An underground drip water monitoring network to characterize rainfall recharge of groundwater at different geologies, environments, and climates across Australia

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Abstract. Understanding when and why groundwater recharge occurs is of fundamental importance for the sustainable use of this essential freshwater resource for humans and ecosystems. However, accurately capturing this component of the water balance is widely acknowledged to be a major challenge. Direct physical measurement identifying when groundwater recharge is occurring is possible by utilizing a sensor network of hydrological loggers deployed in underground spaces located in the vadose zone. Through measurements of water percolating into these spaces from above, we can record the potential groundwater recharge process in action. By using automated sensors, it is possible to precisely determine when recharge occurs (which event, month, or season, and for which climate condition). Combined with daily rainfall data, it is possible to quantify the 'rainfall recharge threshold', the amount of rainfall needed to generate groundwater recharge, and its temporal and spatial variability. Australia's National Groundwater Recharge Observing System (NGROS) provides the first dedicated sensor network for observing groundwater recharge at an event-scale across a wide range of geologies, environments, and climate types representing a wide range of Australian hydroclimates. Utilizing tunnels, mines, caves, and other subsurface spaces located in the vadose zone, the sensors effectively record 'deep drainage', water that can move beyond the shallow subsurface and root zone to generate groundwater recharge. The NGROS has the temporal resolution to capture individual recharge events, with multiple sensors deployed at each site to constrain the heterogeneity of recharge between different flow paths, and to quantify (including uncertainty bounds) rainfall recharge thresholds. Established in 2022, the network is described here together with examples of data being generated.

1 Introduction

For the sustainable use of our essential groundwater resources an understanding of when and why groundwater recharge occurs is of fundamental importance (Gleeson et al., 2012). At the catchment or regional scale, estimates of the diffuse rainfall recharge of groundwater used by the international research community are generally inferred from water chemistry and water level information that we obtain from boreholes (e.g., Crosbie et al., 2010; Jasechko and Taylor, 2015). However, even with the latest methodologies and syntheses (e.g., Jasechko, 2019; Crosbie and Rachakonda, 2021; Berthelin et al., 2023), these recharge estimates are typically uncertain long-term averages (e.g., annual averages). Such methods, and data, cannot identify specific recharge events and are often

affected by groundwater abstraction. In contrast, techniques that measure infiltration at the surface can do so at
the event scale but provide limited understanding about the portion of water that may recharge the groundwater,
as much of this infiltrated water will be removed by evapotranspiration (Shanafield and Cook, 2014). Geophysical
estimates of total subsurface water can be obtained from the Gravity Recovery and Climate Experiment and
Follow On products (GRACE/GRACE–FO), with recent attempts to use this data to derive large-scale quantified
groundwater recharge estimates (Hu et al., 2023). This approach is computationally intensive, has a coarse spatial
resolution (~200 x 200 km) and is not able to separate the recharge process from soil moisture storage. The large
uncertainty means that the international research community uses the word 'estimate' when referring to recharge
calculations using existing methods (Healy, 2010). Crucially, existing methods are 'snapshots in time' that are not
long enough or of sufficient temporal resolution to identify the relationships between climate and groundwater
recharge (Rau et al., 2020). This knowledge gap means that it is difficult to manage the resource sustainably.

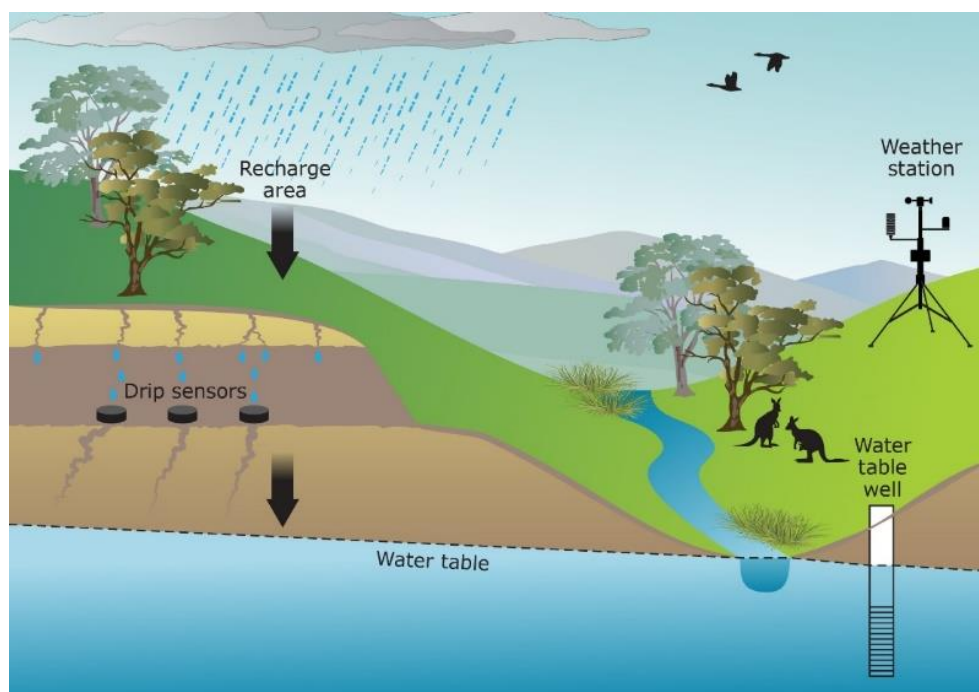



Figure 1. Rainfall "events" drive water flow through the terrestrial environment, percolating through the ground - especially where the bedrock contains fractures that permit flow through the upper layers of soil to the water table below. The NGROS system has placed sensors in tunnels, mines and other subsurface spaces to measure recharge over time and space and utilise locally available rainfall data to calculate "event-based" recharge following rainfall.

Direct physical measurement identifying when groundwater recharge is occurring is possible by utilizing a sensor
network of hydrological loggers deployed in underground spaces located between the soil and the aquifer (Fig.
1). Through measurements of water percolating into these spaces from above, we can record the groundwater
recharge process in action. By using automated sensors, it is possible to determine when recharge events occur
(which event, month, or season, and which climate condition). If rainfall event data is available, it is possible to
quantify the amount of rainfall needed to generate groundwater recharge. This is referred to as the 'rainfall

recharge threshold' and importantly, can vary temporally as well as spatially (e.g., Baker et al., 2021). Australia's National Groundwater Recharge Observing System (NGROS) provides the first dedicated sensor network for observing the recharge of groundwater at the event-scale across a wide range of geologies, environments, and climate types that represent a wide range of Australian hydroclimates. Utilizing tunnels, mines, and other subsurface spaces located between the soil and the groundwater table in the unsaturated zone, the sensors (Fig. 2) effectively record 'deep drainage', water that can move beyond the shallow subsurface and root zone to generate groundwater recharge. The NGROS has the temporal resolution to capture individual recharge events, with multiple sensors deployed at each site to constrain the heterogeneity of recharge between different flow paths, and to quantify (including uncertainty bounds) rainfall recharge thresholds. This infrastructure can identify that threshold wherever recharge is monitored. These data, openly accessible via a database, will inform the understanding of the recharge process, the most difficult term in the water balance (Ajami, 2021); improve water resource assessments, and improve the sustainable management of groundwater.

