# Upland Peatlands of Eastern Australia as Important Water Storage Reservoirs

*Kirsten L. Cowley[1,2], Kirstie A. Fryirs[2], Tim J. Cohen[3,4], Sam Marx[4], Matt Forbes[3,4], Martin Krogh[1]

[1]Science Division - Environment, Energy and Science Group - Department of Planning, Industry and Environment, 3 Weeroona Rd, Lidcombe, NSW, 2141;
[2]Department of Earth and Environmental Sciences, Macquarie University, North Ryde, NSW, 2109;
[3]ARC Centre of Excellence for Australian Biodiversity and Heritage (CABAH), University of Wollongong, Northfields Ave, Wollongong NSW, 2522;
[4]GeoQuest Research Centre, University of Wollongong, Northfields Ave, Wollongong NSW, 2522;
* Corresponding author: kirsten.cowley@mq.edu.au

Published on 19 October 2020 at https://openjournals.library.sydney.edu.au/index.php/LIN/index

Cowley, K.L., Fryirs, K.A., Cohen, T.J., Marx, S., Forbes, M. and Krogh, M. (2020). Upland peatlands of eastern Australia as important water storage reservoirs. *Proceedings of the Linnean Society of New South Wales* **142**, 67-76.

The Greater Blue Mountains World Heritage Area contains over 5,000 ha of peat forming upland swamps (n = 1,858) and numerous freshwater lagoons and lakes such as the Thirlmere Lakes southwest of Sydney. These systems are well known for their water storage capacity, even during dry spells. Here we use peat depth measurements and water content calculations to quantify potential water storage capacity within Lake Baraba in the Thirlmere Lakes National Park. We find that total water storage capacity of the peat in Lake Baraba is 150±17.3 ML. We also calculate total water storage of peat-forming upland swamps across the Blue Mountains World Heritage Area which totals ~60,600 ±33,500 ML. The implications of climate change and anthropogenic disturbance on the water storage and supply functions of these systems as part of the Sydney water supply catchment provides a strong case for their conservation.

Manuscript received 25 May 2020, accepted for publication 6 October 2020.

KEYWORDS: Climate change, lakes, organic soils, peat soils, peatlands, upland swamps, water holding capacity, wetland.

## INTRODUCTION

Peatlands are recognised globally as significant water storage reservoirs, storing about 10% of all freshwater despite occupying only ~3% of the land surface (Boelter 1964; Price and Schlotzhauer 1999; Rezanezhad et al 2016). Peatlands both in Australia and globally are largely Holocene in age. Many of these peatlands began forming at the end of the last glacial maximum between 15 and 9 kyr cal. BP when increases in temperature and moisture increased organic matter deposition within saturated sediments (Gorham and Rochefort 2003; Hope et al, 2009; Fryirs et al. 2014; Hope and Nanson, 2015; Garneau et al 2014; Bispo et al 2016). Anoxic conditions commonly exist within the peat sediments which constrains decomposition and allows for organic matter preservation. It is this organic matter, and to lesser extent, fine clays within the sediment matrix that control the water storage capacity of these peatland systems.

Australian peatlands are primarily found in the uplands along the Great Dividing Range of Eastern Australia (Whinam et al 2003; Pemberton 2005). These peatlands are found from the northern wet tropics to temperate and alpine zones and include various types of tropical wetlands, alpine meadows, temperate upland swamps and freshwater lakes (Pemberton 2005). Although smaller in area than peatlands elsewhere, Eastern Australian peatlands share similar evolution and water storage capabilities to their Northern Hemisphere counterparts (Heathwaite 1993; Holden and Burt 2003; Evans and Warburton 2010). Until recently however, relatively little research has been conducted on the water storage capacity of upland peatlands found in Eastern

