Research papers

Rainfall recharge thresholds in a subtropical climate determined using a regional cave drip water monitoring network

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ABSTRACT

Quantifying the combination of climatic and hydrological conditions required to generate groundwater recharge is challenging, yet of fundamental importance for groundwater resource management. Here we demonstrate a new unsaturated zone physical method of determining rainfall-recharge thresholds in karst using a regional cave drip water monitoring network. For limestones of the Upper and Lower Macleay Valley, eastern Australia, set in a subtropical climate, we observe thirty-one cave drip water recharge events over a five-year monitoring period. Comparison to antecedent precipitation demonstrates a median observed recharge threshold of 76 mm/week precipitation (Lower Macleay) and 79 mm/week precipitation (Upper Macleay), with lower precipitation thresholds (down to 30 mm/week) possible. We use a simple water budget model to quantify soil and epikarst water storage volumes and to test hypotheses of the hydrological controls. Modelled soil and epikarst water storage capacities of about 65 mm (Lower Macleay) and 80 mm (Upper Macleay) confirm a correspondence between observed weekly precipitation thresholds and soil and epikarst capacities. However, discrepancies between observed and simulated recharge events helps elucidate the likely recharge processes including focussed recharge bypassing the soil and epikarst store, overflow and drainage between multiple karst stores, and tree water use from depth. Our observed recharge thresholds and modelled soil and epikarst storage capacities are comparable to recharge thresholds estimated across a range of water-limited environments globally. The method is readily applicable to any karst region where drip loggers can be installed in a cave system in close proximity to surface climate data.

1. Introduction

Groundwater recharge is the "downward flow of water reaching the water table, adding to groundwater storage" (Healy, 2010). Recharge can be both diffuse (infiltration through the unsaturated zone occurring over large areas from precipitation) and focused (from losing or 'leaking' rivers, lakes and wetlands, and in karst areas, the base of closed depressions) (Scanlon et al., 2002). Diffuse recharge occurs below what is defined as the zero flux plane (ZFP; Healy 2010), which separates the zones of upward and downward moving waters, and is often assumed to be equivalent to the depth of rooting zone. The identification and quantification of recharge sources and the processes determining when recharge occurs is of fundamental importance for our understanding of the sustainability of groundwater resources

(Gleeson et al., 2020) e.g. for water resource allocation, protection of groundwater supplies and the sustainability of dryland farming and irrigated agriculture.

However, it can be difficult to separately quantify diffuse and focused recharge, as most groundwater level measurements and water samples are obtained via wells (or bores) which integrate all possible recharge sources and are affected by lateral groundwater flow. A notable exception in karst regions is the use of spring geochemistry (water hardness) to identify recharge type in temperate climates (Worthington et al., 1992). Nevertheless, in dryland regions, if precipitation is identified as the sole recharge source, field-based recharge estimates can be derived from water level fluctuations, chloride mass balance determinations and radiogenic isotopic techniques (Cuthbert et al., 2019, Scanlon et al., 2006; Crosbie et al., 2010). However, in carbonate