2 The monitoring concept

The monitoring concept for NGROS is to (1) provide data on the timing of recharge at the event timescale and (2) determine the amount of precipitation needed to generate recharge at an event scale. The observing system is distributed to cover a range of geologies, environmental and climate types, to quantify the relationship between these factors and the number of recharge events and the amount of precipitation needed to generate recharge. For logistical reasons, the NGROS was initially established in southern and eastern Australia, with the aim to expand the network over time. The sites focus on fractured-rock lithologies; this is important for the success of the approach as it ensures sufficiently rapid, fracture-flow water movement that will preserve frequent event-based responses to recharge (as opposed to smoothed recharge through porous vadose zones). At locations within these sites where water movement was identified, sensors (drip counters) were deployed. At each site, between three and twelve sensors are deployed to provide a quantification of the heterogeneity of groundwater recharge. While the regional groundwater at each site may also be influenced by regional groundwater flow, groundwater abstraction, and at some sites focused recharge from streams, the sensor network at each site strictly monitors the local vertical recharge through the vadose zone.

Where possible, NGROS site selection complements other initiatives that seek to understand vadose zone processes e.g., by co-location with Critical Zone Observatories or exiting groundwater monitoring bores or soil moisture monitoring infrastructure. Furthermore, at selected sites, the NGROS project has also engaged with local stakeholders and communities to understand existing groundwater recharge knowledge. All groundwater recharge data will be made available through an open-access database and the findings from conversations with stakeholders will be shared through multiple means, including blog posts on the website and peer-review publications, as well as presentations with stakeholders.

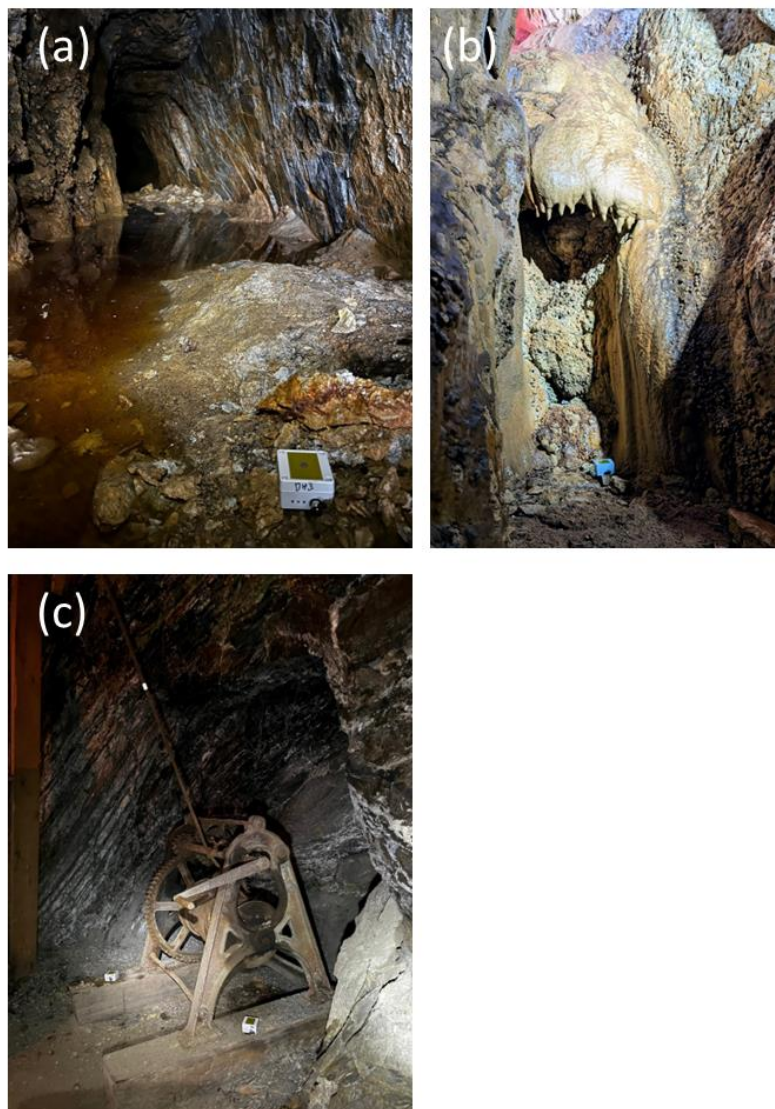



Figure 2. Example logger deployment. (a) Durham Lead. The logger is situated on the floor, recording water dripping from the mine roof (b) Capricorn Caves. The logger is situated beneath a flowstone, an actively forming calcium carbonate speleothem formed by flowing water. Water flows along the cave walls and drips onto the logger (c) Walhalla Long Tunnel. Two loggers are visible, both recording water dripping from the mine roof.

2.1 Site descriptions

Fourteen NGROS sites were initially established in 2022, after consultation with potential partners that included

National Parks, local and regional government, local and national speleological organizations, private landowners,

and private operators of heritage and commercial mines, tunnels, and caves. Their location is shown in Fig. 3, and descriptions of these sites are provided below. The NGROS project is continuing to expand on this initial network

105 of sites. All sites were selected to ensure that the only source of recharge is from precipitation onto the land surface above the site.

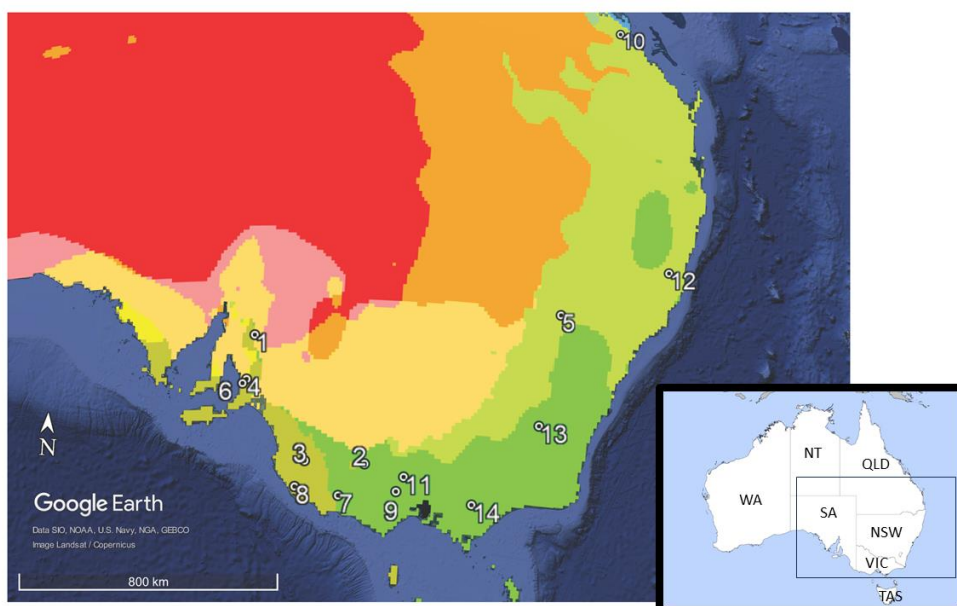



Figure 3. Main image shows the location of the initial NGROS sites. Site numbers are in order of increasing precipitation and match the subsection headings for Sect. 2.2. 1: Burra Mine Adit. 2: Stawell Mine. 3:

110 **Naracoorte Caves. 4: Montecute Mine. 5: Phosphate Mine. 6: Old Sleep's Rail Tunnel. 7: Byaduk Lava Cave. 8: Tantanoola Cave. 9: Durham Lead. 10: Capricorn Caves. 11: Daylesford Ajax South. 12: Willi Willi. 13: Harrie Wood Cave. 14: Walhalla Extended Long Tunnel Mine. The colours refer to Köppen–Gieger climate zones and from Peel et al (2007). Lime green: Cfb; Light Green: Cfa; Khaki: Csb; Yellow: Csa; Sandy: Bsk; Orange: Bsh; Red: Bwh. The Google Earth basemap has image data provided by Landsat**