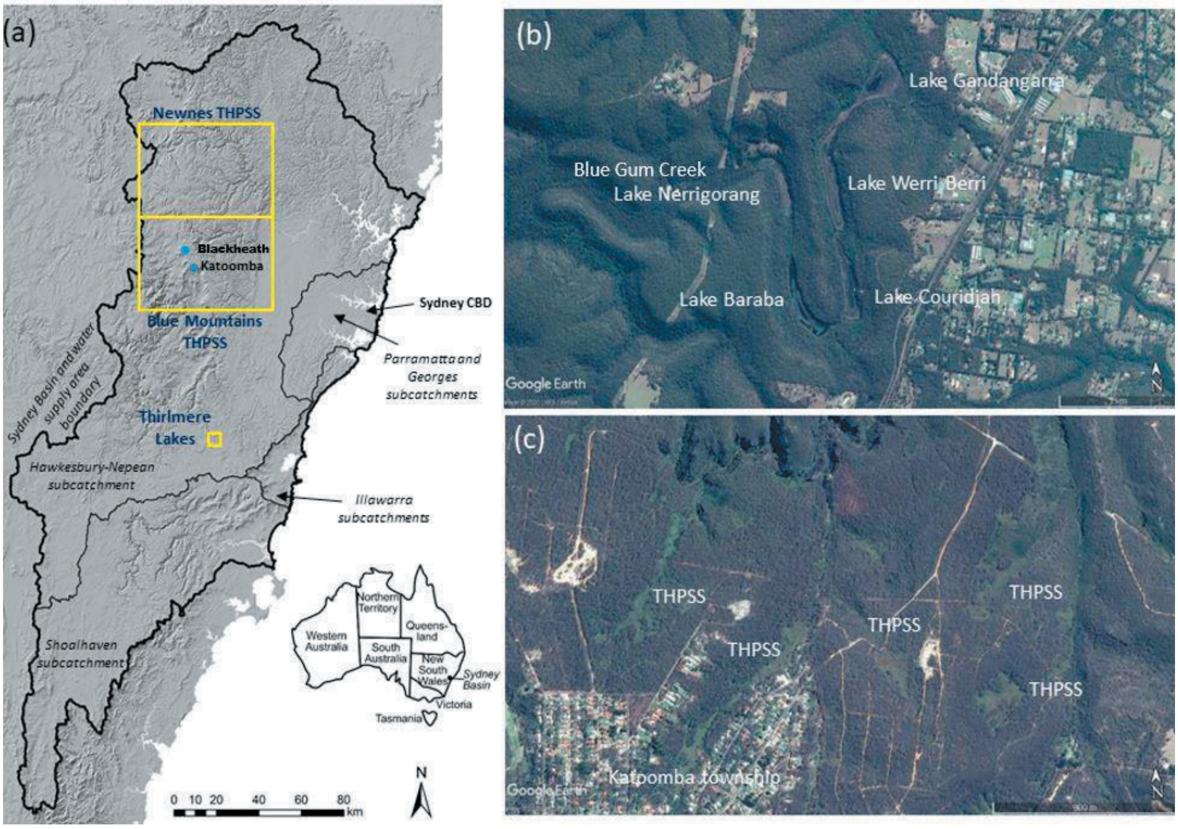


**Fig 1a) Location of THPSS in the Newnes and Blue Mountains regions of the World Heritage Area (Source; Fryirs et al., 2019) b) Location map of Thirlmere Lakes, c) Examples of THPSS near Katoomba in the Blue Mountains**

Australia, particularly at a regional scale, despite the prominence of some of these peatlands within the drinking water catchments of towns and cities (Fryirs et al 2014a; Fryirs et al 2014b;).

Thirlmere Lakes are a set of five lakes within an entrenched meander valley in the Hawkesbury-Nepean catchment (Fig. 1b). Recent declines in lake water levels has led to the development of a targeted research program aimed at understanding the evolution and hydro-dynamics of the lake system (NSW Department of Planning, Industry and Environment 2019a). Recent research has found that climatic variables such as rainfall and evapotranspiration can explain water levels in four of the five lakes (Chen et al 2019). In contrast to the other lakes, Lake Baraba, has maintained a higher water level during a significant drought period between 2017-2019 (NSW Department of Planning, Industry and Environment 2019a). It is possible that the resilience of Baraba's water levels may be due to the presence of large volumes of peat with a high water storage capacity that helps to sustain high water-table levels (Black et al 2006; Mooney & Triantafilis, 2019).

Temperate Highland Peat Swamps on Sandstone (THPSS) are located in the upland headwaters of low order streams on the plateaus upstream of the Eastern Australia escarpment (Fig 1c). THPSS are the primary peat-forming systems within the Blue Mountains World Heritage Area (WHA), where they occupy an area of approximately 5,400 ha (Fryirs and Hose 2016; Fryirs et al. 2019). Most occur as valley bottom swamps that discharge to small bedrock streams (Commonwealth of Australia 2014; Cowley et al 2016; Fryirs et al 2016). The capacity of THPSS to maintain base flow to lower catchment waterbodies during dry periods makes them important water sources for Sydney's drinking water supplies (Cowley et al 2018; Cowley et al 2019).

In the near (2030) and longer (2090) term, Eastern Australia is predicted to experience increasing temperatures and evapotranspiration, decreases in winter rainfall, increasing intensity of droughts and harsher fire weather (Dowdy et al 2015; Bureau of Meteorology and CSIRO 2018). These impacts pose a significant threat to the hydrological function of peatland systems in Eastern Australia. As such, a better understanding of their hydrological characteristics is needed to strengthen the case for the conservation of these important water storage systems.

This paper calculates water storage capacity within both the Thirlmere lakes (Lake Baraba) and THPSS peat-forming systems, in order to gain an appreciation of the total water storage capacity of these systems. We hypothesise that despite their relatively small surface area, these lake and upland swamp systems are collectively important water storage reservoirs.

**Regional setting**

The Thirlmere Lakes are located about 70 km southwest of Sydney ($34^0$ 13' S; $150^0$ 32' E) (Figs 1a and 1b). The Lakes, Gandangarra, Werri Berri, Couridjah, Baraba and Nerrigorang are generally oriented north-south. Although situated close to one another, the lake beds have different elevations, ranging from 298 to 304 m above sea level (m AHD). Lake Baraba in the south, lies at 304 m AHD and has the second largest catchment area of 82 ha (Chen et al 2020). The geological basins within which the lakes occur are considered to be up to 15 million years old (Black et al, 2006) and are topographically and hydrologically disconnected from each other by sandy sills except during high rainfall events when the lakes overflow and become hydrologically connected (David et al 2018). Similarly, hydrological connection to Blue Gum Creek (Fig. 1b), located to the west of the lake system can occur following high rainfall.