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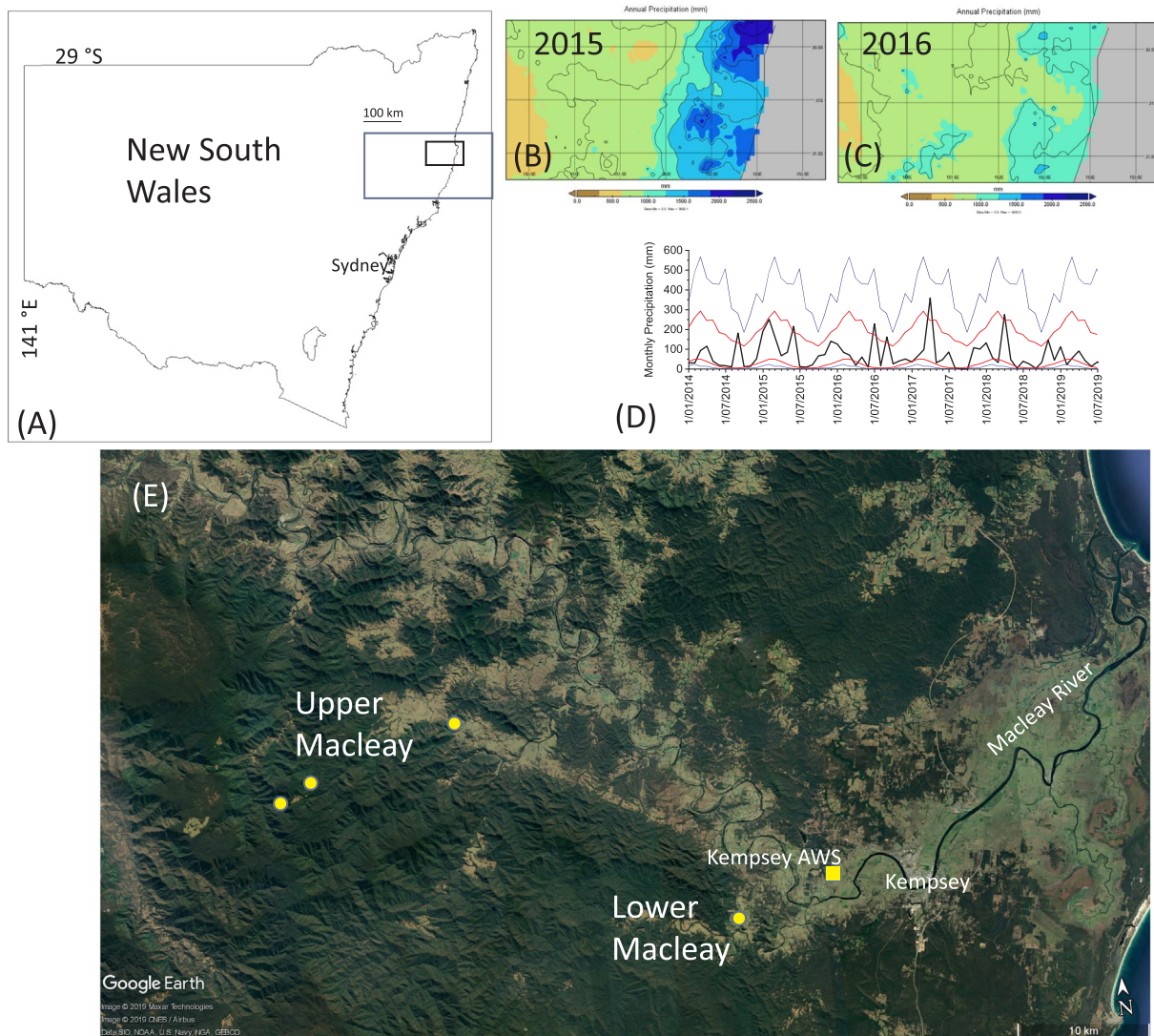   *E-mail address:* a.baker@unsw.edu.au (A. Baker).

Fig. 1. (a) Location of the Macleay Karst region. Large inset box shows the region displayed in (b) and (c). Smaller inset box shows the area displayed in (e). (b) Annual precipitation in mm in the wettest year (2015) for the Macleay Catchment (c) Annual precipitation in mm in the driest year (2016) for the Macleay catchment (d) Monthly precipitation time series in mm for the monitoring period for the Macleay catchment (black line) together with 1 and 99 (blue) and 10 and 90 (red) percentiles for the catchment (1910–2019). (e) Location map of the Upper and Lower Macleay cave monitoring sites (circles) and the nearest weather station (Kempsey automated weather station). All precipitation data is from the Australian Landscape Water Balance gridded data. Base image in (e) is from Google Earth, used with permission.

aquifers, the majority of the groundwater flux is in conduits, and the monitoring of wells (or bores) is unlikely to represent the direct recharge response as they are more likely to intercept and record the indirect response of secondary conduits, and have a low probability of intercepting primary conduits (Smart, 1999). Scanlon et al. (2006) review ~140 studies globally from arid and semi-arid regions (P/PET from 0.05 to 0.5) and show average recharge rates of 0.2 to 35 mm yr^{-1}, or 0.1 to 5% of long-term annual precipitation. Crosbie et al. (2010) compiled 172 Australian groundwater recharge studies to determine regression-based estimates of annual recharge from average annual precipitation. Crosbie et al. (2010) show that, for specific soil and vegetation classes, total annual rainfall could predict total annual recharge with 60% of the variance explained, and recharge for a given annual average rainfall in Australia was less than that determined by Scanlon et al. (2006) in their global analysis of recharge. For the Australian continent, Barron et al. (2012) modelled the rainfall recharge to groundwater using an unsaturated zone model and compared that to historical climate data and a range of climate, soil and vegetation parameters to obtain rainfall recharge estimates. In addition to soil and

vegetation controls, they observed that modelled recharge had a stronger correlation with parameters based on a rainfall intensity threshold as opposed to total annual rainfall. A non-linear relationship between recharge and rainfall was observed due to antecedent moisture conditions.

