation data can be used to estimate lake losses, but transpiration and evaporation of intercepted rain on vegetation remain unknown. These would need to be estimated to get a complete picture of evapotranspirative water losses from the catchment. Evapotranspiration can, however, be measured or estimated using several different methods.

Indirect approaches to estimate evapotranspiration:

- Catchment water balance

Evapotranspiration may be estimated by creating an equation of the water balance of a drainage basin. The equation balances the change in water stored within the basin (ΔS) with inputs and exports:

$$\Delta S = P - ET - Q - D$$

The input is precipitation (P), and the exports are evapotranspiration (which is to be estimated), streamflow (Q), and groundwater recharge (D). If the changes in storage, precipitation, streamflow, and groundwater recharge are all estimated, the missing flux (ET), can be estimated by rearranging the above equation as follows:

$$ET = P - \Delta S - Q - D$$

- Hydrometeorological equations

The most general and widely used equation for calculating reference ET is the Penman equation. The Penman-Monteith variation is recommended by the United Nations Food and Agriculture Organization (Allen et al. 1998).

- Energy balance

The energy balance model can also be used to estimate ET:

$$\lambda E = R_n - G - H$$

where λE is the energy needed to change the phase of water from liquid to gas, R_n is the net radiation, G is the soil heat flux and H is the sensible heat flux. Using instruments like a scintillometer, soil heat flux plates or radiation meters, the components of the energy balance can be calculated and the energy available for actual evapotranspiration can be estimated.

Experimental methods for measuring ET

- Weighing lysimeter

The weight of a soil column is measured continuously and the change in storage of water in the soil is modelled by the change in weight. The change in weight is converted to units of length based on the surface area of the weighing lysimeter and the unit weight of water. ET is computed as the change in weight plus rainfall minus percolation.

- Remote sensing

In recent decades, estimating ET has been improved by advances in remote sensing, particularly in agricultural studies. However, quantifying ET from mixed vegetation environs is still challenging due to the heterogeneity of plant species, canopy covers, microclimates, and because of costly methodological requirements.

- Eddy covariance

The most direct method of measuring evapotranspiration is with the eddy covariance technique, in which fast fluctuations of vertical wind speed are correlated with fast fluctuations in atmospheric water vapor density. This directly estimates the transfer of water vapor (evapotranspiration) from the land (or canopy) surface to the atmosphere.

In response to the Thirlmere Lakes Inquiry findings and recommendations, a weather station has now been constructed at Lake Nerrigorang. This station currently measures:

- precipitation
- net radiation
- solar radiation
- wind speed/direction
- air relative humidity
- air temperature.

What we don't know yet

At this juncture, it is possible to estimate daily evapotranspiration using indirect measures (i.e. using hydrometeorological equations such as the Penman-Montieth equation); however, the contribution of ET to the overall water budget for Thirlmere Lakes has not been investigated. Further research using energy balance (scintillometer and heat fluxes) and eddy covariance techniques may be required if errors in indirect estimates of evapotranspiration are significant in terms of the overall water balance.

4.2.2 Surface water to groundwater connections

As identified earlier, exchange of groundwater and surface water occurs in most watersheds and is governed by the difference between water table and surface water elevations (Winter et al. 1998; Healy 2012). If the water table is lower than the stream stage (or lake level), surface water can flow from the stream/lake to the subsurface and is referred to as a *losing stream/lake*. More detailed modelling of groundwater, lakes and streams in the area is needed to understand the potential flux of surface water in the lakes to groundwater.

What we don't know yet

As identified earlier, very little is known about the connectivity of surface water and groundwater in the vicinity of Thirlmere Lakes.

4.2.3 Creek flow

The Thirlmere Lakes Inquiry Committee considered the issue of flow from the lakes to the Blue Gum Creek catchment. Surveying suggested that when the upper three lakes reach a level of approximately 306mAHD, they spill downstream into Lake Baraba and then into Lake Nerrigorang, which then overflows into Blue Gum Creek⁵ (Riley et al. 2012). There is a limit to the amount of water that can be stored in Thirlmere Lakes before they overflow and the lake system would therefore drain into Blue Gum Creek if full to overflowing.

The location and elevation of the Lake Nerrigorang outlet dictates that water depths in Lake Nerrigorang have to reach 6–7m before it overflows into Blue Gum Creek (Riley et al. 2012). This depth accorded with readings taken by Vorst (1974) when the lake was full. To complicate matters, there was some suggestion by the community that the outlet may have been partially dammed with several loads of sand to enhance levels in Lake Nerrigorang and also excavated to remove 'mosquitoes and weeds' (Riley et al. 2012).

The groundwater level recorded in the piezometer at the outlet to Lake Nerrigorang was approximately 0.5m below ground surface, which suggested there was a disconnection in the groundwater flow through the outlet col from Lake Nerrigorang to Blue Gum Creek. Groundwater may actually be flowing back into Lake Nerrigorang in the vicinity of the outlet rather than discharging downstream into Blue Gum Creek (Riley et al. 2012).