The geology underlying the Thirlmere Lakes consists of Triassic Hawkesbury sandstone containing quartz rich interbedded massive and cross-bedded sandstones with associated fluvial overbank deposits (David et al 2018). Unconsolidated and semi-consolidated alluvium/colluvium occurs on the valley floor to depths of 30 m. Quaternary (possibly Tertiary) valley floor and valley margin sediments consist of colluvial material from slope debris and alluvial fans and lacustrine sediment (Vorst 1974). Surficial lake sediments consist of highly organic rich peats and clays that overlie lacustrine clays and sands (Vorst 1974; Black, et al, 2006; Allenby 2018; Barber 2018).

Regional rainfall averages 796 mm/year (Picton Council Depot), falling primarily in the summer months (Bureau of Meteorology 2020a). Annual rainfall for 2019 at Thirlmere Lakes was only 55% of mean annual rainfall for Picton at 442 mm and the region has experienced a particularly severe drought in recent decades (Bureau of Meteorology 2020a; WaterNSW 2020).

The upland swamps or THPSS within the Blue Mountains WHA cover a combined total area of 54 $km^2$ and are located approximately 100 km west of Sydney in two key areas, the Blue Mountains and on the Newnes Plateau (Figs 1a and 1c). At these locations, THPSS occur at elevations of between 600 m to over 1,000 m AHD. The geology underlying the Blue Mountains THPSS is largely comprised of Triassic quartz sandstones and interbedded claystones dissected by steep dendritic gorges (Pickett 1997). Mean annual rainfall is 1400 mm/year at Katoomba and falls primarily in the summer months (Bureau of Meteorology 2020b).

## METHODS

**Lake Baraba**

Peat depths were measured along transects every 20-30 m in a total of 224 locations from the edge of the lake toward the centre with a 2 m metal rod pushed into the lake sediment to refusal. Peat depths at the lake centre were also recorded during sediment coring. The peat depth and location of each site was recorded as a waypoint on a Garmin GPS which was downloaded to ArcGIS 10.4. A raster surface of the lake was interpolated with the waypoint shapefile using the natural neighbour tool in 3D analyst. The peat volume of Lake Baraba was then calculated using the surface volume tool in 3D analyst.

A Russian D-section corer was used to recover 19 cores from the bed of Lake Baraba to a maximum depth of 5.6 m where a yellow/white clay layer or sand layers could be identified. Sediment stratigraphy was logged during the coring. A total of 58 sediment samples were collected at 20-50cm depth intervals and analysed for bulk density, volumetric moisture content and organic matter content by loss on ignition (LOI).

**Blue Mountains and Newnes THPSS**

The physical attributes of THPSS including surface area and regional swamp area were derived from the THPSS mapping database available at https://datasets.seed.nsw.gov.au/dataset/temperate-highland-peat-swamps-on-sandstone-thpss-vegetation-maps-vis-ids-4480-to-4485and previously reported in Fryirs and Hose (2016) and Fryirs et al. (2019). The Blue Mountains and Newnes THPSS datasets were combined to calculate overall peat volume and water holding capacity for both regions. To estimate peat volumes, the surface area of each swamp was multiplied by mean depth for the primary water holding textural units in intact THPSS, as reported in Cowley et al. (2016). To estimate THPSS water holding capacity, mean volumetric moisture content was calculated by multiplying mean gravimetric moisture content and mean bulk density for the primary swamp forming sedimentary layers – the Surface Organic Fines (SOF) and Alternating Organic Sands (AOS) (see Fryirs et al. 2014; Cowley et al. 2016 and below). These were multiplied by peat volume of each swamp in the dataset.

**Bulk density, volumetric moisture content and organic matter content**

Bulk density samples were collected by pushing a small brass tube with a volume of 1.57 $cm^3$ into the sediment cores and capping with foil. All samples were weighed at field moisture then dried at $105^0$ C for a minimum of 12 hours.

Bulk density was calculated as:

$P = Mdry/Vwet$

Where $P$ is bulk density in g/$cm^3$, $Mdry$ is the dry sample mass in g and $Vwet$ is the wet sample volume in $cm^3$.

Volumetric moisture content was calculated as:

$Vm =\{[(Mwet-Mdry)/Mdry] *P\}*100$

Where $Vm$ is volumetric moisture content in % and $Mwet$ is the wet sample weight in g.

Organic matter content was measured as loss on ignition (LOI), by combusting 2 g of dry peat sample in a Lindberg furnace at $550^0$ C for five hours, with the organic matter content representing the sample weight difference post combustion. LOI was calculated as the percentage lost from oven dry samples.

Students t-tests were undertaken on sedimentary units to determine whether there were significant differences in mean bulk density, volumetric moisture content and organic matter between the peat and underlying clay/sand units with the Shapiro-Wilk test for normality applied. Where the dataset was not normal, the Mann-Whitney Sum Test was applied.

Water storage capacity in Lake Baraba was calculated from mean moisture content multiplied by peat volume as calculated from ArcGIS and converted to ML. Peat volumes for THPSS in the Blue Mountains WHA were calculated from swamp area multiplied by mean peat depth. Water storage was calculated from mean moisture content multiplied by peat volume for each swamp which was summed to arrive at total water storage capacity for Blue Mountains THPSS. Uncertainty in water holding capacity and THPSS peat volume estimates were calculated using measurement standard deviations for error propagation, assuming the errors for different measures were uncorrelated (Kirchener,2001).

## RESULTS

The stratigraphy of Lake Baraba consists of highly organic, fine-grained peats (mean LOI 76%), overlying yellow/white clays interbedded with clayey sands and sandy clays. The maximum peat depth in Lake Baraba was 4.9 m with a mean depth of 1.4±0.9 m (Table 1). Total peat volume of the lake was calculated at ~154,400 $m^3$ with a total water holding capacity of 150± 17.3 ML.