115 **/ Copernicus and map data from the SIO, NOAA, U.S. Navy, NGA and GEBCO, with the NGROS sites and the Köppen-Gieger classifications added as kml (the latter from Peel et al., 2007). Inset shows Australia, with the box defining the area of the main image. State boundaries are shown with the state and territory abbreviations. WA: Western Australia. SA: South Australia. NSW: New South Wales. VIC: Victoria. NT: Northern Territory. QLD: Queensland. The Australian Capital Territory (ACT) is not labelled. The outline**

120 **map is from Wikimedia Commons, shared under the CC3.0 license.**

The sites are listed by increasing annual precipitation, with rainfall obtained from on-site Bureau of Meteorology weather stations with daily precipitation data where available, or from gridded daily precipitation using the Australian ~5 km by ~5 km resolution data (Jones et al., 2009) from the Australian Water Resources Assessment Landscape model (AWRA–L) and accessed through the Australian Water Outlook website (awo.bom.gov.au).

125 AWRA-L is a daily 0.05° gridded, distributed water balance model, which models water movement through the landscape from the initial precipitation through vegetation and soil moisture stores and losses of evapotranspiration, runoff and deep drainage. The current version (v7; Frost and Shokri, 2021; Frost et al., 2021) provides historical daily precipitation data (1985 CE onwards) that will be used by NGROS to determine rainfall recharge thresholds.

Additional hydroclimate information for the sites is provided by historical modelled annual (synthetic) pan evaporation, obtained from the AWRA–L v7 output (1985-present). AWRA–L data is also used for mean annual temperature, except in the case that there is a Bureau of Meteorology weather station at the site. Climate classifications use the Köppen–Geiger system (Peel et al., 2007). Overall, the sites cover a mean annual temperature range from 11 to 24 °C with annual precipitation ranging from 424 to 1290 mm and modelled annual pan evaporation ranging from 1492 to 2525 mm. All sites are water-limited over annual timescales, with the modelled annual pan evaporation always greater than annual precipitation.

2.1.1 Burra Mine Adit, SA, Ngadjuri Country (33.7° S, 138.9° E, ~500 m asl (above sea level))

This short, hand-dug adit forms part of a copper mine complex which at its peak was the largest copper mine in Australia, and it is now part of a National Heritage Area. The mine lies within the Adelaide geosyncline, a thick Neoproterozoic to Cambrian sedimentary succession (Preiss, 2000). At the surface, there are loamy soils over rock (Hall et al., 2009), and a layer of fine loam was apparent at the edges of the adit entrance. The depth of the adit is approximately 5 m below ground where the shaft opens into the engine house (Wallis, L. pers. comm. 2022), dug through flaky sandstone. To take advantage of the deepest portion of the adit, five loggers were placed approximately 2 m apart along the sides of the adit beginning from the engine house end. Burra sits within a landscape of temperate grasslands. The local climate has a mean annual temperature of 14.8 °C, mean annual rainfall is 424 mm and modelled pan evaporation of 2211 mm. The climate according to the Köppen–Geiger system is BSk (arid steppe, cold). The site is currently under the management of the National Trust of South Australia.

2.1.2 Stawell Mine, Stawell, VIC, Djab Warrung Country (37.6° S, 142.8° E, ~250 m asl)

This mine adit is in an operating gold mine with large blasted and excavated access tunnels. The loggers are placed in an access tunnel at a level approximately 100 m below surface, suspended approximately 30 cm down from the fractured rock roof that is supported with rock-bolts, and some minor roof areas with reinforcing mesh. Sections of the tunnel roof with shotcrete has been avoided. Gold-quartz veins here are associated with altered Cambrian slate or schist and metavolcanics adjacent to a Devonian intrusive body (Miller et al., 2006). The local climate has a mean annual temperature of 14.2 °C, mean annual rainfall 480 mm and modelled pan evaporation of 1680 mm. The climate is at the northern limit of Cfb (warm summer, no dry season, temperate), close to a transition to BSk (arid steppe, cold). The vegetation directly overlying the drip loggers is dry shrub and woodland with sodic clay subsoil (Sodosol) (Soil Health Knowledgebase, 2023). The mine site is privately owned, with Arete Capital Partners owning the majority share.

2.1.3 Naracoorte Caves, SA, Meintangk Country (37.0° S, 140.8° E, ~80 m asl)

Numerous shallow caves are present at Naracoorte, situated in the Miocene-age Mt Gambier limestone. The local climate has a mean annual temperature of 14.3°C, mean annual rainfall of 485 mm and modelled pan evaporation of 1872 mm. The climate is CSb (temperate, dry summer, warm summer). Loggers have been placed in two caves at locations where fracture-flow could be identified, with five loggers at irregular intervals in Blanche Cave and four loggers in Victorian Fossil Cave. Blanche Cave had a pine plantation above it for a period but is now

revegetated with established native trees, and Victorian Fossil Cave is covered mostly by native scrub. This site is managed by National Parks and Wildlife Service of the Government of South Australia.

2.1.4 Montecute Mine, SA, Kaurna Country (34.9° S, 138.7° E, ~150 m asl)

This short, hand-dug adit is situated at the northern end of the metropolitan Adelaide region on private land and
170   privately managed. It is unknown whether load-bearing ore was found in this adit, although cobalt, copper, gold, lead, nickel and silver are all found within a small radius of this site (Mining at Montacute, 2023). The adit is situated within a steep, wooded hillside dominated by native vegetation adjacent to a dolomite quarry and quartzite cliffs. Five loggers were placed at 1-2 m intervals beneath active drip sites starting approximately 10 m from the entrance to the adit. The local climate has a mean annual temperature of 14.7 °C, mean annual rainfall of 612 mm
175   and modelled pan evaporation of 2090 mm. The climate is CSb (temperate, dry summer, warm summer).

2.1.5 Phosphate Mine, NSW, Wiradjuri Country (-32.6° S, 148.9° E, 340 m asl).

With native box grassland vegetation cover, and mid-Devonian marmorized reef limestone geology, this site is located near the top of a shallow (~40 m above the nearby river alluvium) ridgeline formed by the reef limestone. The local climate has a mean annual temperature of 17.2 °C, mean annual rainfall 620 mm and synthetic pan
180   evaporation of 2231 mm. The climate is Cfa (temperate, no dry season, hot summer). The only source of recharge is from precipitation onto the ridge above the site. This hand-dug heritage mine was developed for the possible extraction of mineralized bat-guano accumulated in karst passages. Loggers have been placed in the lowest mine passages, closest to the groundwater. This site complements existing long-term cave-based groundwater recharge monitoring at Cathedral Cave in the same formation (Jex et al., 2012), groundwater monitoring bores established
185   at the site, a soil moisture network at the site (Berthelin et al., 2020), and the nearby (~10 km) UNSW Wellington Field Station (Rutlidge et al., 2023), and a newly established Critical Zone Observatory. This site is managed by the Government of New South Wales and Dubbo Regional Council.

