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RESEARCH ARTICLE

A multimethod approach to inform epikarst drip discharge modelling: Implications for palaeo-climate reconstruction

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Abstract

Resolving the hydrological processes that form speleothems and the palaeo-climate archives that they contain is difficult. Typical approaches to hydrological investigation are not suited to karst landscapes, geophysics are seldom applied, drip monitoring and modelling have limitations, and ignoring potential hydrological impacts can result in a proxy record that does not reflect the external environment. We aim to understand the processes and controls that have created a palaeo-climate proxy record preserved in a speleothem (JC001) in the "Grotto of Oddities," part of the Jersey Cave at the Yarrangobilly Caves, Australia, to infer the likely nature and resolution of this record. Electrical resistivity tomography (ERT), traditional surveying, and drip discharge monitoring (April 2013 to February 2015) were used to investigate the structure and hydrology of the epikarst overlying the Grotto of Oddities. Data collected through these methods were then used to construct a physically informed and parsimonious drip hydrology model. Geophysics showed that changes in hillslope above the Grotto of Oddities are collocated with a region of low resistivity, which forms an epikarstic reservoir acting to supply enhanced discharge to the speleothem. Drip monitoring showed hysteretic behaviour with a distinct threshold response, and a simple drip classification indicated that the speleothem associated with the drip has the potential to record palaeo-seasonality or an annual–decadal signal. Discharge modelling indicated discharge was comprised of quick and slow flow, and that discharge is probably perennial. These multimethod results together indicate that the speleothem likely represents a palaeo-climate record of a length and resolution unprecedented for nonglacial areas of the Southern Hemisphere and for Australia in particular and will significantly enhance current knowledge of the climate of southeast Australia. Although ERT methods have previously been applied in the karst landscape, to our knowledge, this represents the first application of these multiple methods in combination as an approach to assess the fidelity of a speleothem, based on an understanding of the hydrological processes for palaeo-climate reconstruction.

KEYWORDS

geophysics, hydrology, karst, palaeo-climate, speleothem

1 | INTRODUCTION

Speleothems contain palaeo-climate proxies which place them at the "forefront of paleoclimatology" (Lachniet, 2009, p. 413). They can record data at a range of temporal scales (potentially seasonal to subannual), and with multiple proxies. An understanding of the local hydrological processes and pathways that result in speleothem growth underpins the correct and reliable interpretation of the palaeo-environmental proxies contained within them (Cobb, Adkins, Partin, & Clark, 2007; Fairchild, Tuckwell, Baker, & Tooth, 2006; Lachniet, 2009). Here, the results of a multimethod approach taken to understand the processes and controls that have impacted the growth of a stalagmite in New South Wales, Australia, and the associated palaeo-climate proxy, are presented. A combination of geophysics, stalactite discharge analysis, and discharge modelling was used.

Understanding the hydrology associated with speleothems in karst is challenging due to the high degree of heterogeneity, with water movement occurring via the complex interactions of three modes of flow—primary (matrix flow), secondary (fracture flow), and tertiary (conduit flow)—as well as soil water and reservoir storage (Fairchild & Baker, 2012; Ford & Williams, 2007). This heterogeneity can lead to drip waters exhibiting variable stable isotope (and other proxy) values as a result of different flow pathways, and local reservoirs causing variable mixing of old and new waters (Lachniet, 2009). The stable oxygen isotope ($\delta^{18}O$) values of coeval stalagmites within the same cave have been shown to vary by as much as 4‰ PDB (Peedee Belemnite), which may be attributed to complex flow pathways (Serefiddin, Schwarcz, Ford, & Baldwin, 2004). Water residence times can vary from several months to decades (Cobb et al., 2007), and the relationships between depth, discharge, residence time, and mixing are complex.

A recent study from Harrie Wood Cave at the Yarrangobilly Caves found only a weak link between depth (−18 to −32 m) and mean (r^2 = .3), and maximum discharge (r^2 = .31), and the link between depth and discharge lag time was only marginally stronger (r^2 = .52; Markowska et al., 2015). Markowska et al. (2015) did not consider isotopic variability of drip waters; however, other work from around the world has shown that drip-water geochemical and isotopic values can vary over a range of temporal and spatial scales, and that these values can be impacted by subsurface processes (e.g., mixing and evaporation; Baldini, Mcdermott, & Fairchild, 2006; Cobb et al., 2007; Fairchild et al., 2006; Polk, van Beynen, & Wynn, 2012; Riechelmann et al., 2011). Clearly, the heterogeneity of the medium does not allow for generalised assumptions between depth, hydrological pathways, and associated palaeo-climate proxy records.

In the interpretation of speleothem palaeo-records, a range of different approaches are applied. The simplest approach is to ignore the hydrological processes and to directly regress the proxy record against climatic records or other palaeo-climate reconstructions (Denniston et al., 2013; Duplessy, Labeyrie, Lalou, & Nguyen, 1970; Linge, Lauritzen, & Lundberg, 2001; Wang et al., 2001). Although this approach can appear successful, a growing trend has been to more explicitly consider the hydrological pathways and the conditions that have controlled and influenced speleothem growth, and therefore, the palaeo-climate record (Cuthbert et al., 2014; Lachniet, 2009; Treble et al., 2013). These approaches can be divided into three types—geophysical (to directly investigate the nature of the overlying karst), empirical drip response research, and drip modelling studies—and are summarised below and within Table 1.

1.1 | Geophysics

Traditional methods to study unsaturated zone hydrological processes are of limited value in karst speleothem hydrology studies; bore networks, slug and pump tests, and other common methods are inappropriate due to the smaller subcatchment scale (i.e., in cave drip-water hydrology), and heterogeneity of the medium including the proportion of bypassing and fractured pathway flows, the influence of local reservoirs, and voids within the karst (Carrière, Chalikakis, Sénéchal, Danquigny, & Emblanch, 2013; White, 2002). Noninvasive and nondestructive geophysics methods have been used in the karst

TABLE 1 Summary of methods that may be applied to investigate karst structure and hydrology relating to stalagmite formation

Method	Advantages	Limitations	Applications	References
Geophysics	Noninvasive, nondestructive, techniques can be combined; see below for breakdown by method.	Individual techniques may not provide high-resolution results in karst; see below for breakdown by method.	See below for breakdown by method.	El-Qady et al., 2005; Leucci, 2006; Carrière et al., 2013
Ground-penetrating radar (GPR)	Can be applied to image a large variety of structures and properties.	Results may be impacted by depth, uneven ground (signal attenuation), clayey soils, and wet soils.	Geologic structure: Gross epikarst structure, presence of large voids and fractures, conduits, bedding planes, karrens, compact and massive rock, and karstified rock. Groundwater.	Butnor et al., 2001; Al-fares et al., 2002; Roth & Nyquist, 2003
Electrical resistivity tomography (ERT)	Flexibility to scale nodes and application to trade-off depth and resolution	May not provide high-resolution results in karst, especially 2D ERT.	Geologic structure: Voids, bedrock, sinkholes, and karstic dissolution zones. Groundwater: Location of wet/dry areas, local reservoirs, and zones of soil water storage.	Zhou et al., 2000; van Schoor, 2002; Valois et al., 2010; Cardarelli et al., 2010; Carrière et al., 2013; Martínez-Moreno et al., 2014
Empirical drip studies	Widely used and accepted; techniques are robust and commonly used in the community. Drip monitoring allows for statistical classification of hydrology (e.g., "type" of flow).	Without water chemistry, drip monitoring cannot tell age of water, level of mixing, or transmission times. Geological structure/hydrology as inferred from drip monitoring may be erroneous.	Used to describe the hydrology that has formed a speleothem; heterogeneity of karst means studies are highly localised. Drip monitoring often used as baseline for drip modelling.	Smart & Friedrich, 1987; Baker & Brunsdon, 2003; Tooth & Fairchild, 2003; Baldini et al., 2006; Fernández-Cortés, 2007; Riechelmann et al., 2011
Stalactite drip modelling	Discharge can be modelled forward or backwards in time, and can be used to investigate the hypothetical response to changing climate.	Like all models, stalactite drip models represent a simplification of the processes—key behaviour may not be replicated.	Used to characterise drip response and explore variables (e.g., mixing, preferential flow, and lag) that may impact the drip response.	Bradley et al., 2010; Fairchild & Baker, 2012; Treble et al., 2013