**Table 1. Statistics for Lake Baraba peat sampling. Statistical significance of differences between textual units was undertaken using a student's t-test**

| | Sample size | Minimum | Maximum | Mean ± SD | Statistical significance ($p < 0.05$) |
|---|---|---|---|---|---|
| Peat depth (m) | 243 | 0 | 4.9 | 1.4 (±0.9) | NA |
| Peat bulk density (g/$cm^3$) | 38 | 0.08 | 0.35 | 0.2 (±0.06) | <0.001 |
| Sand/clay bulk density (g/$cm^3$) | 18 | 0.2 | 1.4 | 1 (±0.3) | |
| Peat moisture content (%) | 31 | 65 | 113 | 97 (±11) | <0.001 |
| Sand/clay moisture content (%) | 18 | 14 | 130 | 77 (±22) | |
| Peat organic matter content (%) | 32 | 41 | 94 | 79 (±14) | <0.001 |
| Sand/clay organic matter content (%) | 25 | 7 | 63 | 23 (±19) | |

**Table 2. Statistics for Blue Mountains THPSS. Statistical significance of differences between textual units was undertaken using a student's t-test (Source, Cowley et al. (2016) raw data)**

| | Sample size | Minimum | Maximum | Mean (± SD) | Statistical significance ($p < 0.05$) |
|---|---|---|---|---|---|
| SOF/AOS depth (m) | 12 | 0.5 | 2.5 | 1.62 (±0.7) | NA |
| SOF/AOS bulk density (g/cm$^3$) | 60 | 0.14 | 2.1 | 0.98 (±0.5) | <0.001 |
| FCS/BSG bulk density (g/cm$^3$) | 14 | 1.05 | 2 | 1.5 (±0.3) | |
| SOF/AOS Moisture content (%) | 60 | 30 | 121 | 69 (±24) | 0.004 |
| FCS/BSG moisture content (%) | 12 | 34 | 63 | 48 (±10) | |
| SOF/AOS organic matter content %) | 103 | 0.4 | 55 | 12.5 (±11) | <0.001 |
| FCS/BSG organic matter (%) | 13 | 1.3 | 6.7 | 3.6 (±1.9) | |

The stratigraphy of intact Blue Mountains' THPSS consists of a surficial layer, the SOF, that is a highly porous fine silt/sand layer with living organic matter in the matrix and a mean thickness of 0.29 m. The primary peat forming layer, the AOS underlies the SOF and has a mean thickness of 1.3 m consisting of fine to medium grained black, highly organic sandy loams and loamy sands. Fine Cohesive Sands (FCS) underlie the AOS layers with a mean thickness of 0.13 m and consist of fine white sandy clay or clayey sands. Basal sands and gravels underlie the FCS layer and consist of grey coarse sands and gravels with low organic matter with a mean thickness of 0.16 m (Cowley et al, 2016; Fryirs et al, 2014a, b). Mean peat depths within the Blue Mountains and Newnes THPSS were much shallower than in Lake Baraba; with an average depth of 1.62±0.7 m (Table 2). The THPSS have a mean volumetric moisture content of 69±24 % (Table 2). Collectively, peat volumes for THPSS within the Blue Mountains WHA (representing 1,856 peat swamps) were calculated at ~87,842,000±37,900,000 m$^3$. This equates to a total water holding capacity of ~60,600±33,500 ML.

## DISCUSSION

Peat forming systems such as Thirlmere Lakes are significant water storage systems within the landscape. The water storage capacity of the surficial peat in Lake Baraba is more than three times the surface water volume of the lake that was recorded after an east coast low rain event in June 2016 (S. Chen pers.comm.), meaning that the peat holds considerably more water than the lake itself at high water level. This remarkable water holding and storage capacity of the peat may go some way to explaining the resilience of Lake Baraba to drought relative to the other Thirlmere lakes. During the most recent drought from 2017 - 2019, Lake Baraba has maintained surface water much longer than the other Thirlmere Lakes (Fig. 2).

THPSS are also significant water storage reservoirs within the Blue Mountains WHA with water released to downstream water supply catchments via bedrock streams. Sydney Water (2019) estimates that Sydney residents have a weather corrected per capita water usage of 298 L per day or 108,770 L per annum. The water stored in THPSS across the WHA equates to the annual water consumption of 557,000 Sydney residents.

Peat forming systems such as the Thirlmere Lakes and THPSS are vitally important for threatened groundwater dependent biota such as the endangered giant dragonfly (*petalura gigantea*) and Blue Mountains skink (*Eulamprus leuraensis*), the rare freshwater sponge (*Radiospongilla sceptroides*) and endangered Australasian bittern (*Botaurus poiciloptilus*) (Benson and Baird, 2012; NSW Department of Planning, Industry and Environment, 2019b).