2.1.6 Old Sleep's Hill Rail Tunnel, SA, Kaurna Country (35.0° S, 138.6° E, 115 m asl)

This disused, heritage-listed train tunnel is located on private land in the Adelaide metropolitan region. The tunnel
190   was built in 1883 to carry commuters from the Adelaide central business district to suburbs in the inner Adelaide Hills region Southeast of the city centre, and for long-distance trains between Adelaide and Melbourne. The tunnel is constructed in the western foothills of the Mount Lofty Ranges with loamy to clayey soil over weathered sandstone (Hall et al., 2009). The tunnel has sandstone arches and piers lined with eight layers of brick, and was used for trains until 1919, after which it has been used for storage of valuable state possessions during World War
195   II and commercial mushroom cultivation; it is now empty. The area above the tunnel is steep terrain with native soil and rock and largely consists of a conservation park for the remnant grey box eucalypt forest; loggers were placed about 10 m inside the tunnel at locations where drips were observed. The local climate has a mean annual temperature of 16.8 °C, mean annual rainfall of 700 mm and modelled pan evaporation of 2170 mm. The climate is CSb (temperate, dry summer, warm summer). This site is privately owned and managed.

200   ### 2.1.7 Byaduk Lava Cave, VIC, Djab Warrung Country (37.9° S, 142.0° S, ~150 m asl)

This basalt lava cave is in Late Quaternary age basalts that derive from the volcanic eruption of Mt. Napier c. 36,000 years ago, the most recent active volcanism in Australia. The local climate has a mean annual temperature of 13.1 °C, mean annual rainfall of 747 mm and modelled pan evaporation of 1600 mm. The climate is CSb (temperate, dry summer, warm summer). The overlying vegetation is native shrub and open woodland with organic loam soil (Tenosol) (Soil Health Knowledgebase, 2023). The site is managed by the Government of Victoria through Parks Victoria and is located upstream of the Budj Bim Cultural Landscape, listed by UNESCO in 2019 (UNESCO World Heritage Convention, 2023)

2.1.8 Tantanoola Cave, SA, Bungandidj Country (37.7° S, 140.5° E, ~50 m asl)

This karst cave was formed in Miocene-age bryozoan dolomite, with sandy soils at the surface. The cave is set into a cliff face which is believed to have been exposed to wave action during a period of higher sea levels (DEH, 2008). Above the cave is a hilltop of native vegetation that has been highly disturbed by agricultural activities prior to the protection of the area as a conservation park in 1972. The local climate has a mean annual temperature of 14.2 °C, mean annual rainfall of 778 mm and modelled pan evaporation of 1692 mm. This site is managed by National Parks and Wildlife Service of the Government of South Australia.

2.1.9 Durham Lead, Clarendon Forest, VIC, Wadawurrung Country (37.7° S, 143.9° E, ~360 m asl)

This historic hand-dug adit located on private property is relatively short and of small diameter and is situated in gold deposits associated with Devonian quartz mineralisation of Ordovician sedimentary rocks. The local climate has a mean annual temperature of 13.0 °C, mean annual rainfall of 779 mm and modelled pan evaporation of 1678 mm. Native woodland and sodic clayey subsoil (Sodosol) overlie this adit. The climate is Cfb (temperate, no dry season, warm summer).

2.1.10 Capricorn Caves, QLD, Darumbal Country (23.16° S, 150.5° E, ～ 270 m asl)

Daylight Cave is situated in a national park comprising cleared dry and subtropical rainforest with remnant vegetation. The site was burnt over by a containment (control) fire during the 2019/20 Australian wildfires. The limestone geology is Permian in age and comprises calcareous mudstone, crinoidal limestone and reef limestones. The ~60 km belt of limestone has been highly folded and faulted post-deposition, leading to the limestone retaining low primary porosity and becoming highly fractured. Adjacent to and overlying the cave is a soil moisture network comprising 20 randomly distributed soil moisture probes (an extension of the network described in Berthelin et al., 2020). Loggers are placed in the upper and lower levels of this cave to allow comparison between potential recharge events and soil moisture characteristics. The local climate has a mean annual temperature of 18.7 °C, mean annual rainfall of 1218 mm and modelled pan evaporation of 1879 mm. The climate is Cfa (temperate, no dry season, hot summer). The site is managed by the Government of New South Wales through the NSW National Parks and Wildlife Service.

2.1.11 Daylesford Ajax South, VIC, Dja Dja Wurrung Country (37.3° S, 144.1° E, ~550 m asl)

This historic hand-dug adit, located on private property, is relatively short and of small diameter and associated with the gold deposits of the Castlemaine Supergroup (Lower Ordovician) sediments. The local climate has a

mean annual temperature of 11.7 °C, mean annual rainfall of 879 mm and modelled pan evaporation of 1728 mm. Chromosol soils and scattered tall trees and grass overlies the adit. The climate is Cfb (temperate, no dry season, warm summer).

2.1.12 Willi Willi, NSW, Djangadi Country (30.9° S, 152.5° E, 270 m asl).

240 Daylight Cave is situated in a national park comprising cleared dry and subtropical rainforest with remnant vegetation. The site was burnt over by a containment (control) fire during the 2019/20 Australian wildfires. The limestone geology is Permian in age and comprises calcareous mudstone, crinoidal limestone and reef limestones. The ~60 km belt of limestone has been highly folded and faulted post-deposition, leading to the limestone retaining low primary porosity and becoming highly fractured. Adjacent to and overlying the cave is a soil

245 moisture network comprising 20 randomly distributed soil moisture probes (an extension of the network described in Berthelin et al., 2020). Loggers are placed in the upper and lower levels of this cave to allow comparison between potential recharge events and soil moisture characteristics. The local climate has a mean annual temperature of 18.7 °C, mean annual rainfall of 1218 mm and modelled pan evaporation of 1879 mm. The climate is Cfa (temperate, no dry season, hot summer). The site is managed by the Government of New South Wales

250 through the NSW National Parks and Wildlife Service.

2.1.13 Harrie Wood Cave, NSW, Ngarigo Country (35.7° S, 148.5° E, ~980 m asl)

This former tourist cave is situated in Silurian limestone that has low primary porosity and is highly fractured and is a long-term hydrological monitoring site (Markowska et al., 2015; Chapman et al 2023). Located in the Kosciuszko National Park, the local vegetation comprises sub-alpine open snow gum woodland, although above

255 the cave the steep slopes limit the extent of soil cover and vegetation. The site was burnt over in the 2019/20 Australian wildfires. This site provides data from a sub-alpine location that experiences seasonal snowfall, a site that is recovering from wildfire, and a site from which stalagmite paleoclimate records have been obtained (Tadros et al., 2022). Loggers are located on a depth transect from the cave entrance to a depth approximately 50 m below land surface. The local climate has a mean annual temperature of 11.1 °C (recorded at the on-site weather station),

260 mean annual rainfall of 1260 mm and modelled pan evaporation of 1492 mm. The climate is Cfb (temperate, no dry season, warm summer). The site is managed by the Government of New South Wales.

2.1.14 Walhalla Extended Long Tunnel Mine, VIC, Gunaikurnai Country (37.9° S 146.5° E, ~400 m asl)

Walhalla is a large-scale historic goldmine, with one level managed as a tourist site: lower levels of the historic mine are flooded with groundwater. The gold deposits are associated with Devonian age dykes found within the

265 Devonian metasedimentary rocks of the eastern Victorian gold province. The local climate has a mean annual temperature of 13.2 °C, mean annual rainfall of 1290 mm and modelled pan evaporation of 1565 mm. Native forest with tall trees and thick understory occurs on the slopes with thin soils (Chromosol) above the mine. The climate is Cfb (temperate, no dry season, warm summer). The site is a crown land reserve and is managed by the Victoria Government through the Walhalla Board of Management.