landscape to identify potential sinkholes, bedrock surface, karst conduits, and cavities (Al-fares, Bakalowicz, Guérin, & Michel, 2002; Carrière et al., 2013; Roth & Nyquist, 2003; Valois et al., 2010; van Schoor, 2002; Zhou, Beck, & Stephenson, 2000). Martínez-Moreno et al. (2014) used a range of geophysical methods to characterise the karst at Gruta de las Maravillas in Spain to determine the most informative methods. They used magnetic profiles, electrical resistivity tomography (ERT), induced polarisation, seismic prospection, and ground-penetrating radar (GPR), supplemented by topographical data. They concluded that a combination of microgravimetry and microtopography was the most effective to establish the main ducts, but that ERT and induced polarisation were well suited to cavity detection. GPR was also capable of detecting cavities, although only the top and laterals of cavities were well defined. Nonetheless, GPR has been applied to analyse karst aquifer structure (Al-fares et al., 2002), although it is limited where clayey and wetter soils are present and over rough terrain due to signal attenuation (Al-fares et al., 2002; Butnor, Doolittle, Kress, Cohen, & Johnsen, 2001; Roth & Nyquist, 2003). Due to these constraints, GPR was not considered to be an appropriate method for this study.

ERT has been used to investigate the near-surface karst at a range of sites. Carrière et al. (2013) interpreted a region of moderate resistivity, in proximity to a perennial discharge point, as a water-filled reservoir, which may operate to maintain the associated perennial flow. Valois et al. (2010) applied a two-dimensional (2D) ERT survey to highlight local karstic morphologies in relation to the preservation of an archaeological site. Their results showed an anomaly at the study site (a conductive structure), interpreted to be a karstic conduit, which had been in-filled with water or clay. The technique has also been employed to detect cavities (Cardarelli, Cercato, Cerreto, & Di Filippo, 2010; Martínez-Moreno et al., 2014) and to assess the risk of sinkhole formation (Zhou et al., 2000). van Schoor (2002) used ERT to detect sinkholes and concluded that the technique was ideal for discovering and monitoring such features. ERT was therefore deemed to be an appropriate method for investigating the near-surface structure of the epikarst in this study.

Nondestructive geophysics techniques (including ERT, GPR, and other methods) may be useful to profile the epikarst; however, their resolution inherently decreases with depth. As a result, the closer a speleothem is to the surface, the more informative the geophysics will be about the hydrological conditions surrounding it, but the fine-scale heterogeneities will still remain unresolved. They are also limited by topography and other physical factors. Nonetheless, when possible, geophysical methods offer the potential to provide insight into subsurface conditions.

1.2 | Empirical drip studies

Monitoring of stalactite discharge using acoustic and optical instruments has been widely used to investigate local karst hydrology (Baker & Brunsdon, 2003; Baldini et al., 2006; Fernández-Cortés, 2007; Riechelmann et al., 2011; Tooth & Fairchild, 2003). Some of the earliest drip classification was undertaken by Friedrich and Smart (1982) who used maximum discharge and discharge variability to distinguish four drip classes. The classes split flow broadly into quickflow and baseflow, and then into subclasses of shaft flow, vadose flow, seepage flow, percolation stream, and subcutaneous flow. Later, Smart and Friedrich (1987) discarded the idea of numbered class types but continued to categorise flow with descriptors (seepage, percolation, vadose, shaft, and subcutaneous).

Baldini et al. (2006) adapted this framework to infer the potential resolution of the associated stalagmite palaeo-climate record. They defined three classes of discharge within Smart and Friedrich's (1987) matrix of discharge types (see Baldini et al., 2006, p. 394). Class 1 drips had the potential to preserve palaeo-seasonality, Class 2 drips were not actively depositing stalagmites, and Class 3 drips were associated with annual–decadal signals. It should be noted that the classes used by Baldini et al. (2006) do not correspond to the flow classes developed by Friedrich and Smart (1982).

Although drip monitoring can give useful information, without accompanying drip chemistry data, it is not possible to determine the age of water, mixing of event waters, or transmission time distributions. That is, although drip rates may respond rapidly to an event, the associated discharge may not have precipitated during that event. Monitoring of the hydrology of stream and hillslope waters suggests that discharge is likely to be predominantly “old” water, that is, primarily preevent water that is mobilised by the rain event (Kirchner, 2003). It is still unclear to what extent this mixing is evident in speleothem studies. Equally, drip monitoring only allows the inference of karst structure and processes occurring between the ground surface and the speleothem. The high degree of variability of $\delta^{18}O$ in coeval stalagmites in proximity shows the potential of karst hydrology to complicate the interpretation of the proxy record, and that even at the local cave level, individual speleothems need to be treated as being influenced by discrete hydrological factors and as potentially independent records (Serefiddin et al., 2004).

Stalactite drip monitoring can be a useful tool to describe the local hydrology. A key strength of the method is that the instrumentation (i.e., Driptych Stalagmate or similar) is robust and economical and can be left in situ for extended periods. This is helpful as many caves occur in rugged and remote environments that may not allow extended or frequent fieldwork. A key weakness is that, without water chemistry data, the extent of mixing and preferential flow cannot be ascertained. Overall, drip monitoring is a useful tool for understanding the response of the hydrology to external climatic forcing. Drip monitoring often underpins and informs the development of drip models.

1.3 | Drip modelling

Modelling of drip hydrology is undertaken to understand the hydrology and may also include the drip-water chemistry. This can be a powerful approach to further the understanding of the karst environment, as integrated hydrology–geochemistry model outputs can indicate flow regimes and variation in water chemistry composition over time (Fairchild & Baker, 2012). Fairchild et al. (2006) constructed a two-component linear systems model to explain discharge behaviour and water chemistry variability. Their simple model successfully replicated the discharge characteristics, but not the hydro-chemical behaviour. Bradley, Baker, Jex, and Leng (2010) developed a generic lumped parameter model to investigate the physical processes that dictate water routing through the soil, epikarst, and karst aquifer. They applied this model to three distinct climatic zones and successfully estimated the range of both drip water and stalagmite $\delta^{18}O$ for each climatic zone. Treble et al. (2013) used a version of Bradley et al.'s (2010) lumped parameter model to simulate flow routing in a shallow dune calcarenite in south-west Western Australia, where they identified three hydrological regimes (low flow, mixed flow, and high flow).

Two broad philosophies have been identified in hydrological modelling: the bottom-up (upward) approach and the top down (downward) approach (Sivapalan, 2003; Sivapalan, Blöschl, Zhang, & Vertessy, 2003). The conventional bottom-up approach has been described as a reductionist approach, which starts with complex physical descriptions of processes at small scales and up-scaling these small-scale processes to the large scale with models that attempt to explicitly account for the subsurface heterogeneity. Such approaches result in overly complex models that are difficult to apply, calibrate, and validate (Sivakumar, 2004). Conversely, the downward approach represents an alternative that encompasses a more data-driven learning philosophy (Sivapalan et al., 2003) and has been defined as an expansionist approach (Sivakumar, 2004). Klemeš (1983, p. 7) described this approach as "the route that starts with trying to find a distinct conceptual node directly at the level of interest (or higher), and then looks for the steps that could have led to it from a lower level." Most speleothem-scale hydrological modelling has followed the downward approach (even if their philosophical basis is not explicitly stated) as much subcatchment karst hydrological modelling is built on empirical observational data (Bradley et al., 2010; Fairchild et al., 2006; Treble et al., 2013).