For regions where the precipitation water isotope 'amount effect' occurs (Dansgaard, 1964), a comparison of amount-weighted precipitation stable water isotopic composition to groundwater values, using different monthly rainfall amount thresholds, can determine a recharge threshold. Across sub-Saharan Africa, precipitation thresholds were also observed to govern the onset of recharge in both dryland and more humid environments; while larger thresholds were generally associated with increased aridity, they were also highly variable depending on the local variability in precipitation intensity, geology and soils (Cuthbert et al., 2019).

In a global analysis of fifteen long-term groundwater water isotope datasets, Jasechko and Taylor (2015) demonstrated a pronounced bias in tropical groundwater recharge to intensive rainfall months (> 70th intensity decile). Jasechko (2019) further reviewed the water stable

isotopic evidence that high-intensity rainfall contributes disproportionally to recharge in tropical and sub-tropical regions. Despite numerous limitations of this approach, including a requirement for there to be a precipitation isotope composition vs amount relationship and a single recharge source, Jasechko (2019) demonstrates that there is a wet season bias to recharge. Other examples of quantified monthly rainfall amounts that lead to recharge are (a) over 150–200 mm/month (central Australia, Harrington et al., 2002); (b) 190–200 mm/month (Caribbean carbonate systems; Jones and Banner, 2003) and (c) > 100 mm/month (Sydney Basin, Australia) and > 150 mm/month (Northern Queensland, Australia) Hollins et al. (2018).

Despite multiple methods that can be applied to derive recharge estimates and recharge thresholds, the latter have predominantly been determined using isotopic methods in tropical to sub-tropical environments where there is a precipitation water isotope amount effect. Not only are these isotopic methods spatially limited to regions where there is a water isotope amount effect, they also integrate over time and multiple events, which makes it difficult to discern details of the physical processes controlling recharge. Approaches that can determine diffuse recharge thresholds at the event-scale and which can be applied widely would therefore be of considerable value. In that regard, we report for the first time the use of high-temporal frequency and continuous discharge time series of drip water infiltrating into caves as an unsaturated zone physical method (Healy, 2010) to quantify the precipitation thresholds for diffuse recharge in an environment where annual P/PET is in the range ~0.6 to ~1.1. Continuous drip discharge time series from 2014 CE onwards, within and below the zero flux plane, in a karstified, fractured limestone, are presented from multiple caves of varying depths and vegetation cover in the Lower and Upper Macleay Valley of the mid-north coast of New South Wales, Australia (Fig. 1). Thirty-one recharge events, identified by increases in drip discharge, are compared to surface precipitation records to elucidate diffuse recharge thresholds for each recharge event. Results are compared to those simulated from a simple soil and karst water balance model and observed recharge thresholds and modelled soil and karst water storage capacity are compared to results reported elsewhere, and implications discussed in the context of the sustainable use of groundwater.