270 **2.2. Technical description of loggers**

The NGROS uses commercially available Stalagmate © loggers as shown in Fig. 2. These use a pressure transducer within a sealed unit to detect water dripping onto their sealed surface, with hardware detecting drip impacts over noise (e.g., vibrations). The units use a TinyTag© body manufactured by Gemini Data Loggers UK Ltd. Memory capacity is 4 years for data collected at hourly intervals, high energy 3.6V half-AA cells provide power for at least 3 years of continuous deployment. Manufactured initially for cave scientists recording water flux to stalagmites (Collister and Mattey, 2009), they have previously been demonstrated to be suitable for long-term deployment in underground spaces. For example, loggers deployed to investigate the heterogeneity of recharge by Jex et al., (2012) are still in service despite the cave chamber being flooded by groundwater multiple times, as are those used in the hydrological characterisation of flow paths (Markowska et al., 2015), to quantify the effects of wildfire on recharge event hydrographs (Bian et al., 2019) and to quantify groundwater recharge thresholds and soil and unsaturated zone storage (Baker et al., 2020, 2021). Published applications of the use of the loggers for their original application of monitoring individual cave drip waters are global in extent e.g., in China (Hu et al., 2008), USA (Onac et al., 2008; Wortham et al., 2021) and Europe (Surić et al., 2017).

3 Initial results from the first year of monitoring

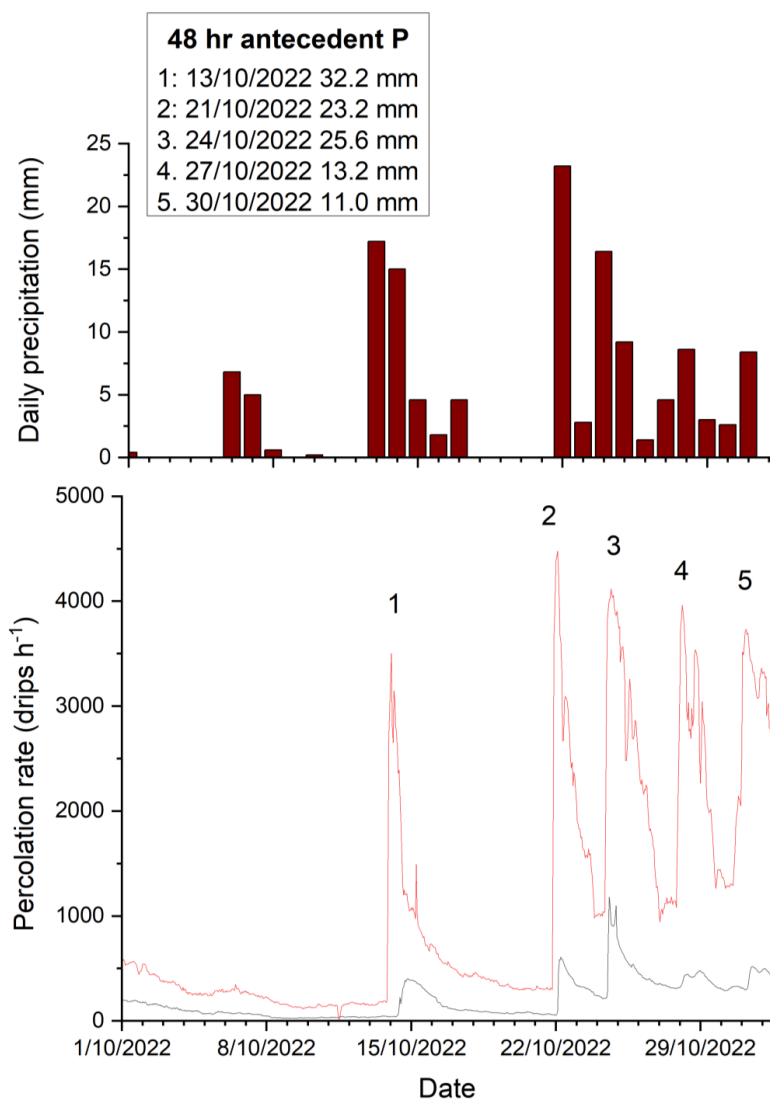
As examples of the types of data and interpretations that are possible, we present one-month of data from three contrasting sites from the first year of monitoring. At the Byaduk Lava Cave (VIC), Fig. 4 shows five recharge events that occurred in October 2022. This included four events that occurred over a 10 day period. At this site, recharge occurs within 24 h of rainfall. This allows for event-scale determination of the amount of rainfall necessary to generate recharge. Because rainfall data is at daily resolution and individual rain events can occur over two recording days, we calculate the 48 h total rainfall recharge thresholds. At the site, in Austral spring, these thresholds vary from 32.2 mm prior to the first recharge event to 11.0 mm prior to the fifth event. A decreasing amount of rainfall needed to generate recharge over time is observed over the four recharge events that occur over 10 days.

At the Phosphate Mine (NSW), Fig. 5 shows three recharge events that occurred in the month of April 2022. At this site, recharge also occurs within 24 hours of rainfall, although not all monitoring locations record recharge at all events. The 48 h total antecedent rainfall varies between 36.2 and 19.4 mm. During April 2022 there are 48 h rainfall amounts of ~10 to 17 mm and these do not generate recharge.

At Naracoorte Caves (SA), Fig. 6 presents two recharge events in October 2022. At this site, recharge again occurs within 24 hours of rainfall occurring. In contrast to the other sites, a complex recharge response to rainfall can be observed. Although the two monitoring sites increase in water flux, there is a non-linear response to the second recharge event, with some inverse correlations in flow rates occurring at the two monitoring sites that are indicative of flow-switching. For these two recharge events, the 48 h rainfall recharge thresholds vary between 31.2 and 15.0 mm. However, a subsequent rainfall event with ~16 mm of rainfall did not generate further recharge at these monitoring sites.

Our example NGROS data demonstrates how rainfall recharge thresholds can be obtained at an event timescale. As data accumulates over time, we anticipate being able to investigate how rainfall recharge thresholds vary with season and under different climate drivers. With this example, with data analysed from the Austral spring and autumn, we observe a similar range in 48 h antecedent rainfall that is required to generate recharge at sites with contrasting geology (basalt, fractured marble, and porous limestone) and water-limited sites that have total annual

precipitation < 750 mm and modelled pan evaporation at least twice that amount. At Byaduk (Fig. 4), we believe

this is the first data presented using drip loggers in the unsaturated zone of basalt.