Like drip monitoring, drip modelling is an effective method to improve the understanding of the hydrological processes that contribute to stalagmite formation. Hydrological modelling allows researchers to investigate the drip behaviour over time. An advantage of this method is that the drip can be modelled both forward and backward in time, allowing for researchers to investigate the response to different climatic regimes. However, like all modelling, drip hydrology models are a simplification of the processes and may miss key aspects of the behavioural response. And, like discharge monitoring, drip modelling only allows us to infer which hydrological processes are operating, although it does allow inferences to be statistically tested. Overall, drip modelling is a useful tool for understanding the contemporary hydro-climatology of speleothem records.

1.4 | Multimethod approach

As outlined above, the conventional approaches to study hydrological processes in karst environments are of limited value by themselves. Much past work has focused on approaches applying geophysics, drip monitoring, and/or drip modelling, each of which has limitations. The overall aim of this paper is to determine whether a multimethod approach is able to resolve the conditions under which a stalagmite (JC001) formed. In forthcoming work, JC001 will be analysed to develop a palaeo-climate record for the Australian Alps. We evaluate whether geophysics (ERT) can be used to characterise the near-surface karst, and to preclude the presence of any intermediate structures or cavities. Conventional approaches to classification of drip monitoring data are used. Both the geophysics and the drip monitoring data are then used as the basis for the development of a conceptual model to inform the construction of a simple drip model, following the philosophy of the downward approach. By using multiple methods, we hope to mitigate the effects of limitations associated with each method.

A critical result of this research is to demonstrate the application of a multimethod approach to investigate some of the controlling factors that dictated the growth of a stalagmite. This will aid the (future) interpretation of a detailed palaeo-climate record from that stalagmite.

2 | STUDY REGION AND METHODS

2.1 | Study setting

The Yarrangobilly limestone is a massive Silurian formation located in the subalpine area of the northern region of Kosciusko National Park, southeastern Australia (Figure 1). The region may provide critical data to understand the palaeo-climate of both southeastern Australia and the Southern Hemisphere, due to the location of the caves complex, which experiences precipitation sourced from southern mid-latitudes to the tropics (Callow, McGowan, Warren, & Speirs, 2014; Theobald, McGowan, Speirs, & Callow, 2015). Despite this, there is very little published research conducted on the speleothems and associated hydrology of this region (see Markowska et al., 2015; Spate, Jennings, Ingle Smith, & James, 1976; Webb et al., 2014).

The Yarrangobilly Caves complex is located between 950 to 1,050 m above Australian Height Datum. The climate is characterised by a cool-season precipitation regime, which includes both snow and rainfall, although rainfall is dominant. Annual precipitation displays interannual variability (σ = 236.2 mm; μ = 1,147 mm; range = 976.1 mm) (Australian Bureau of Meteorology, 2014c). Although snowfall does occur at the site during the winter, there is no permanent snowpack maintained throughout the season. Data from the proximal Snowy Hydro Limited snow course site at Three Mile Dam (1,460 m Australian Height Datum and 18-km distance) show that at this altitude, a snowpack is maintained from June to mid-October that peaks at 30 cm deep on average (based on 1957–2002 data; Hennessy et al., 2008). The caves are therefore well below the mean seasonal snowline. Mean annual air temperature is approximately 12 °C (Desmarchelier, 1999), and the temperature in the Jersey Cave ranges between 10 and 11 °C. Data collection was primarily associated with the "Grotto of Oddities," a small, highly decorated section of the Jersey Cave that is located south of the main entrance, approximately 7–8 m below the surface.

2.2 | Surveying and geophysics

The hillslope overlying the Jersey Cave and the position of JC001 within the cave were surveyed using a Leica FlexLine TS02plus Total Station to position three 2D ERT survey transects and to interpolate a ground surface model for the ERT using ArcMap 10.2.1 (ESRI, 2013; Figure 1). The ERT survey was conducted using the dipole–dipole array as it provides a compromise between lateral and vertical resolution, measurements could be obtained rapidly, and the near-surface

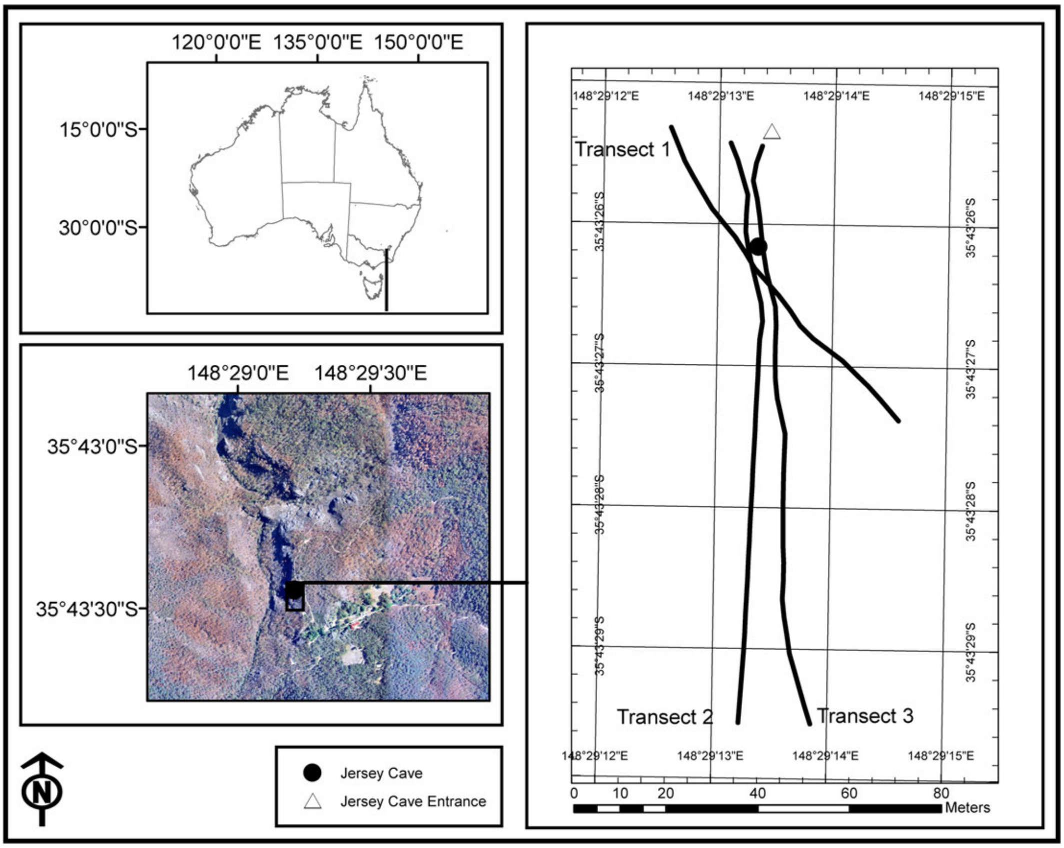

FIGURE 1 Site map showing the Yarrangobilly karst, the position of the Jersey Cave, and the electrical resistivity tomography transects

resolution was high (Loke, 2004). Electrodes were placed at 2-m intervals along the ground surface, with transects concentrated around the site above JC001. Up to 56 electrodes were used on each transect. Results were processed with EarthImager 2D Resistivity and IP Inversion Software (Advanced Geosciences Inc., 2007) with the aim of minimising error between the measured and modelled apparent resistivity pseudo-sections (Leucci, 2006). Topographical coordinates were added to the final inversion model.