Climate change projections for Eastern Australia in the 21st Century are for increased temperatures,

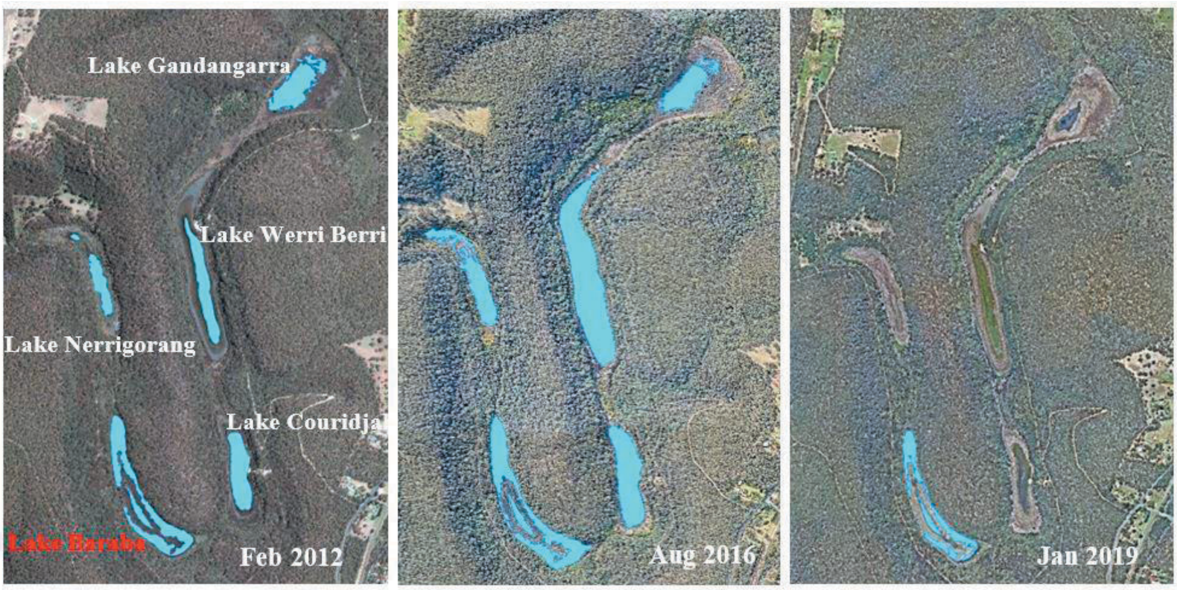


**Fig. 2 Historical aerial photographs between 2012 and 2019 showing surface water maintenance in Lake Baraba when the other Thirlmere lakes were dry (Source: Cowley personal data)**

evapotranspiration and decreased soil moisture (Dowdy et al 2015). Drought duration is also expected to increase (Dowdy et al 2015). These predictions could potentially lead to significant declines in water resource availability. The magnitude of the impact of climate change on the water storage capacity of peat forming lakes and upland swamps in Eastern Australia remains unknown, but like elsewhere it is likely that these climatic changes will impact on their hydrological function (Price and Schlotzhauer 1999; Holden et al 2006; Whittington and Price 2006). These impacts are expected to lower water tables within THPSS, reducing the ability of these peatlands to form peat that stores water and compromising downstream flows (Roulet et al 1992; Bloomfield et al 2003; Cowley et al 2019). In both THPSS and Lake Baraba, prolonged water table drawdown resulting from climatic change could result in significant decomposition of organic matter within the peat matrix which can cause the peat to dry out and compress, further reducing the ability of the peat to store water (Joosten et al 2012; Leifeld et al 2012; Cowley et al 2016).

As is well documented in Australia and overseas, anthropogenic activities such as underground mining, groundwater extraction and urbanisation can also lead to the lowering of water tables within peatland and swamp systems (Holden et al 2006; Worrall et al 2007; Luscombe et al 2016; Cowley et al 2019). Many swamps on the Newnes and Woronora plateaus have experienced rapid declines in water table levels due to impacts associated with longwall mining (Krogh 2007; Goldney et al 2010; Benson and Baird 2012; Commonwealth of Australia 2014; IEPMC 2019; MSEC 2019). High rates of vegetation mortality, peat degradation and water discharge losses all occurred following the undermining of these swamps (Goldney et al 2010; Benson and Baird, 2012; Commonwealth of Australia 2014; IEPMC 2019; MSEC 2019). These changes have likely been exacerbated at impacted swamps on the Newnes Plateau as a result of recent fires in the catchment (Baird and Benson, 2020; Fryirs et al., subm.). Urbanisation also impacts on the function of the water table in these peatland systems (Cowley et al. 2018). Channelised THPSS within urbanised catchments in the Blue Mountains have highly variable water tables and discharge, with increased water table drawdowns during dry periods relative to intact swamps located within conservation areas (Cowley et al. 2018).

Irrespective of whether the cause of degradation is due to climate change or anthropogenic disturbance, the secondary consequences of altered hydrological function on these systems can lead to their permanent loss, or significant impairment. The recovery time from such disturbances can be long, assuming restoration is possible and irreversible change has not occurred. Widespread peatland loss through desiccation, channelisation and fire is common in many places (Freeman et al, 1992; Price, 2003; Tomkins and Humphreys, 2006; Wösten et al. 2006; Ise et al, 2008; Evans and Warburton 2011; Holden et al 2011; Page and Hooijer 2016; Turetsky et al 2016). For example, work on *Sphagnum* peatlands, suggest that once the hydrological function of a peat-forming system is altered (e.g. via channelisation), it may take up to 10 years to re-establish a stable high water table and up to 30 years for a the recovery of functioning ecosystem that accumulates peat after appropriate restoration actions are emplaced (Gorham and Rochefort 2003; Whinam et al. 2003; Hope et al. 2009; Lucchese et al. 2010).