315   **Figure 4. Byaduk Lava Cave. Top: daily precipitation. Bottom: percolation rate recorded by two loggers in the lava cave (shown by red and black lines). Five recharge events are recorded, the 48-hour antecedent precipitation shown in the inset table.**

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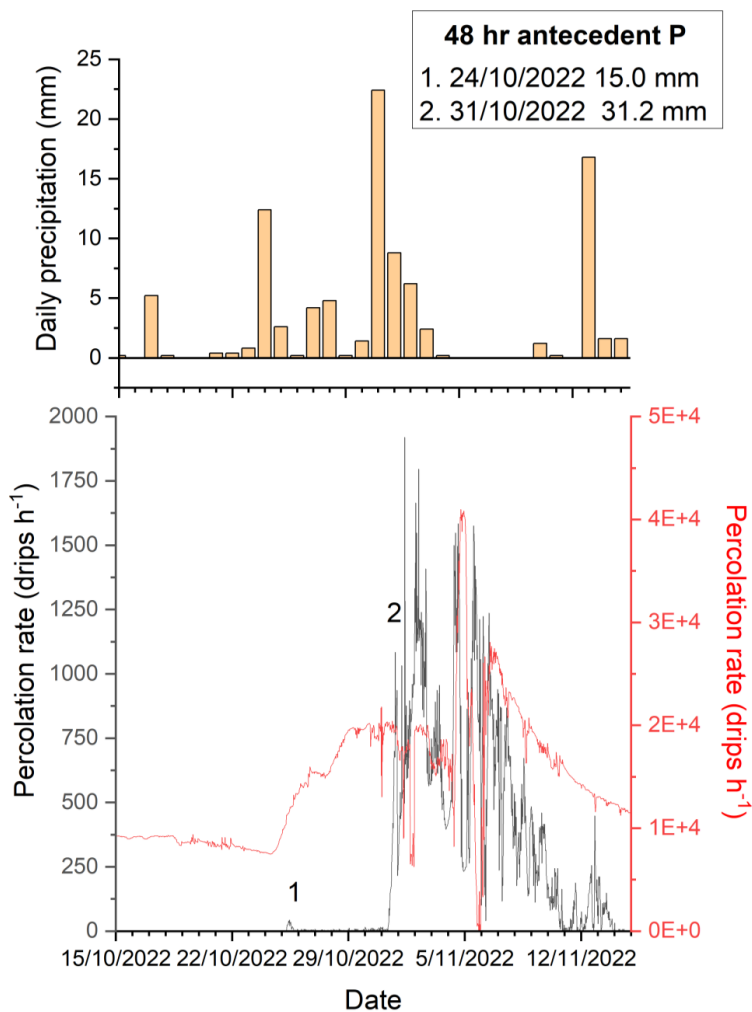
Figure 5. Naracoorte Caves. Top: daily precipitation. Bottom: percolation rate recorded by two loggers in the cave (shown by red and black lines). Note the different y-axis scales. Two recharge events are recorded, the 48-hour antecedent precipitation shown in the inset table.

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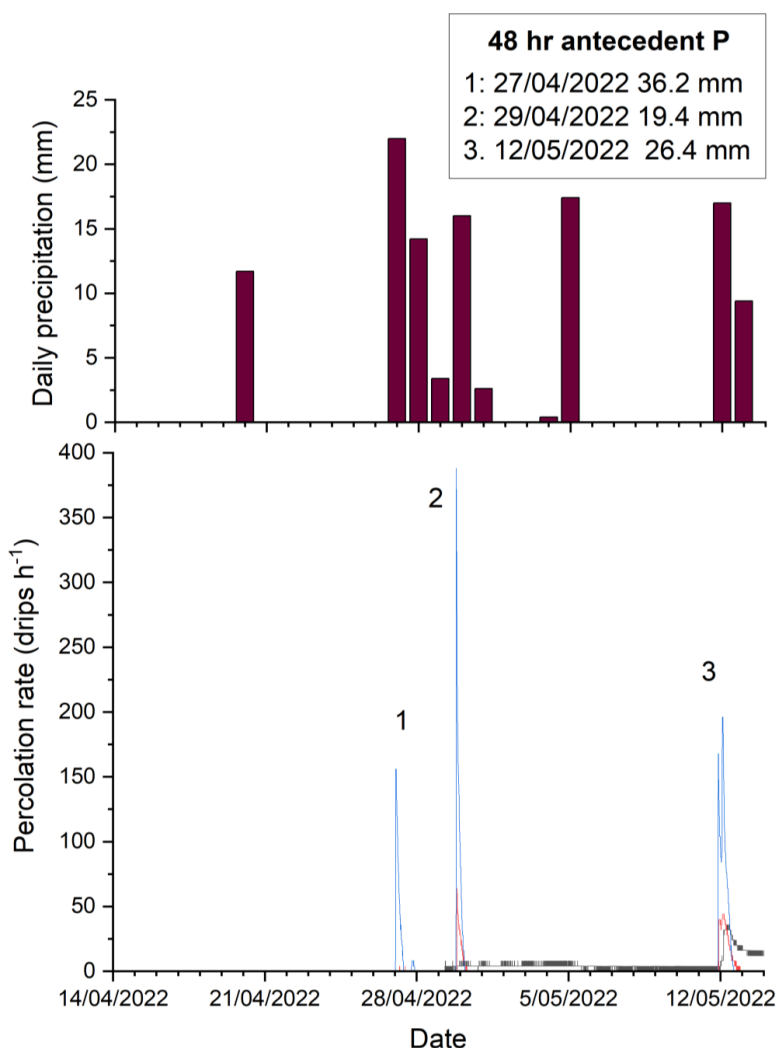
Figure 6. Phosphate Mine. Top: daily precipitation. Bottom: percolation rate recorded by three loggers in the cave (shown by red, blue and black lines). Three recharge events are recorded, the 48-hour antecedent precipitation shown in the inset table.

4 Summary and Outlook

The NGROS is established in Australia, a country where groundwater is of particular importance. In 2013, it was estimated that groundwater was worth AU$ 6.8 billion Gross Domestic Product equivalent to the Australian economy (National Centre for Groundwater Research and Training, 2013), mainly supporting extractive minerals and agricultural activities. Currently, groundwater makes up around 17% of accessible water in Australia and accounts for more than 30% of total water consumption. This is expected to increase as surface water resources diminish due to climate change and prolonged drought (Enemark et al., 2019). Indeed, the recent 'Millennium' and 2016-2019 droughts have shown how groundwater provides essential water security in water-scarce regions

of Australia, with the use of groundwater increasing drastically over the course of the Millennium drought, accounting for as much as 70% of irrigation water across the Murray Darling Basin (Richardson et al., 2011).

Due to Australia's dependence on finite groundwater resources and the mounting pressure on it from a warmer, and in some places drier, climate, as well as expanding agricultural and mining developments, groundwater and drought resilience is a particular focus of the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia's national science research agency. Real-time monitoring of groundwater recharge variability provided by NGROS will help further the science around hydroclimate variability, drought frequency and intensity, as well as other climate extremes to complement and support groundwater research being undertaken at CSIRO. Particularly their Drought Resilience Mission, in which the goal is to reduce the impacts of drought in Australia by 30% by 2030 (https://www.csiro.au/en/about/challenges-missions/Drought-Resilience). As demonstrated in Figure 4, the observing system has demonstrated the capability to determine rainfall recharge thresholds at an event scale from a range of geologies, environments, and climate zones. The heterogeneity of recharge can also be investigated. The NGROS data will complement the data collected by other field infrastructure estimating vadose zone water fluxes such as the newly funded Australian Critical Zone Observatory network (https://www.tern.org.au/critical-zone/) and field point verification for nationally gridded hydrological data products such as the Australian Water Resources Assessment Landscape model (AWRA–L).