2.3 | Drip monitoring

A Driptych "Stalagmate" acoustic drip monitor was installed to monitor discharge to JC001 between April 2013 and February 2015, consistent with methods described by Genty and Deflandre (1998). Statistical analyses of discharge variation were undertaken following methods developed by Friedrich and Smart (1982), Smart and Friedrich (1987), and Baldini et al. (2006). Plotting the coefficient of variation of discharge against maximum discharge enables the inference of the hydrological pathways and potential palaeo-climate proxy resolution. Although drip volume was not measured, two assumed values were used for this analysis; 0.15 ml drip^{-1} is a common volume (Baker & Barnes, 1998; Baker & Smart, 1995; Baldini et al., 2006; Fairchild et al., 2006), whereas 0.37 ml drip^{-1} was derived from a linear equation developed by Genty and Deflandre (1998) who showed that, under low flow conditions, drip volume increased as drip rate decreased. The drip rate observed here was slower than that used by Genty and Deflandre (1998), and we assume the linear relationship holds for such slow discharge rates. However, 0.37 ml drip^{-1} is a useful endpoint, as the actual mean drip volume likely lies somewhere between the two assumed volumes.

2.4 | Stalactite discharge model

A parsimonious (downward) approach was taken to iteratively develop a drip discharge model, with increases in complexity included only as required. The model described daily drip rates and had one input, effective precipitation, that is, precipitation minus potential evapotranspiration. Precipitation data for the Yarrangobilly Caves were sourced from the Australian Bureau of Meteorology (2014c), and daily potential evapotranspiration was estimated using the Priestley–Taylor equation (Priestly & Taylor, 1972) as applied in the EcoHydRology package in *R* (Fuka, Walter, Archibald, Steenhuis, & Easton, 2014). Inputs to the package included maximum, minimum, and average temperature, as well as aspect, slope, and latitude. Temperature data were sourced from nearby Cabramurra, NSW (Australian Bureau of Meteorology, 2014a, 2014b). Although the equation assumes zero ground heat flux, which may not be correct, the parsimonious philosophy of the downward approach and the agreement of the modelled and observed discharge, as well as the use of this equation in similar studies (Mahmud et al., 2016) and at the catchment scale (Teuling, Lehner, Kirchner, & Seneviratne, 2010), means that it was not necessary to add additional detail. However, this discrepancy may add some uncertainty to the drip hydrology model. The model was optimised to maximise the Nash–Sutcliffe efficiency (NSE; Equation 1):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{\mathrm{obs}} - Y^{mean}\right)^2}, \quad (1)$$

where Y_i^{obs} is the ith observed value, Y_i^{sim} is the ith simulated value, and Y^{mean} is the mean of the observed values.

The model development was informed primarily by the analysis of discharge behaviour and was calibrated using 493 days of observed discharge. Although discharge was measured as drips per 10-min interval, it was aggregated to daily data and converted to a volume (with an assumed volume of 0.15 ml drip^{-1}). Some of the model structure and function was informed by interpretation of the geophysics results, principally, the absence of overlying cavities and the presence of a region of local water storage, which suggested a relatively simple hydrological link between the surface and the cave. The store of water present above the cave in summer appears to sustain flow during dry periods. These results (Section 3) suggested that rapid non-Darcian flow was less likely to be a dominant mechanism for water flow.

The model describes a simple mass balance for a set of interconnected leaky stores. The equations for the final model (Equations 2–9) are below, and the rationale for its development follows. All discharges (Q_1 to Q_5, Equations 3, 5, and 6–9) are constrained to positive values (≥0). An upper soil store is described by

$$\frac{ds_1}{dt} = \begin{cases} A_1 EP - Q_1 - Q_2 & for\ s_1 > 0 \\ 0 & for\ s_1 = 0 \end{cases}, \quad (2)$$

where s_1 is the volume of water in Bucket 1, A_1 is the surface area of Bucket 1, EP is effective precipitation, and Q_1 and Q_2 are discharges from Bucket 1. Discharge Q_1 contributes to the quickflow component of drip discharge as described by

$$Q_1 = \max\left(\frac{s_1}{\tau_1}, 0\right), \quad (3)$$

where τ_1 is a rate constant. The contribution from s_1 to the more slowly responding epikarst store, s_2, was given by

$$Q_2 = \max\left(\frac{s_1 - T_1}{\tau_2}, 0\right), \quad (4)$$

where T_1 is a threshold that must be exceeded for Q_2 to be initiated, and τ_2 is its rate constant. The mass balance for the baseflow store, s_2, is given by

$$\frac{ds_2}{dt} = \begin{cases} A_2 EP + Q_2 - Q_3 - Q_4 - Q_5 & for\ s_2 > 0 \\ 0 & for\ s_2 = 0 \end{cases}, \quad (5)$$

where A_2 is its area, and Q_3, Q_4, and Q_5 are its discharges. Discharge Q_3, which represents the baseflow component of the modelled discharge and makes up the largest proportion of modelled discharge, is given by

$$Q_3 = \max\left(\frac{s_2 - T_2}{\tau_3}, 0\right), \quad (6)$$

where T_2 is a threshold and τ_3 the associated rate constant.

The sum of Q_1 and Q_3 comprises the simulated discharge (Q_{mod}):

$$Q_{\mathrm{mod}} = Q_1 + Q_3. \quad (7)$$

Discharges from s_2 that bypass the measured stalactite as baseflow are given by Q_4:

$$Q_4 = \max\left(\frac{s_2}{\tau_4}, 0\right), \quad (8)$$

and, following saturation of s_2, by Q_5

$$Q_5 = \max(s_2 - T_3, 0), \quad (9)$$

where, as before, T_3 is a threshold storage and τ_4 a rate constant. These discharges represent contributions to discharge from other stalactites in the highly decorated Grotto of Oddities. Lateral transport of epikarst water at large scales (>80 m) has been observed in such systems (e.g., Williams, 2008).

Equations 2 to 9 and Figure 2c describe the final hydrologic model. This model was developed in iterations. In each iteration, the conceptual model was designed and calibrated, and model behaviour was evaluated both quantitatively, through the use of the Nash–Sutcliffe and root mean square error (RMSE), and qualitatively. After each iteration, a new model structure was hypothesised to attempt to capture missing aspects of the simpler model (Figure 2). For example, the initial model (Figure 2a) could capture rapidly variable discharge dynamics or the seasonal pattern, but it could not do both, nor could it describe the threshold jump in discharge seen early in the season. The second model (Figure 2b) incorporated two buckets with variable flow rates and thresholds. Although this model replicated mean behaviour, especially of the seasonal recession, it still did not capture the threshold response. The final model (Figure 2c) consisted of coupled buckets: one representing a slowly responding store and the other responding rapid flow. Coupling occurred via a threshold. The model structure allowed discharge to vary seasonally in proportion to the stored volume; that is, discharge was greater (lesser) when the stored volume of the bucket was larger (smaller). This was achieved through the use of proportional drainage functions (rate constants). Inflows into this store increased rapidly when the smaller and more dynamic store s_1 filled and spilled, thus providing for a seasonal threshold dynamic. The threshold response is simulated by the interplay between the climate and the different buckets and occurs when a storage value is exceeded, which allows for increased discharge from the bucket. Other flows simulate lateral movement of water away from the contributing stores. These are represented in Figure 2 by Q_4 (baseflow) and Q_5 (rapid flow). The parameters, initial values, and their descriptors for the final iteration can be found in Table 2. Parameters and their descriptors for all iterations of the model are in Table S1 for comparison. Table S1 also includes the physical basis for parameters and variables and their initial values of the final iteration of the model.