2. Site description and methods

2.1. Site description and monitoring network

The location of the cave monitoring sites in the Macleay catchment of the mid-north coast of New South Wales, Australia, together with hydroclimate characteristics of the region, are shown in Fig. 1. The climate of the mid-north coast of NSW, Australia is classified as temperate humid subtropical (class Cfa in the Köppen classification). Long-term climate statistics for the Bureau of Meteorology (BOM) Kempsey Airport Automatic Weather Station (AWS, shown in Fig. 1e), situated in the Lower Macleay Valley, is a mean annual temperature (MAT) of 18.6 °C and total annual precipitation (P) of 1218 mm. There is a strong seasonality in temperatures and seasonal bias in precipitation. Rainfall is highest during summer (November to March, Fig. 1d). The wettest months are in late summer (February mean 145 mm; March mean 162.9 mm) due to the location of the subtropical ridge being at its most southernmost extent, allowing the development of SE trade winds over the region and generally associated with an inland eastern low pressure trough which leads to convective rainfall over the region (Fig. 1c, d). Over the drip water recharge monitoring period, the MAT was similar to the long-term average (18.66 °C). Large inter-annual variability of P occurred over the study period (2014 CE 1229 mm; 2015 CE 1431 mm; 2016 CE 856 mm; 2017 CE 1227 mm; 2018 CE 872 mm); maps of precipitation for the wettest and driest years are shown in Fig. 1b,c. Annual potential evapotranspiration (PET) over the study period measured at Kempsey Airport was 1340 mm (standard deviation

48 mm) and annual P/PET varied between 0.62 (2016 CE) to 1.13 (2015 CE).

Daily rainfall and actual evapotranspiration data for the Upper and Lower Macleay cave monitoring sites was taken from the Australian Water Resources Assessment Landscape model (AWRA-L) version 6.0 (Viney et al., 2015; Frost et al., 2018). AWRA-L is a daily, distributed water balance model at 0.05° (~5 × 5 km) resolution, which simulates water flow through vegetation, upper and lower soil moisture stores and a groundwater store, with model outputs which include actual and potential evapotranspiration, runoff and deep drainage (Frost and Wright, 2018). Daily precipitation grids are produced from approximately 6,500 rain gauge stations and interpolated to a national grid (Jones et al., 2009) and this data is displayed in Fig. 1b,c,d. Actual Evapotranspiration is estimated from (1) water evaporated directly from the canopy interception, the upper soil water store and the groundwater store; (2) water loss by transpiration from the lower soil water store, the deep soil water store and the groundwater store.

The cave monitoring sites are situated in the Macleay Karst Arc (NSW DECC and Water NSW, 2010). The limestone in which the caves are formed 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 as part of the New England Fold belt. This has led to the limestone retaining low primary porosity and becoming highly fractured. It is highly karstified, with hundreds of known caves (NSW DECC and Water NSW, 2010). Due to low primary porosity of the limestone and the highly karstified landscape, recharge is hypothesised to be focused around surface karst features such as solutionally widened fractures and dolines (Berthelin and Hartmann 2020).

Six cave sites were selected for cave hydrological monitoring, determined as they were known to be hydrologically active, with the aim of monitoring caves of differing geomorphological settings, spatially spread through the Macleay Valley (Fig. 1e). All of the caves are wild caves situated within National Parks and many in remote and difficult-to-access terrain. A summary of cave characteristics is provided in Table 1 and photographs of the sites in the Supplemental Materials.

In the Lower Macleay Valley, Stalagmate © drip loggers were placed within the Yessabah Nature Reserve, a small, highly karstified limestone hill typified by dry and subtropical rainforest, poor to absent soil development, and extensive karren features (see Fig. S1). Drips in Deep Slide Cave were monitored at a depth of approximately 3–5 m below the surface from 2014 CE. Disturbance of the loggers by wildlife accessing the caves meant that these were relocated in 2017 CE, and a second cave monitoring site in Dam Cave was commenced from 2017 CE. Dam Cave monitoring sites were at an approximate depth of 3 m below the surface. Due to their shallow depth, both sites are considered to be above the zero flux plane. Deep Slide Cave contains an active, intermittent streamway, whilst Dam Cave is largely hydrologically inactive, with just a few active, speleothem forming infiltration waters. Both caves are approximately 50 m above the local water table, which is visible in caves at the base of the hill, and as standing water at the base of the limestone hill.

In the Upper Macleay, drip loggers were placed within the Mount Sebastopol, Willi Willi National Park and The Castles Nature Reserve. At Mount Sebastopol, loggers were placed in Daylight Cave from 2014 CE, and are located at a depth of approximately 16 m below land surface, just below the zero flux plane. The overlying land cover is former farmland, with native vegetation locally cleared, although native trees (*Olea paniculata, Ficus rubiginosa, Eucalyptus* spp., Fig. S2) occur in dolines and depressions above Daylight Cave, with large roots visible in the upper ~10 m of the cave. The cave is intermittently hydrologically active, and disturbance and damage to loggers during flooding has led to discontinuous data from this site.