With climate change it is highly likely that the water storage capacity of peat forming systems will be most impacted during dry periods and droughts. Additionally, the vulnerability of these systems to anthropogenic impacts such as groundwater interference and urbanisation may exacerbate these changes and inhibit the potential for recovery. The capacity for peat to recover after drought and/or anthropogenic disturbance has not yet been investigated for either the Thirlmere Lakes or THPSS systems. Robust conservation and rehabilitation measures are needed to ensure the resilience of these systems in the future. This is particularly relevant for those systems that are contained within the Sydney water supply catchment that supports a large and growing population.

This paper has demonstrated the remarkable water storage capacity of peat forming systems in Eastern Australia. Not only are these water storage reservoirs vital for the maintenance of groundwater dependent ecosystems and threatened species, their capacity to maintain base flow to lower catchment waterbodies during dry periods makes them important water sources for Sydney's drinking water supplies.

## ACKNOWLEDGEMENTS

This project was supported by a grant awarded by the NSW Government through the former Office of Environment and Heritage. We thank Alex Wall and Fabian Boesl from University of Wollongong and Joanne Ling and Wayne Kuo from Science Division - Environment, Energy and Science Group - Department of Planning, Industry and Environment for help with fieldwork. We thank Shengyang Chen for additional data on surface water volumes in Lake Baraba. We also thank Jackson Allenby from the University of Wollongong for additional Lake Baraba core data.

## REFERENCES

Allenby, J. (2018). Thirlmere Lakes; A degraded environment or an environment sensitive to natural hydroclimate variability? (Honours Thesis) University of Wollongong, Australia, available from <https://ro.uow.edu.au/thesesuow/>.

Baird, I. R., & Benson, D. (2020). Serious impacts of longwall coalmining on endangered Newnes Plateau Shrub Swamps, exposed by the December 2019 bushfires. Australasian Plant Conservation: Journal of the Australian Network for Plant Conservation, 29(1): 12.

Barber, E.J. (2018). Crossing Three Deep Valleys: The Sedimentology, Geomorphology and Palaeo-environments of Thirlmere Lakes, NSW. (Honours Thesis) University of Wollongong, Australia, available from <https://ro.uow.edu.au/thesesuow/>.

Benson D., Baird I.R. (2012). Vegetation, fauna and groundwater interrelations in low nutrient temperate montane peat swamps in the upper Blue Mountains. New South Wales. *Cunninghamia.* **12,** (4):267-307.

Bispo, D.F. A., Silva, A.C., Christofaro, C., Silva, M.L.N., Barbosa, M.S., Silva, B.P.C., ... and Fabris, J.D. (2016). Hydrology and carbon dynamics of tropical peatlands from Southeast Brazil. *Catena*, **143**, 18-25.

Black M.P., Mooney S.D., Martin H.A. (2006). A> 43,000-year vegetation and fire history from Lake Baraba, New South Wales, Australia. *Quaternary Science Reviews*. **25,** (21-22):3003-3016.

Boelter D.H. (1964). Water storage characteristics of several peats in situ. *Soil Science Society of America Journal*. **28,** (3):433-5.

Bureau of Meteorology (2020a). Daily Rainfall, Picton Council Depot, Climate Data Online, available from <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=068052> (17 January 2020).

Bureau of Meteorology (2020b). Monthly Rainfall Katoomba, Climate Data Online, available from <http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=139&p_display_type=dataFile&p_startYear=&p_c=&p_stn_num=063039> (6 March 2020).

Bureau of Meteorology and CSIRO. (2018). State of the Climate 2018. Commonwealth of Australia, available from <http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml> (6 March 2020).

Chen, S., Johnson, F., and Glamore, W. (2019). Fusing remote sensing data with numerical simulation to estimate historical water levels in Thirlmere Lakes. In Elsawah, S. (Ed.) MODSIM2019, 23rd International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, Canberra, Australia.https://mssanz.org.au/modsim2019/documents/MODSIM2019_Book_of_Abstracts.pdf (22 September 2020)

Chen S., Johnson F.M., Drummond C., Glamore, W, (2020): A new method to improve the accuracy of remotely sensed data for wetland water balance estimates, *Journal of Hydrology: Regional Studies*, **29,** 100689.

Commonwealth of Australia. (2014). Temperate Highland Peat Swamps on Sandstone: evaluation of mitigation and remediation techniques, Knowledge report, prepared by the Water Research Laboratory, University of New South Wales, for the Department of the Environment, Commonwealth of Australia.

Cowley K.L., Fryirs K.A., Hose G.C. (2016). Identifying key sedimentary indicators of geomorphic structure and function of upland swamps in the Blue Mountains for use in condition assessment and monitoring. *Catena*. **147**, 564-77.

Cowley, K.L., Fryirs, K.A., Chisari, R., and Hose, G.C. (2019). Water Sources of Upland Swamps in Eastern Australia: Implications for System Integrity with Aquifer Interference and a Changing Climate. *Water*, **11,** (1), 102.

Cowley K.L., Fryirs K.A., Hose G.C. (2018). The hydrological function of upland swamps in eastern Australia: The role of geomorphic condition in regulating water storage and discharge. *Geomorphology*. **310,** 29-44.

David, K., Timms, W., Rau, G., Andersen, M. and McMillan, T. (2018). A multidisciplinary study of groundwater conditions in sedimentary strata at Thirlmere Lakes (NSW). *ASEG Extended Abstracts*, **2018,** (1), 1-5.