The model was calibrated by a quasi-Newton method to maximise the NSE (Equation 1) by comparing modelled drip rate to the observed drip rate data (Moriasi, Arnold, & Van Liew, 2007; Nash & Sutcliffe, 1970). Model development and calibration continued until the NSE reached an acceptable value of between 0.75 and 1.00, which reflected "very good" model performance, whereas an NSE of less than

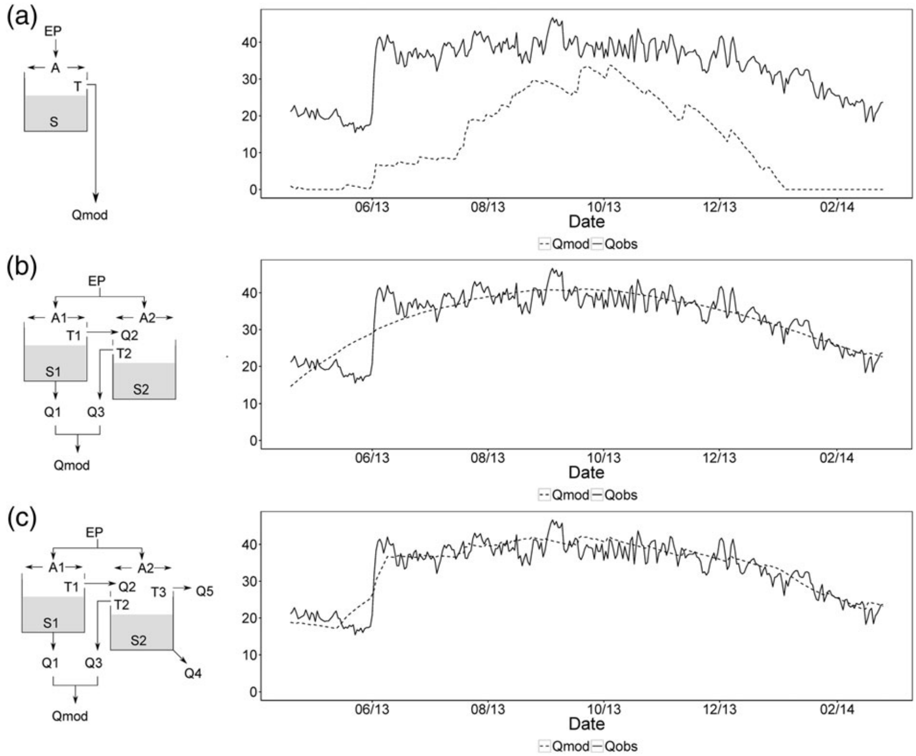

FIGURE 2 The progression of the Jersey Cave conceptual drip hydrology model, showing conceptual models, equations, and modelled (Qmod) and observed (Qobs) discharge for each iteration. (a) Initial conceptual model (single bucket with threshold). (b) Two connected buckets to represent quickflow and baseflow—simulated the recession limb but not the threshold response. (c) Two connected buckets with lateral flows added (Q4 and Q5) that do not contribute to Qmod. (c) Simulates mean discharge behaviour and the threshold response. (c) The final iteration of the conceptual model. EP (effective precipitation); A, A1, and A2 (areas of the bucket); S, S1, and S2 (volumes of the stored water in buckets); Q1 (baseflow from S1 to Qmod); Q2 (overflow from S1 to S2); Q3 (threshold discharge from S2 to Qmod); Q4 (lateral baseflow away from S2); Q5 (lateral overflow away from S2)

TABLE 2 Parameters, their initial values, and their descriptors for the final iteration of the model

Parameter	Initial value	Purpose
A_1	161.84 cm^2	Surface area of Bucket 1
A_2	5.82 cm^2	Surface area of Bucket 2
T_1	5,200.57 ml	Threshold to impede overflow discharge from Bucket 1 to Bucket 2
T_2	50 ml	Threshold to impede contribution of Bucket 2 to Q_{mod}
T_3	6,654.38 ml	Threshold to impede overflow from Bucket 2 to other parts of the system (does not contribute to Q_{mod}). Acts as maximum volume of s_2
S_1	10,000 ml	Volume of water in Bucket 1
S_2	184.3 ml	Volume of water in Bucket 2
τ_1	8,031.73 days	Proportional drainage function that controls rate of flow from S_1 via Q_1 to Q_{mod}
τ_2	67.9 days	Proportional drainage function that controls rate of flow from S_1 via Q_2 to S_2
τ_3	200.59 days	Proportional drainage function that controls rate of flow from S_2 via Q_3 to Q_{mod}
τ_4	2,786.96 days	Proportional drainage function that controls rate of flow from S_2 via Q_4 out of the model

0.50 was considered “unsatisfactory” (Moriasi et al., 2007). Parameters were constrained to be positive (≥0), and parameterisation was done iteratively using box constraints (Byrd, Lu, Nocedal, & Zhu, 1995). Over the calibration period (April 19, 2013, to August 25, 2014), the model performed well (NSE = 0.84; RMSE = 21.12 drips day^{-1}). The calibration period is shown by the black bar in Figure 3. A limited validation period (172 days) was included, which contained part of the seasonal recession limb of 2014. Although the model did not perform well during this period (NSE = 0.12; RMSE = 25.78 drips day^{-1}), it captured the trend of the recession limb (see the grey bar in Figure 3). The short validation period was due to the short observational record. Although it would have been preferable to include the 2014 threshold response in the validation, it was more pragmatic to include it in the calibration to ensure that that behaviour was simulated by the model. The NSE for the entire observed period was 0.8, and the RMSE was 22.42 drips day^{-1}.

Mean behaviour was simulated well, although daily variability was not (Figure 3). The model also simulated the threshold response

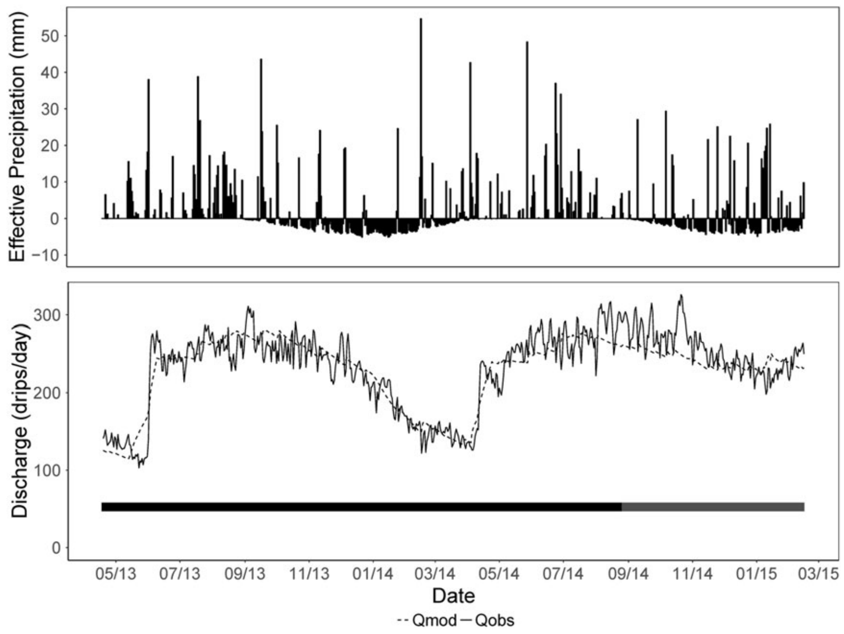

FIGURE 3 Effective precipitation, daily observed (Qobs) and simulated (Qmod) discharge, April 19, 2013, to February 16, 2015, with calibration period (black bar) and validation period (grey bar)

observed in June 2013 and again in April 2014, which is a key feature of the inherent heterogeneity of the karst system.