The Castles Nature Reserve comprises dense forest cover. At Carter Cave, the overlying vegetation is subtropical rainforest (*dominant trees include: Argyrodendron actinophyllum, Dendrocnide excelsa, Ficus* spp.,

Table 1
Site descriptions. Where available, further cave descriptions can be found in the relevant issues of the Kempsey Speleological Society journal TROG.

Cave Name	Elevation -ASL (m)	Logger Depth below tag (m)	Northings	Eastings	Vegetation	Cave description	Reference
LOWER MACLEAY							
Deep Slide Cave	100	−3	−31° 06′	152° 41′	dry and subtropical rainforest	NNW orientated cave. < 100 m of 20-25° descending passage with intermittent active streamway	
Dam Cave	100	−3	−31° 06′	152° 41′	dry and subtropical rainforest	Shallow cave, max depth 5 m, total passage length 100 m	TROG 21(6) 1985
UPPER MACLEAY							
Daylight Cave	270	−16	−30° 567′	152° 29′	Cleared dry and subtropical rainforest with remnant vegetation	NE fracture-orientated cave. Hydrologically active. < 50 m of descending passage entered via doline.	TROG 15(5) 1976
Carter Cave	570	−5	−30° 58′	152° 22′	subtropical rainforest	NNE orientated cave. < 100 m of largely hydrologically inactive passages. Horizontal cave intercepted by present day hillside	TROG, August 1971
Coorumbene Cave	700	0	−30° 59′	152° 20′	subtropical rainforest	NW orientated cave with total passage length < 100 m	TROG 30(4) 1994
Carrai Bat Cave	630	−20	−30° 59′	152° 20′	subtropical rainforest	NW orientated cave comprising two wide passages of < 100 m length	

Cryptocarya obovata; Fig. S3) and the shallow cave (5 m below surface) is intercepted by tree roots (Fig. S4). As such, the drip loggers are situated above the zero flux plane. Two loggers have been continuously logging drip recharge since 2015 CE, and due to the undisturbed nature of the site, a further three loggers were added in 2017 CE.

Both the Carrai Bat Cave and the Coorumbene Cave are overlain by subtropical rainforest similar to that at Carter Cave (the vegetation near Carrai Bat Cave is shown in Figure S5). Both caves have been continuously monitored since 2017 CE (an example monitoring of a recharge zone in Coorumbene Cave is shown in Figure S6). Both caves are similar to the other monitoring sites, having < 100 m total passage that exhibits a preferred orientation, relatively shallow depth below surface (with Carrai Bat Cave the deepest monitored with loggers at 20 m below surface) and localised recharge zones.

The regional cave drip water monitoring network therefore comprises data from fourteen Stalagmate © loggers from six caves, with all loggers providing near-continuous time series for at least two years over the period September 2014-December 2019. Loggers were programmed to sum the number of drips in a 15-minute period, enabling data collection for ~ 11 months before logger memory capacity is reached. Two periods of no data occurred, between 5/4/2015 to 31/5/2015 and between 2/5/2018 to 4/6/2018, when the caves could not be accessed before logger memories were full. The first data gap resulted in recharge from a rainfall event in May 2015 being only partially observed.

2.2. Data analysis and modelling

Recharge events were defined as occurring whenever (1) drip rates first increase either from a baseline drip rate or from no recharge (zero drip rate) and (2) the drip water response has the properties typical of a karst hydrological response (e.g. rapid increase in drip rates, with varied patterns of drip rate decrease).

To determine rainfall recharge thresholds, the 7, 14, and 21-day antecedent precipitation was determined for the days prior to, and including, the day of recharge, to derive descriptive precipitation statistics for each period, for both the Lower and Upper Macleay regions. This approach accounts for the effect of a prolonged rainfall period on recharge (Barron et al., 2012) and allows for potential retardation of water flow through epikarst water stores.