Our vision with this project in the long term is to contribute to the conversations about groundwater recharge, sustainable groundwater management and to understand what stakeholders know about groundwater. We plan to increase the spatial scale of the network by adding more sites nationally, and potentially form part of an international network of similar infrastructure. We also aim to maintain the network for as long as possible, to enable the collection of recharge data relevant to the predicted rainfall intensification with climate change (Fowler et al., 2021) and under different climate drivers (e.g., changes in the southern Annular Mode and El Niño – Southern Oscillation). With multi-year data, we will be able to quantify the annual total recharge at each of our monitoring sites and investigate the relationship between that and annual climate parameters. This approach will also allow the investigation of recharge characteristics at sites where fracture flow is not dominant and individual event-based recharge characterization is not possible. Finally, by maintaining a high temporal resolution of sampling (hourly or more frequent), the data generated by NGROS can be used to identify recharge pathways e.g., time-series analysis to identify non-linear flow behaviour typical of karst systems (Baker and Brunsdon, 2003) and identify the role of tree water use where daily drip rate fluctuations occur at times of tree water stress (Coleborn et al., 2016).

The data generated by the network will support training opportunities for students, researchers, and stakeholders, providing data about groundwater recharge across Australia that is essential to understand what is possible in terms of management. The engagement with stakeholders that depend on groundwater, but also with managers and people that interact with spaces of groundwater (e.g., caves), will give us the opportunity to map out knowledges and possibilities to build capacity for maintaining monitoring systems. A critical consideration relating to the data collected by NGROS is its translation in terms of informing human-groundwater relations. In particular, how does the NGROS contribute to broader groundwater literacy in Australia? As Baldwin et al., (2012) have noted, for groundwater planning to be effective, there is a critical need for scientists to *exchange* knowledge and understanding with local communities (Baldwin et al., 2012). This has not always happened. As they further

note there is a need for all relevant knowledge to be understood and considered effectively by key stakeholders in "an open, inclusive and transparent decision-making process" as well as "integrating local and Indigenous

380   knowledge" into groundwater considerations and assessments" (Baldwin et al 2012, 75). In an Australian context – but also many contexts globally – First Nations knowledges and relationships with groundwater is a key consideration. Moggridge (2020, 23) in his research on Australian groundwater, for example, has observed how "Over many thousands of years, Aboriginal people have accumulated a comprehensive and astounding knowledge of groundwater" that needs to be taken in consideration by governments and groundwater managers. These

385   groundwater knowledges have often been learnt and shared in Dreamtime stories relating to sites being created and then passed on from one generation to another (Moggridge, 2020). An area of interest for the NGROS project is to learn from ancient knowledges of groundwater and use tools, like the geoscientific instrumentation used for this project, to better interact and manage groundwater. As the current sample of sites shows, in addition to each site having its own unique physical characteristics, they are on Indigenous Countries under various ownership and

390   management regimes (e.g., government, corporate, family). Understanding these complex layers of history, management and the physical environment is the intention of the NGROS.

Data availability. The preliminary data shown in this article is available within the larger NGROS database accessible from groundwater.unsw.edu.au (from October 2023).

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Competing Interests. The authors declare that they have no conflict of interest.

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References

Ajami, H.: Geohydrology, in: Groundwater. Encyclopedia of Geology (Second Edition), edited by Alderton, D.
410   and Elias., S. A., Oxford, Academic Press, 408-415, ISBN 9780081029084, 2021.

Baker, A. and Brunsdon, C.: Non-linearities in drip water hydrology: an example from Stump Cross Caverns, Yorkshire. J. Hydrol., 277, 151-163, https://doi.org/10.1016/S0022-1694(03)00063-5, 2003.

Baker, A., Berthelin, R., Cuthbert, M. O., Treble, P. C., Hartmann, A. and the KSS Cave Studies Team: Rainfall
recharge thresholds in a subtropical climate determined using a regional cave drip water monitoring network. J.

415   Hydrol., 587, 125001, https://doi.org/10.1016/j.jhydrol.2020.125001, 2020.

Baker, A., Scheller, M., Oriani, F., Mariethoz, G., Hartmann, A., Wang, Z. and Cuthbert, M. O: Quantifying
temporal variability and spatial heterogeneity in rainfall recharge thresholds in a montane karst environment. J.
Hydrol., 594,125965, https://doi.org/10.1016/j.jhydrol.2021.125965, 2021.

Baldwin, C., Tan, P. L., White, I., Hoverman, S., and Burry, K.: How scientific knowledge informs community

420   understanding of groundwater. J. Hydrol., 474, 74-83, https://doi.org/10.1016/j.jhydrol.2012.06.006, 2012.

Berthelin, R., Rinderer, M., Andreo, B., Baker, A., Kilian, D., Leonhardt, G., Lotz, A., Lichtenwoehrer, K.,
Mudarra, M., Padilla, I. Y., Pantoja Agreda, F., Rosolem, R., Vale, A., and Hartmann, A.: A soil moisture
monitoring network to characterize karstic recharge and evapotranspiration at five representative sites across the
globe, Geosci. Instrum. Method. Data Syst., 9, 11–23, https://doi.org/10.5194/gi-9-11-2020, 2020.

425   Berthelin, R., Olarinoye, T., Rinderer, M., Mudarra, M., Demand, D., Scheller, M., and Hartmann, A.: Estimating
karst groundwater recharge from soil moisture observations – a new method tested at the Swabian Alb, southwest
Germany, Hydrol. Earth Syst. Sci., 27, 385–400, https://doi.org/10.5194/hess-27-385-2023, 2023.

Bian, F., Coleborn K., Flemons, I., Baker, A., Treble, P. C., Hughes, C. E., Baker, A., Andersen, M. S., Tozer, M.
G., Duan, W., Fogwill, C. J. and Fairchild, I. J.: Hydrological and Geochemical Responses of Fire in a Shallow

430   Cave System. Sci. Total Environ., 662, 180-191, https://doi.org/10.1016/j.scitotenv.2019.01.102, 2019

Chapman, R. G., Baker, A., McDonough, L. K., Markowska, M. and Laffan, S.: Spatiotemporal Variation in Cave
Percolation Waters: A Functional Approach, EarthArXiV [preprint], https://doi.org/10.31223/X5Q08Z, 2023

Coleborn, K., Rau, G. C, Cuthbert, M. O., Baker, A and Navarre, O.: Solar forced diurnal regulation of cave drip
rates via phreatophyte evapotranspiration. Hydrol. Earth Syst. Sci., 20, 4439-4455, https://doi.org/10.5194/hess-

435   20-4439-2016, 2016.

Collister, C. and Mattey, D.: Controls on water drop amount at speleothem drip sites: An experimental study, J.
Hydrol., 358, 259–267, https://doi.org/10.1016/j.jhydrol.2008.06.008, 2008.

Crosbie, R. S., Jolly, I. D., Leaney, F. W. and Petheram, C.: Can the dataset of field based recharge estimates in
Australia be used to predict recharge in data-poor areas? Hydrol. Earth Syst. Sci., 14, 2023–2038,

440   https://doi.org/10.5194/hess-14-2023-2010, 2010.