3 | RESULTS

3.1 | Geophysics

ERT results show the Grotto of Oddities void as indicated by areas of high resistivity (≈10,000 Ω·m; Figure 4, A) located about 7–8 m below ground level. Also noticeable in these images is the area of very low resistivity (≤100 Ω·m; Figure 4, B), just above the void where JC001 was located. This void was named the Grotto of Oddities by Trickett (1906) because of the high concentration of decorations in this area, which indicate that it is anomalously wet in comparison to other parts of the Jersey Cave. Regions of low resistivity are generally associated with enhanced soil water storage and/or clay material.

ERT results supported Total Station surveying. Surveying of the site surface topography and inside the cave to determine the location of the Grotto of Oddities indicated that the cave is located 7–8 m below the

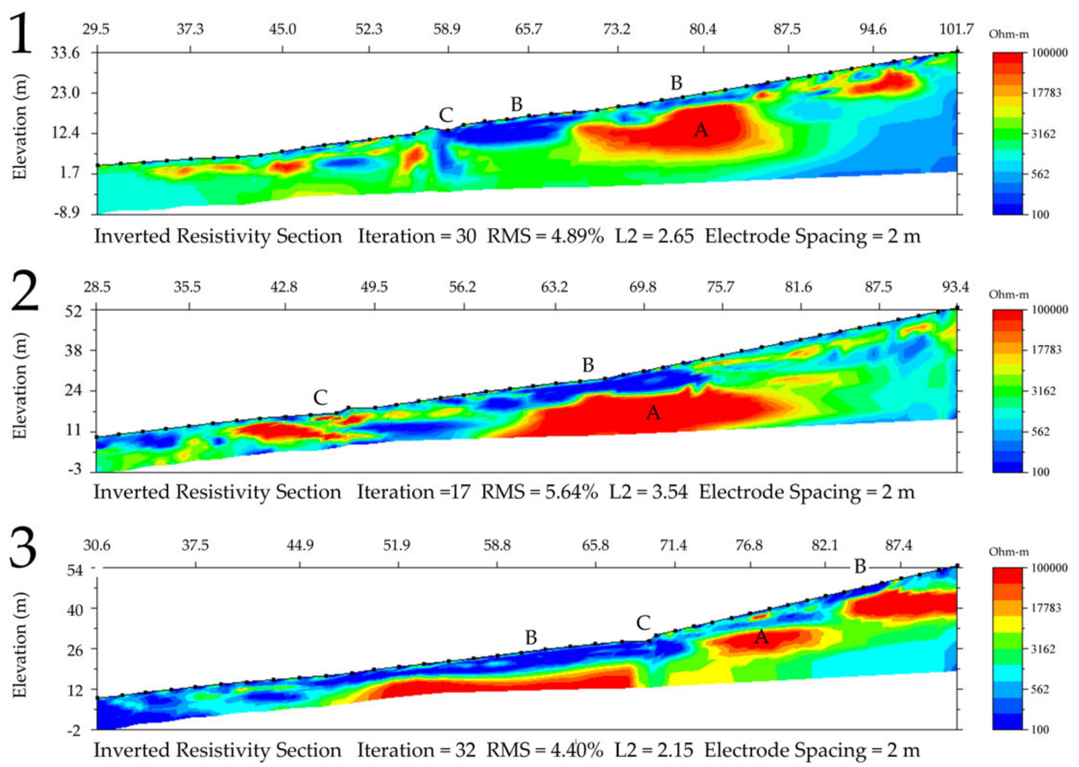

FIGURE 4 Inverted resistivity sections of electrical resistivity tomography transects 1, 2, and 3. The "Grotto of Oddities" is clear (1A, 2A, and 3A), as is the region of anomalously low resistivity (1B, 2B, and 3B) and the dip in topography (1C, 2C, and 3C). RMS = root mean square

surface. Furthermore, results showed that the overlying epikarst and vadose zone is free of any large cavities, which may significantly impact the hydrological pathways. Of particular interest is the region of low resistivity (denoted by a "B" in Figure 4). This area of low resistivity directly overlies the cavity and extends to the surface and is associated with a change in the surface profile (Figure 4, C), suggesting that the surface–subsurface flow network results in localised preferential recharge to this area and is responsible for the increased decorations and speleothem formation activity in the Grotto of Oddities.

3.2 | Drip monitoring

The dripstraw above JC001 maintained a mean drip rate of 225 drips day^{-1}, and discharge consistently exceeded 70 drips day^{-1} during the observational period (April 19, 2013, to February 16, 2015). Discharge was hysteretic (Figure S2) and displayed seasonal variability with a distinct threshold switch in June 2013 and again in April 2014. The drip rate jumped from 118 to 239 drips day^{-1} over a period of 2 days in 2013, and from 150 to 240 drips day^{-1} over 3 days in 2014 (Figure 3). In both instances, this threshold response came after low discharge rates at the end of summer, followed by an increase in precipitation, and therefore discharge, at the onset of wetter conditions at the start of autumn/winter. Seasonally responsive drips are widely reported in studies of drip typologies, and this relates to both the climatic regime (see Section 2.1) and localised hydrology. Although there was no clear rain-event response, discharge was more variable during periods of high flow than during periods of low flow (high flow μ = 253.16 drips day^{-1}, σ = 26.58 drips day^{-1}; low flow μ = 143.48 drips day^{-1}, σ = 18.29 drips day^{-1}). Results also suggest that water storage in the epikarstic reservoir has an upper limit, as indicated by the lack of response of the monitored drip to discrete precipitation events after the change in flow regime from low to high flow. This observation informed the development of the discharge model as we implemented maximum storage to the model "buckets."

Following Friedrich and Smart (1982), Smart and Friedrich (1987), and Baldini et al. (2006), the JC001 drip is primarily fed by seepage flow, which is consistent with the structure of the hydrological model (see Section 2.4) and can be classified as either Class III or Class I (Figure 5). Figure 5 shows coefficient of variation of discharge plotted against maximum discharge for two different assumed drip volumes (0.15 or 0.37 ml drip^{-1}). 0.15 ml drip^{-1} is a commonly cited drip volume (see Baker & Barnes, 1998; Baker & Smart, 1995; Baldini et al., 2006; and Fairchild et al., 2006), whereas 0.37 ml drip^{-1} is a drip volume based on a linear relationship between drip rate and drip volume identified by Genty and Deflandre (1998), who noted that drip volume increases as drip rate decreases. However, 0.37 ml drip^{-1} is unlikely to be correct for this site as drip rates observed here were much lower than those observed by Genty and Deflandre (1998), and it is unknown at what point the linear relationship fails. As such, it is likely that the drip volume for this site lies somewhere between 0.15 and 0.37 ml drip^{-1}.

3.3 | Stalactite discharge model

The model simulated continuous discharge for the entirety of the continuous Yarrangobilly Caves precipitation record (January 1, 1978 to February 16, 2015; Figure 6). After initial model spin-up (i.e., the model ran through one hydrological year), discharge did not fall below 70 drips day^{-1}. The maximum modelled daily discharge was 327 drips day^{-1}, and mean simulated discharge was 235 drips day^{-1} (excluding the first year to allow for model run-up). Variations in drip behaviour conform well to known environmental events such as the Millennium Drought (2001–2009). The dry periods in the 1980s and during the Millennium Drought are amongst the driest periods for the last 500 years based on a reconstruction of Murray River inflows (McGowan, Marx, Denholm, Soderholm, & Kamber, 2009).