Dowdy, A. Abbs, D., Bhend, J., Chiew, F., Church, J., Ekstrom, M.…and Whetton, P. (2015). East Coast Cluster Report, Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Cluster Reports, eds. Ekstrom, M. et al., CSIRO and Bureau of Meteorology, Australia.

Evans, M.G. and Warburton, J. (2010). Peatland geomorphology and carbon cycling. *Geography Compass*, **4,** (10), 1513-1531.

Evans, M.G. and Warburton, J. (2011). 'Geomorphology of upland peat: erosion, form and landscape change'. (John Wiley & Sons, UK).

Freeman, C., Lock, M.A., and Reynolds, B. (1992). Fluxes of $CO_2$, $CH_4$ and $N_2O$ from a Welsh peatland following simulation of water-table draw-down: potential feedback to climatic change. *Biogeochemistry*, **19,** (1), 51-60.

Fryirs, K.A., Cowley, K. and Hose, G.C. (2016). Intrinsic and extrinsic controls on the geomorphic condition of upland swamps in Eastern NSW. *Catena*, **137**, 100-112.

Fryirs, K.A., Cowley, K.L., Hejl, N., Chariton, A., Christiansen, N., Dudaniec, R.Y., Farebrother, W., Hardwick, L., Ralph, T., Stow, A., Hose, G. subm. Do peat swamps burn? The extent and impact of the 2019-2020 Australian bushfires on upland swamps in the Blue Mountains, NSW. *International Journal of Wildland Fire*.

Fryirs, K.A., Farebrother, W. and Hose, G.C. (2019). Understanding the spatial distribution and physical attributes of upland swamps in the Sydney Basin as a template for their conservation and management. *Australian Geographer*. **50,** (1), 91-110.

Fryirs, K., Freidman, B., Williams, R. and Jacobsen, G. (2014a). Peatlands in eastern Australia? Sedimentology and age structure of temperate highland peat swamps on sandstone (THPSS) in the Southern Highlands and Blue Mountains of NSW, Australia. *The Holocene*, **24,** (11), 1527-1538.

Fryirs, K., Gough, J. and Hose, G.C. (2014b). The geomorphic character and hydrological function of an upland swamp, Budderoo Plateau, Southern Highlands, NSW, Australia. *Physical Geography*, **35,** (4), 313-334.

Fryirs, K. and Hose, G. (2016). The spatial distribution and physical characteristics of temperate highland peat swamps on sandstone (THPSS). *Ecological Management and Restoration*.

Garneau, M., van Bellen, S., Magnan, G., Beaulieu-Audy, V., Lamarre, A. and Asnong, H. (2014). Holocene carbon dynamics of boreal and subarctic peatlands from Québec, Canada. *The Holocene*, **24,** (9), 1043-1053.

Goldney, D., Mactaggart, B, Merrick, N. (2010). Determining whether or not a significant impact has occurred on Temperate Highland Peat Swamps on Sandstone within the Angus Place colliery Lease on the Newnes Plateau Report. Department of the Environment, Water, Heritage and the Arts.

Gorham, E. and Rochefort, L. (2003). Peatland restoration: a brief assessment with special reference to Sphagnum bogs. *Wetlands Ecology and Management*, **11,** (1-2), 109-119.

Heathwaite, A.L. (1993). Disappearing peat-regenerating peat? The impact of climate change on British peatlands. *Geographical Journal*, 203-208.

Holden, J. and Burt, T.P. (2003), Runoff production in blanket peat covered catchments, *Water Resources. Research.*, **39**, 1191.

Holden, J., Evans, M.G., Burt, T.P. and Horton, M. (2006). Impact of land drainage on peatland hydrology. *Journal of Environmental Quality*, **35,** (5), 1764-1778.

Holden, J., Wallage, Z.E., Lane, S.N. and McDonald, A.T. (2011). Water-table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology*, **402,** (1-2), 103-114.

Hope, G. and Nanson R.A. (2015). Peatland carbon stores and fluxes in the Snowy Mountains, New South Wales, Australia. *Mires and Peat,* **15** (11), 1-23.

Hope, G., Nanson, R.A. and Flett, I. 2009. Technical Report 19. The Peat-forming Mires of the Australian Capital Territory. Canberra: Territory and Municipal Services.

IEPMC (2019) Report of the Independent Expert Panel for Mining in the Catchment: Part 2 Coal Mining Impacts in the Special Areas of the Greater Sydney Water Catchment 14 October 2019, available from <https://www.chiefscientist.nsw.gov.au/reports/independent-expert-panel-for-mining-in-the-catchment>.

Ise, T., Dunn, A.L., Wofsy, S.C. and Moorcroft, P.R. (2008). High sensitivity of peat decomposition to climate change through water-table feedback. *Nature Geoscience*, **1,** (11), 763-766.

Joosten, H., Tapio-Biström, M.L. and Tol, S. (2012). Peatlands: guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Food and Agriculture Organization of the United Nations.

Kirchner, James. "Data Analysis Toolkit #5: Uncertainty Analysis and Error Propagation" (PDF). Berkeley Seismology Laboratory. University of California, available from <http://seismo.berkeley.edu/~kirchner/eps_120/Toolkits/Toolkit_05.pdf>.

Leifeld, J., Steffens, M. and Galego-Sala, A. (2012). Sensitivity of peatland carbon loss to organic matter quality. *Geophysical Research Letters*, **39,** (14).