Crosbie R. S. and Rachakonda P. K.: Constraining probabilistic chloride mass-balance recharge estimates using
baseflow and remotely sensed evapotranspiration: the Cambrian Limestone Aquifer in northern Australia.
Hydrogeol. J., 29, 1399-, https://doi.org/10.1007/s10040-021-02323-1, 2021

Department for Environment and Heritage, Government of South Australia: Tantanoola Caves Conservation Park

445   Management   Plan   2008.   Available   online:
https://cdn.environment.sa.gov.au/environment/docs/tantanoola_caves_mp.pdf, last access June 2023

Enemark T., Peters, L. J. M., Malants, D. and Batelaan, O.: Hydrogeological conceptual model building and
testing: A review. J. Hydrol., 569, 310-329, https://doi.org/10.1016/j.jhydrol.2018.12.007, 2019

Fowler, H. J., Lenderink, G., Prein, A. F., Westra, S., Allan, R. P., Ban, N., Barbero, R., Berg, P., Bleninsop, S.,

450   Do, H. X., Guerreiro, S., Haerter, J. O., Kendon, E.J., Lewis, E., Schaer, C., Sharma, A., Villarini, G., Wasko., C.
and Zhang, X.: Anthropogenic intensification of short-duration rainfall extremes. Nat. Rev. Earth Environ., 2,
107–122, https://doi.org/10.1038/s43017-020-00128-6, 2021

Frost, A. J., and Shokri, A.: The Australian Landscape Water Balance model (AWRA-L v7). Technical Description of the Australian Water Resources Assessment Landscape model version 7. https://awo.bom.gov.au/assets/notes/publications/AWRA-Lv7_Model_Description_Report.pdf ,2021

Frost, A. J., Shokri, A., Keir, G., Bahramian, K. and Azarnivand, A.: Evaluation of the Australian Landscape Water Balance model: AWRA-L v7. Bureau of Meteorology Technical Report. https://awo.bom.gov.au/assets/notes/publications/AWRA-Lv7_Model_Evaluation_Report.pdf, 2021.

Gleeson, T., Wada, Y., Bierkens, M. F. P. and Van Beek, L. P. H.: Water balance of global aquifers revealed by groundwater footprint, Nature 488(7410), 197-200, https://doi.org/10.1038/nature11295, 2012.

Hall, J., Maschmedt, D., and Billing, B.: The soils of southern South Australia. Department of Water, Land and Biodiversity Conservation, Government of South Australia, 2009

Hu, C., Henderson, G. M., Huang, J., Chen, Z. and Johnson, K.R.: Report of a three-year monitoring programme at Heshang Cave, Central China. Int. J. Speleol., 37, 143-151, https://digitalcommons.usf.edu/cgi/viewcontent.cgi?article=1161&context=ijs, 2008

Healy, R. W.: Estimating Groundwater Recharge. Cambridge, UK, Cambridge University Press, https://doi.org/10.1017/CBO9780511780745, 2010.

Jasechko, S. and Taylor, R. G.: Intensive rainfall recharges tropical groundwaters. Environmental Research Letters, 10, 124015, https://doi.org/10.1088/1748-9326/10/12/124015, 2015.

Jasechko, S.: Global isotope hydrogeology-Review. Rev. Geophys., 57, 835-965, https://doi.org/10.1029/2018RG000627, 2019.

Jex, C. N., Mariethoz, G., Baker, A., Graham, P., Andersen, M. S., Acworth, I., Edwards, N. and Azcurra, C.: Spatially dense drip hydrological monitoring and infiltration behaviour at the Wellington Caves, South East Australia. Int. J. Speleol., 41, 285-298, http://dx.doi.org/10.5038/1827-806X.41.2.14, 2012.

Jones, D. A., Wang, W. and Fawcett, R.: High-quality spatial climate data-sets for Australia. Aust. Meteorol. Oceanogr. J., 58: 233-248, 2019

Markowska, M., Andersen, M. S., Treble, P. C., Baker, A., Tadros, C., Hankin, S., and Jex, C. N.: Unsaturated zone hydrology and cave drip discharge water response: Implications for speleothem palaeoclimate record variability. J. Hydrol., 529, 662-675, http://dx.doi.org/10.1016/j.jhydrol.2014.12.044, 2015.

Miller, J. M., Wilson, C. J. L., & Dugdale, L. J.: Stawell gold deposit: A key to unravelling the Cambrian to Early Devonian structural evolution of the western Victorian goldfields. Australian J. Earth Sci., 53, 677-695, https://doi.org/10.1080/08120090600823313, 2006.

Mining at Montecute: https://www.campbelltown.sa.gov.au/library/collections-and-resources/local-history-room/localhistoryarticles/local-history-articles-stories-and-events/mining-at-montacute accessed 11th July 2023

Moggridge, B. J.: Aboriginal people and groundwater. Procs. Royal Soc. Queensland, 126, 11-27, 2020.

National Centre for Groundwater Research and Training: Economic Value of Groundwater in Australia. https://www2.deloitte.com/content/dam/Deloitte/au/Documents/finance/deloitte-au-fas-ncgrt-economic-value-groundwater-31-oct-2013-250914.pdf, 2013

Onac, B. P., Pace-Graczyk, K. and Atudirei, V.: Stable isotope study of precipitation and cave drip water in Florida (USA): implications for speleothem-based paleoclimate studies, Isot. Environ. Health Stud., 44:2, 149-161, https://doi.org/10.1080/10256010802066174, 2008

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, https://doi.org/10.5194/hess-11-1633-2007, 2007.

Preiss, W. V.: The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental

495 reconstruction, Precambrian Res., 100, 21-63, https://doi.org/10.1016/S0301-9268(99)00068-6, 2000.

Rau, G. C., Cuthbert, M. O., Post, V. E. A., Schweizer, D., Acworth, R. I., Andersen, M. S., Blum, P., Carrara, E., Rasmussen T. C., and Ge, S.: Future-proofing hydrogeology by revising groundwater monitoring practice. Hydrogeol. J., 28, 2963-2969, https://doi.org/10.1007/s10040-020-02242-7, 2020.

Richardson S., Evans, R. and Harrington, G.: Connecting science and engagement: setting groundwater extraction

500 limits using a stakeholder led decision-making process. In: Grafton Q., Connell D. (eds) Basin futures: water reform in the Murray-Darling basin. Australia National University Press, Canberra, 2011.

Rutlidge, H., Taschetto, A., Andersen, M.S., and Baker, A.: Negative Indian Ocean Dipole drives groundwater recharge in southeast Australia, (Version 1), Research Square [preprint], https://doi.org/10.21203/rs.3.rs-2755505/v1, 22 May 2023,

505 Shanafield, M., and Cook, P. G.: Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods. J. Hydrol., 511, 518-529, https://doi.org/10.1016/j.jhydrol.2014.01.068, 2014.

Soil Health Knowledgebase. https://soilhealth.ccmaknowledgebase.vic.gov.au/ accessed 11th July 2023

Surić, M., Lončarić, R., Lončar, N., Buzjak, N., Bajo, P. and Drysdale, R. N.: Isotopic characterization of cave

510 environments at varying altitudes on the eastern Adriatic coast (Croatia) – Implications for future speleothem-based studies, J. Hydrol., 545, 367-380, https://doi.org/10.1016/j.jhydrol.2016.12.051, 2017

Tadros, C. V., Markowska, M., Treble, P. C., Baker, A., Frisia, S., Adler, L. and Drysdale, R. N.: Recharge variability in Australia's southeast alpine region derived from cave monitoring and modern stalagmite δ18O records. Quatern. Sci. Rev., 295, 107742, https://doi.org/10.1016/j.quascirev.2022.107742, 2022

515 UNESCO World Heritage Convention. Budj Bim Cultural Landscape. https://whc.unesco.org/en/list/1577/ Accessed 11th July 2023

Wortham, B. E., Montañez, I. P., Bowman, K., Kuta, D., Contreras, N. S., Brummage, E., Pang, A., Tinsley, J. and Roemer-Baer, G.: Monitoring of Sierra Nevada caves reveals the potential for stalagmites to archive seasonal variability. Front. Earth Sci., 9, https://doi.org/10.3389/feart.2021.781526, 2021