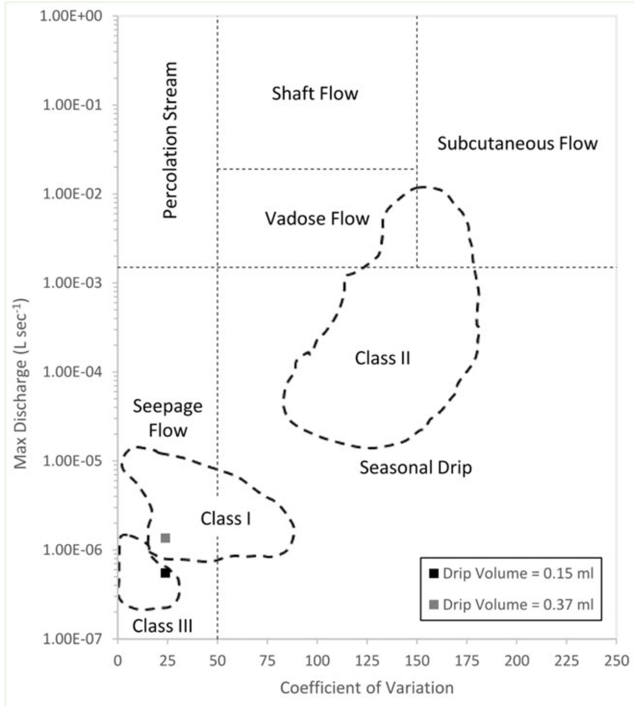

FIGURE 5 Drip classification of the study speleothem after Smart and Friedrich (1987), where drip volume, coefficient of variation, and maximum discharge dictate the "class" of the drip. Dotted lines indicate drip classes from Baldini et al. (2006), the black point indicates the coefficient of variation plotted against the maximum discharge with an assumed drip volume of 0.15 ml (based on Baker & Smart, 1995; Baker & Barnes, 1998; Baldini et al., 2006; and Fairchild et al., 2006), with the grey point based on a similar approach but adopts a potential drip volume of 0.37 ml based on Genty and Deflandre (1998)

The model parameterisation and interpretation of the geophysics appear to be consistent. The geophysics suggests a soil depth of ~7 m over the cave that is relatively wet (Figure 4). Assuming a porosity of 0.5 cm^{3} cm^{-3} and a field capacity of 10% (Ford & Williams, 2007), this would give ~700 mm of water storage above the cave. This is close to the estimated mean annual effective precipitation of ~660 mm, suggesting that during an average year, there is enough recharge to maintain the storage to sustain flows through the unsaturated zone. The combined maximum storage capacity of the two model buckets (S1 and S2) is 66 mm. This would suggest that ~10% of the storage capacity, as inferred by the geophysics, and similarly ~10% of the annual effective precipitation, may be contributing to the drip discharge. This behaviour may account for the threshold behaviour and long recession limb in the observed discharge. Although these

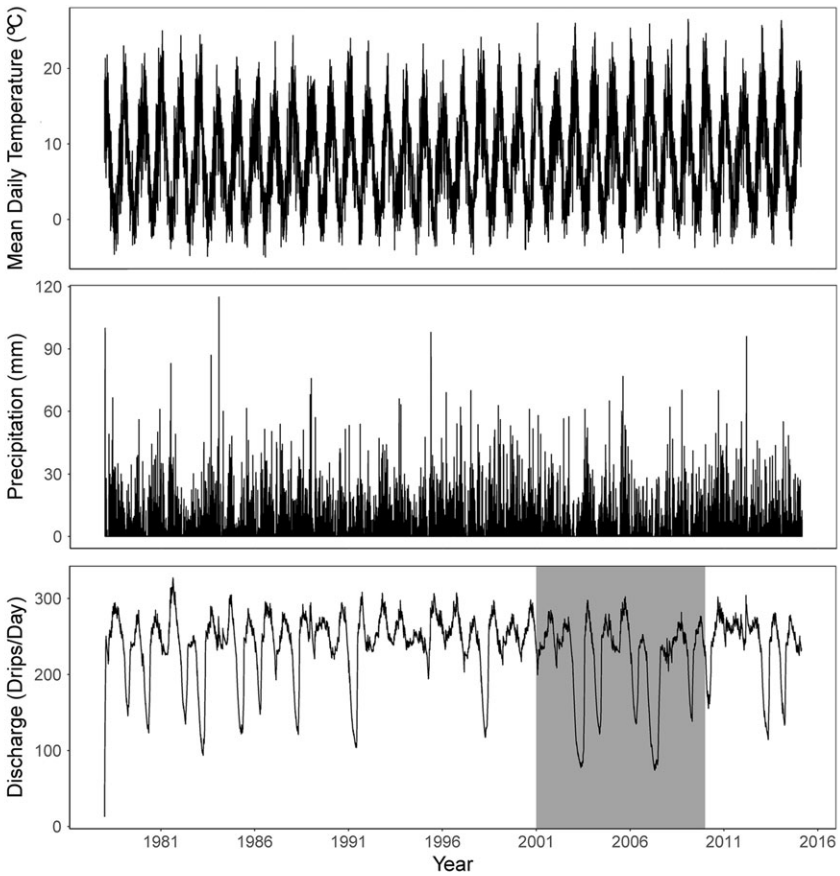

FIGURE 6 Simulated discharge, January 1, 1978, to February 16, 2015; shaded area indicates the duration of the Millennium Drought (2001–2009). Daily precipitation and daily mean temperature are also shown

numbers are not absolute, and bypassing behaviour may occur in karst, the relative proportions of catchment area and volumes in the model appear to be not unreasonable.

4 | DISCUSSION

4.1 | Geophysics

A key aim of this project was to apply multiple techniques to inform our understanding of the hydrological processes and the nature of the epikarst that have controlled the formation of a speleothem palaeo-climate record. Geophysical techniques were used to characterise the morphology of the karst overlying the Grotto of Oddities. Geophysics and traditional surveying agreed that the cave was relatively shallow (7–8 m below the surface). The results allowed for a better understanding and conceptualisation of the local hydrology and eliminated the possibility of moderate to large voids overlying the site. This implies that the hydrological pathways for the transport of meteoric precipitation are, for karst, relatively straightforward, and that the incorporation of an isotope signal into JC001 is in principle likely to be simpler and with less lag time than for speleothems in other caves at Yarrangobilly, which are lower in the landscape and with known caves overlying them.

Geophysics results also presented evidence of a local region of enhanced water storage in the epikarst, or an epikarstic reservoir. Although it has been asserted that the epikarst is a region capable of storing large volumes of water (Perrin, Jeannin, & Zwahlen, 2003; Smart & Friedrich, 1987; Williams, 2008), ERT allowed the presence of this region over the Grotto of Oddities to be verified, and showed its position relative to JC001. The presence of this epikarstic reservoir also provides further supporting evidence that the local hydrology is equipped to supply sufficient discharge to create a continuously growing stalagmite.

A key limitation of near-surface sites is the limited potential for soil water storage, which is required for perennial drip behaviour and the preservation of a continuous palaeo-climate archive. Changes in slope were aligned with changes in electrical resistivity; local surface depressions were collocated with a region of low resistivity, which we assume to represent the epikarstic reservoir. Williams (2008) noted that solution dolines are an indicator of the epikarstic aquifer, and we propose that these local depressions may also act to concentrate groundwater in the area, and allow for enhanced storage in this epikarstic reservoir relative to other parts of the landscape. The presence of this region of low resistivity supports the findings of Carrière et al. (2013) who attributed perennial water flow in the low-noise underground laboratory in Fontaine de Vaucluse basin, France, to a zone of moderate resistivity. This is a significant result, which relates locally enhanced water supply to the many dripstraw stalactites, which are a key feature of the Grotto of Oddities originally noted by Trickett's survey of the cave (Trickett, 1906).