Our recharge model (Fig. 2) is forced on a daily timestep with daily precipitation [mm/day] and actual evapotranspiration [mm/day], obtained from the AWRA-L model. Two 'free' parameters have to be determined, the overflow capacity $V_{OS,max}$ [mm] and a drainage parameter D [mm/day]. The overflow represents the threshold that initiates fast and concentrated recharge R [mm/day] after sufficient wetting up of the soil and epikarst. It conceptually represents the field capacity of
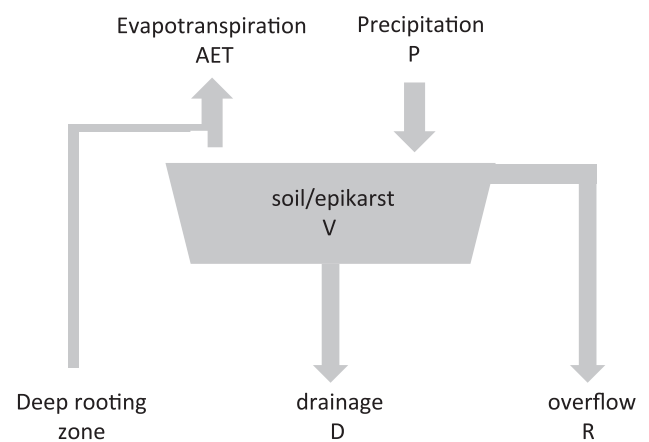

Fig. 2. Schematic description of the model. The simulations are made as daily timesteps, with the overflow representing the simulated recharge (R) in mm/day, which is compared to observed recharge in the cave drips.

the soil and epikarst and was considered previously in a similar manner by several karst modelling studies (Chen et al., 2017; Adinehvand et al., 2017). The drainage parameter represents diffuse continuous flow through narrow fissures mostly in the unsaturated epikarst and has already been included in preceding karst modelling studies (Hartmann et al., 2012; Gunkel et al., 2015).

Using a water balance, the model simulates the water storage of soil and epikarst by adding precipitation to the previous soil/epikarst storage value and subtracting actual evapotranspiration and drainage (with a constant value D). If actual evapotranspiration and drainage are larger than the remaining soil/epikarst storage, they are reduced accordingly. Any remaining AET above what can be taken from available water in the soil/epikarst store is conceptualised to derive from tree water extraction at depths lower than the modelled soil/karst store and is not explicitly modelled. Concentrated recharge is initiated when the soil/epikarst storage exceeds the overflow capacity $V_{OS,max}$. Total recharge is obtained by adding drainage D and concentrated recharge R [mm/d]:

$$V_{os(t)} = Max(Min(V_{os(t-1)} + P - AET - D, V_{os,max}), 0)$$

$$R = Max(V_{os(t-1)} + P - AET - V_{os,max} - D, 0)$$

with
P = precipitation [mm/day]
AET = actual evapotranspiration [mm/day]
$V_{os,max}$ = overflow capacity [mm]
D = drainage [mm/day]
$V_{os(t)}$ = soil/epikarst storage at time t [mm]
R = concentrated recharge [mm/day]

We compare the observed recharge events to the timing of modelled concentrated recharge R. Since observed drip rates are not easily transferrable into recharge volumes, we compare the timings of the observed and modelled recharge. We transfer the simulated recharge of the model into binary values (1: recharge event takes place, 0: no recharge takes place). We included a a 1-week buffer, as the drip response to rainfall varied from a rapid response (same day) to a lag of several days, depending on flow path. In addition, rainfall is a 24 h value until 9 am, but rainfall could be focussed within any part of that 24 h period. The resulting delay of observed drip response is not accounted for explicitly by the model. Instead, for the sake of parsimony, the one-week buffer is implemented. In order to obtain the best combination of the two model parameters, D and $V_{OS,max}$, we vary them systematically to maximise the number of agreements of observed and simulated recharge events. We also include a penalty (-1 event) when the model simulates an event that has not been observed. In our simulation approach, the model simulations can predict two types of error. The first is when an observed drip response is not simulated. The penalty was included in the model optimisation routine to penalise for the second type of prediction error, which is a simulated event without a corresponding drip response. Considering both types of error allow the optimised solution to an overall best - fit (maximum number correct recharge events, minimum number of incorrect recharge events). Model code and input data are available at: https://github.com/KarstHub/Simple-Water-Budget-Model