Lucchese, M., Waddington, J.M., Poulin, M., Pouliot, R., Rochefort, L. and Strack, M. (2010). Organic matter accumulation in a restored peatland: Evaluating restoration success. *Ecological Engineering*, **36,** (4), 482-488.

Luscombe, D.J., Anderson, K., Grand-Clement, E., Gatis, N., Ashe, J., Benaud, P., ... and Brazier, R.E. (2016). How does drainage alter the hydrology of shallow degraded peatlands across multiple spatial scales? *Journal of hydrology*, **541**, 1329-1339.

Mooney, S.D. and Triantafilis, J. (2019). Characterising the carbon and waterholding capacity of a small swamp in the Wolgan Valley (in the western Blue Mountains). *World Heritage on Sydney's Doorstep: The Natural History of the Blue Mountains Geology, Flora, Fauna and Human Impacts*. 2019 Linnean Society of NSW natural History Field Symposium, 7-9 November 2020 < http://linneansocietynsw.org.au///symposia/Blue%20Mountains/Blue_Mountains_Symposium_Abstracts&Field_Guide.pdf> (22 September 2020).

MSEC (2019) Centennial Coal: Angus Place Colliery – LW1001 to LW1015. Subsidence Predictions and Impact Assessments for the Natural and Built Features due to the Mining of the Proposed LW1001 to LW1015 in Support of the Amended Project. Report Number MSEC1046 Revision A, available from < https://www.planningportal.nsw.gov.au/major-projects/project/12641>.

NSW Department of Planning, Industry and Environment, (2019a). Thirlmere Lakes Research Newsletter Autumn 2020, available from <https://www.environment.nsw.gov.au/research-and-publications/our-science-and-research/our-research/water/freshwater-and-wetlands/thirlmere-lakes-research> (16 January 2020).

NSW Department of Planning, Industry and Environment, (2019b). *Thirlmere Lakes National Park Plan of Management*. Environment, Energy and Science, Department of Planning, Industry and Environment, Sydney.

Page, S.E. and Hooijer, A. (2016). In the line of fire: the peatlands of Southeast Asia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **371,** (1696), 20150176.

Pemberton, M. (2005). Australian peatlands: a brief consideration of their origin, distribution, natural values and threats. *Journal of the Royal Society of Western Australia*, **88**, 81.

Pickett, J.W., Alder, D. and Pickett, J.W. (1997). *Layers of time: The Blue Mountains and their geology*. New South Wales Department of Mineral Resources.

Price, J.S. (2003). Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resources Research*, **39,** (9).

Price, J.S. and Schlotzhauer, S.M. (1999). Importance of shrinkage and compression in determining water storage changes in peat: the case of a mined peatland. *Hydrological Processes*, **13,** (16), 2591-2601.

Rezanezhad, F., Price, J.S., Quinton, W.L., Lennartz, B., Milojevic, T. and Van Cappellen, P. (2016). Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists. *Chemical Geology*, **429**, 75-84.

Schädler, S. and Kingsford, R.T. (2016). Long-term changes to water levels in Thirlmere Lakes–drivers and consequences. *Centre for Ecosystem Science, School of Biological, Earth and Environmental Science, University of New South Wales, NSW*, *2052*.

Roulet, N.T., Ash, R. and Moore, T.R. (1992). Low boreal wetlands as a source of atmospheric methane. *Journal of Geophysical Research: Atmospheres*, **97,** (D4), 3739-3749.

Russell, G.N., Green, R.T., Spencer, J. and Hayes, J., (2010). Thirlmere Lakes groundwater assessment. NSW Office of Water, Sydney.

Tomkins, K.M. and Humphreys, G.S., (2006). Technical Report 2: Upland Swamp development and erosion on the Woronora Plateau during the Holocene. Report to SCA by Macquarie University, Ryde.

Sydney Water (2019). Water Conservation Report 2018-2019, available from <https://www.sydneywater.com.au/web/groups/publicwebcontent/documents/document/zgrf/mdq3/~edisp/dd_047419.pdf> (1 May 2020).

Vorst, P.C. (1974). 'Thirlmere Lakes, NSW: geomorphic environment and evolution', Honours Thesis, Macquarie University.

WaterNSW, 2020, Real time data for Lake Nerrigorang, available from <https://realtimedata.waternsw.com.au/> (17 January 2020).

Whinam, J., Hope, G.S., Clarkson, B.R., Buxton, R.P., Alspach, P.A. and Adam, P. (2003). Sphagnum in peatlands of Australasia: Their distribution, utilisation and management. *Wetlands Ecology and Management*, **11,** (1-2), 37-49.

Whittington, P.N. and Price, J.S. (2006). The effects of water-table draw-down (as a surrogate for climate change) on the hydrology of a fen peatland, Canada. *Hydrological Processes*, **20,** (17), 3589-3600.

Worrall, F., Armstrong, A. and Holden, J. (2007). Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water-table depth. *Journal of Hydrology*, **337,** (3-4), 315-325.

Wösten, J.H. M., Van Den Berg, J., Van Eijk, P., Gevers, G.J.M., Giesen, W.B.J.T., Hooijer, A. ... and Silvius, M.J. (2006). Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests. *Water Resources Development*, **22,** (1), 157-174.

Young, A.R. (1986). Quaternary sedimentation on the Woronora Plateau and its implications for climatic change. *Australian Geographer*, **17,** (1), 1-5.