GPR and ERT are commonly used in concert (Carrière et al., 2013; El-Qady, Hafez, Abdalla, & Ushijima, 2005; Leucci, 2006), and some have maintained that individual geophysical techniques do not provide high-resolution results when applied to karst (Carrière et al., 2013). The use of 2D ERT (as opposed to three-dimensional ERT) in highly heterogeneous media has also been criticised (Carrière et al., 2013). Nonetheless, the method has been used to highlight local karstic morphologies such as infilled karst conduits (Valois et al., 2010), and van Schoor (2002) concluded that the method was ideal for monitoring features such as sinkholes. This research has shown that ERT is an effective geophysical method for the investigation of the near-surface karst. Results clearly showed the Grotto of Oddities and an overlying region of water storage, which we interpreted to represent the epikarstic aquifer.

Geophysics may not be appropriate for all situations and studies; however, these methods are perhaps underutilised tools and may be useful for the palaeo-climate community to adopt in order to more easily investigate karst flow pathways, particularly in near-surface systems. ERT has been able to identify that this site is likely to comprise relatively simple hydrological pathways to a near-surface cave, which lacks large fissures and voids, and that there is an important local region of increased water storage collocated with JC001 and with changes in surface topography.

4.2 | Drip monitoring

Drip monitoring showed that discharge was relatively slow in comparison to available published data. Genty and Deflandre (1998) in the Père Noël Cave (Belgium) observed drip rates ranging from 7 to 500 drips per 10-min interval, whereas the maximum observed discharge here was 4 drips per 10-min interval, with a mean discharge of 1.56 drips per 10-min interval. The JC001 drip showed seasonal variation with a distinct threshold switch occurring in June 2013 and April 2014, when discharge moved to a new regime of high discharge associated with the onset of autumn/winter precipitation. Drip behaviour slowly transitioned back to a low flow regime in the 2013–2014 and 2014–2015 hydrological years. Discharge was more variable during periods of high flow, which is consistent with Baldini et al. (2006).

Drip classification indicated that the drip is primarily fed by seepage flow, either Class III (potential to preserve an annual or decadal palaeo-climate signal) or Class I (potential to preserve palaeo-seasonality) type drips. The discrepancy arises from the assumed drip volume used in the calculations. Ongoing collection of drip and meteoric precipitation samples for geochemical analysis will assist in constraining these results and allow the more adequate description of the transport and mixing pathways through the epikarst in future work. However, these preliminary data and the ERT results imply that JC001 is a speleothem of high fidelity, with little chance for the hydrology to obscure the palaeo-climate signal contained within the stalagmite.

4.3 | Stalactite discharge model

Optimised parameters of the hydrology model are physically realistic, based on the current literature that partitions karst discharge by type of flow (through conduits, fractures, and the matrix; Fairchild & Baker, 2012), and the geomorphology and characteristics of the site. As discharge through the matrix is generally negligible (Fairchild & Baker, 2012), the parameters represent both relatively slow and relatively quick movement through the pore space.

Model results indicated that flow was likely maintained to JC001 for at least the length of the continuous observed precipitation record (January 1, 1978, to February 16, 2015), including during the Millennium Drought (2001–2009), which is the most severe drought on record for southeast Australia (McGowan et al., 2009; van Dijk et al., 2013). The year 2006 was the driest in the Yarrangobilly Caves precipitation record, with 552 mm compared to the long-term annual average (1978–2014) of 1,147 mm (Australian Bureau of Meteorology, 2014c). Continued simulated discharge through these events adds to the integrity of JC001 as a continuous palaeo-climate record, as consistent flow is important to avoid growth hiatuses.

Although the model did not simulate daily-scale variability, mean behaviour was well replicated. Fine-scale variability may be attributed to other local conditions such as barometric pressure, which has been shown to impact discharge rates (Fernández-Cortés, 2007). Improvements to the model to better represent this daily-scale variability could inform our knowledge of local surface–subsurface links (e.g., barometric forcing and spatial variability in soil water pressures), which might improve the interpretation of meso-scale climate forcings at long time scales. However, the model did allow inferences to be made about the seasonal hydrology of the overlying karst through the downward approach. No lags were incorporated in the simulation equations. Optimised parameters indicated that the drip included both slow and quickflow components, with interactions between them, and that local water storage is limited, that is, excess water is diverted, potentially to other dripstraw stalactites in the Grotto of Oddities. This is consistent with observations from research in the United Kingdom, which showed that waters covered distances of up to 80 m laterally in karst (Williams, 2008). Mixing may occur during this lateral transport or at any point during the transport period, but these effects have yet to be investigated in the Jersey Cave. The importance of discharge flux and tracer data has been identified in catchment hydrology, where untangling velocity, celerity, and residence time are made possible by using both flux and tracer data (Kogovsek & Petric, 2014; Lange, Arbel, Grodek, & Greenbaum, 2010; McDonnell & Beven, 2014; Perrin, Pochon, Jeannin, & Zwahlen, 2004). The lack of tracer data is a key limitation of this study and an area of future research.

5 | CONCLUSION

A field-based geophysics and drip monitoring approach was undertaken to investigate local karst hydrology of a near-surface system and to infer the potential of the JC001 speleothem as a palaeo-climate archive. ERT and discharge monitoring and modelling methods were applied, in what is believed to be the first use of ERT, discharge monitoring and drip modelling in a multimethod approach to underpin palaeo-climate reconstruction.

Results indicated that the overlying epikarst is relatively simple in structure. Geophysics and topographical surveying agreed that the Grotto of Oddities cavity was located approximately 7 m below ground level. Geophysics showed that changes in hillslope above the Grotto of Oddities are collocated with a region of very low resistivity, which is proposed to form an epikarstic reservoir acting to supply enhanced discharge to the JC001 speleothem, relative to other parts of the

Jersey Cave. The novel application of the ERT methods allowed for unprecedented insight into the local "wetness" above the Grotto of Oddities and the ability to independently resolve the depth of the vadose zone and to ascertain that no large voids existed between the surface and the roof of the Grotto of Oddities.

Drip monitoring showed a distinct threshold response at the onset of the wet season (observed in 2013 and 2014), but limited response to discrete precipitation events. Discharge was hysteretic, which is indicative of non-linearity. This is consistent with the heterogeneous nature of karst and has been observed in other studies (Goldscheider, Meiman, Pronk, & Smart, 2008). A simple drip classification indicated the potential for the JC001 speleothem to record palaeo-seasonality or an annual–decadal signal.

A stalactite drip discharge model indicated that discharge was comprised of both slow and quick flow pathways. Significantly, the model showed that discharge was continuous since at least January 1978, including the Millennium Drought of 2001–2009. Model parameterisation also indicated that the storage volume is subject to a maximum limit.

Through the application of traditional and novel techniques in this study, results show that the growth of the JC001 speleothem is primarily modulated by the presence of an epikarstic reservoir, which maintains perennial flow to the speleothem. Results indicate that the speleothem likely represents a palaeo-climate proxy record that is representative of the regional hydro-climate and which will significantly enhance current knowledge of the climate of southeast Australia. Future work aims to evaluate the factors influencing the incorporation of the stable isotope and geochemistry environmental signal into the JC001 palaeo-climate archive. This work has implications for the development of a palaeo-climate proxy record from the Jersey Cave, Yarrangobilly, and for the use of a multimethod approach in similar studies so that more accurate interpretations are made of speleothem palaeo-climate records. Specifically, it constrains the likely hydro-climate coherency of speleothem palaeo-climate records for JC001 and shows that a multimethod approach can be highly effective in compensating for the shortfalls of each method.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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