While the topography rises west of the lakes the deeply incised streams, such as Blue Gum Creek, are lower than the bed of the lake. The Inquiry Committee concluded that any regional groundwater drainage would be away from the lakes so they were not a regional groundwater sink. The groundwater elevation measured downstream at the Smyth property and the water level in Blue Gum Creek at this point was approximately 301mAHD, which suggested a groundwater gradient upstream towards Blue Gum Creek when water levels in Lake Nerrigorang were less than 301mAHD (Riley et al. 2012). The bed of Lake Nerrigorang is less than 299mAHD, so at least two metres of water have to accumulate in the lake before groundwater flows out of the lake downstream (Riley et al. 2012). There remains the possibility that water is moving through the sediments underneath the lake bed, but this has not been investigated.

Vorst (1974) recognised peat deposits approximately 1.5km downstream of Lake Nerrigorang, in Blue Gum Creek. However, as she told the Inquiry Committee, they were not analysed and there is no certainty that they are the same peats she discovered in her drill hole BH2 (Riley et al. 2012). A review of potential swamp areas along Blue Gum Creek showed that swamp deposits were accumulating today in areas where alluvial fans of tributaries form a barrier to Blue Gum Creek. The swamp at the western edge of Thirlmere Lakes National Park (i.e. at the fence piezometer) owes its origin to an alluvial fan impeding flow in Blue Gum Creek (Riley et al. 2012).

⁵ Blue Gum Creek discharges into the Little River to the west, with the Little River subsequently flowing into the Nattai River and then Lake Burrangong.

What we don't know yet

The Inquiry Committee concluded that there was leakage of groundwater towards the west and down Blue Gum Creek, but it was not possible to determine the relative groundwater flows from the lakes towards the east and west. While WaterNSW has installed a flow gauge in Blue Gum Creek, very little flow has actually been recorded since installation. It is possible that water may be moving through the sediments/alluvial fans that appear to be impeding surface flows to Blue Gum Creek. Further investigation of flows to Blue Gum Creek is required to understand when water moves from the lakes to the downstream catchment and whether any of this flow is subsurface.

5 Surveying

The Thirlmere Lakes Inquiry report provided elevations for a number of important points within the Thirlmere Lakes catchment. Surveying was also undertaken of the WaterNSW monitoring bores following their completion, to aid the understanding of the relative elevations of groundwater levels in the shallow and deep systems (Gleeson 2013). In order to develop a comprehensive water balance, the bathymetric form of the lakes needs to be defined through accurate surveying of the beds and banks of each water body. In addition, the accurate positioning of sampling points, other monitoring sites and topographic setting of areas and locations which are the focus of investigations needs to be undertaken so that the findings can be incorporated into the broader conceptual model.

Based on elevation levels taken during the Thirlmere Lakes Inquiry and subsequent surveys, Lake Baraba appears to sit at a higher elevation in the landscape when compared to the other lakes (see Figure 7 above). The development of a high resolution digital elevation model (DEM) would be of great assistance in verifying elevation levels within the Thirlmere Lakes catchment. A ground-truthed LiDAR survey of the Thirlmere Lakes catchment will also be an important way of accurately measuring the relative position of sampling points, other monitoring sites and the topographic relief and surface flow pathways of the catchment⁶.

6 Research integration

Once the basic data on the geology, geomorphology, hydrogeology and hydrology of Thirlmere Lakes and their environs have been collected, conceptual and mathematical models can be built to describe and simulate hydrological and groundwater processes. This will help provide a more in-depth understanding of how water moves at the surface and within the groundwater systems of the area under varying climatic regimes. As identified earlier, one of the most important aims of the study is to understand the interaction between surface water in the lakes and the underlying groundwater systems. Future linkage of surface water and groundwater models may therefore be critical in understanding the fluctuating water levels within the Thirlmere Lakes and explaining them to the broader community.

⁶ A LiDAR survey was undertaken by Land and Property Information on 27 May 2016 (prior to the June 2016 East Coast Low). The results of this survey are still being processed.

7 Ecosystems

The importance of ecology and ecological processes in and around Thirlmere Lakes has been recognised by their inclusion as part of the national parks estate and Greater Blue Mountains World Heritage Area. Whilst the research priorities are focused on developing a hydrological understanding of Thirlmere Lakes, the ecosystems in and around the lakes and their responses to changing water regimes are also considered to be very important. Very few long-term studies on ecology or ecological processes are available for Thirlmere Lakes. Therefore, whilst the primary focus of the research program is clearly on addressing the knowledge gaps in geology, geomorphology, hydrogeology and hydrology, there may also be a capacity to concurrently investigate aspects of ecological response where the linkage to physical processes can be established.

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