3. Results and interpretation

3.1. Hydroclimate, drip hydrology and recharge thresholds

Hydroclimate data (P, AET, P-PET) for both the Upper and Lower Macleay are presented in Fig. 3a-c for the period July 2014- July 2019. Daily precipitation is typically higher in summer than winter (Fig. 3a). Occasional daily precipitation totals exceed 100 mm (Upper Macleay Maximum: 176 mm; Lower Macleay Maximum: 181 mm). Median daily precipitation is close to zero (Upper Macleay: 0.2 mm; Lower Macleay: 0.1 mm). Daily rainfall at the Lower Macleay and Upper Macleay are

similar (Lower Macleay daily precipitation = 0.98 ± 0.01 Upper Macleay daily precipitation; r_s = 0.82), as are AWRA-L Lower Macleay daily precipitation and the nearby Kempsey AWS (Kempsey AWS daily precipitation = 1.06 ± 0.01 Lower Macleay daily precipitation; r_s = 0.85). Daily actual evapotranspiration has a strong seasonal cyclicity, with a daily median of 2.3 mm (Upper Macleay) and 2.2 mm (Lower Macleay) (Fig. 3b). Winter daily minimum AET (Upper Macleay: 0.6 mm; Lower Macleay: 0.4 mm) is higher than the median daily precipitation, therefore a daily water deficit (AET > P) is the median hydroclimate state over the period of observations. Maximum AET (Upper Macleay: 10.5 mm, Lower Macleay: 6.8 mm) is observed after very high rainfall amount events.

The cumulative water balance (Fig. 3c) shows an increasing water surplus over the monitoring period that is characterised by rapid increases in cumulative water balance after infrequent high-magnitude precipitation events, followed by many months of slow decrease in cumulative water balance. Slightly higher median precipitation and slightly lower median AET in the Upper Macleay compared to the Lower Macleay results in a higher cumulative water balance at the Upper Macleay.

The drip logger time series comprise over 960,000 data points, presented in Fig. 3d as hourly mean drip rates. The raw data is available as Supplementary Dataset 1. Thirty-one unique recharge events are identified (Fig. 2d), with < 10 L of water measured per drip site per recharge event. Summary information on the recharge events is provided in Table 2a, and details for all thirty-one recharge events can be found in Supplementary Table 1. Visual inspection of the precipitation and drip rate time series confirms they align with periods of precipitation. Only 45% (14 of 31) of the 31 recharge events were observed at the Lower Macleay, compared to 87% (27 of 31) at the Upper Macleay. Six recharge events that were only observed in the Upper Macleay occurred in periods where there were consecutive high rainfall events within a 21-day period (11/2015, 12/2015, 01/2016, 1/2018) (Supplementary Table 1). Each of the four periods did generate at least one observed recharge event at the Lower Macleay sites. On three occasions (20/06/2016, 11/08/2016 and 18/03/2017) at one cave site (Deep Slide Cave, Lower Macleay) we observe low volume (< 10^{-1} L), irregular response from a zero baseline after very high rainfall volumes during a period where only one drip logger was operational. We tentatively interpret these as recharge events, where the primary drip source moved location or was partially bypassed. A such, we consider them separately in further analyses.

Descriptive statistics for the 7, 14 and 21-day antecedent daily precipitation amounts for each of the 31 recharge events for the Upper and Lower Macleay are tabulated in Table 1. In the Lower Macleay, the median 7-day antecedent precipitation prior to recharge is 76.2 mm. The 7-day antecedent precipitation total contributes to the majority of the 14 day and 21-day antecedent totals (77% and 60% respectively), identifying 7-day antecedent rainfall as the most appropriate time period when considering diffuse recharge at these sites. The lowest 7-day precipitation needed to generate recharge was 33.3 mm. Not all periods of high 7-day precipitation led to recharge: three high precipitation events (> 150 mm over 7-days) led only to small drip responses as discussed previously, where the primary drip source moved location or was partially bypassed. In the Upper Macleay, the median 7-day antecedent precipitation prior to recharge is 79.4 mm. The minimum 7-day precipitation amount to generate recharge is 30.1 mm. The 7-day antecedent precipitation total contributes to the majority of the 14-day and 21-day antecedent totals (74% and 53% respectively), further identifying 7-day antecedent rainfall as the most appropriate time period when considering diffuse recharge at these sites.

3.2. Water balance modelling

The results of the water balance modelling are summarised in Table 2b, with additional information in Supplementary Table 1, and
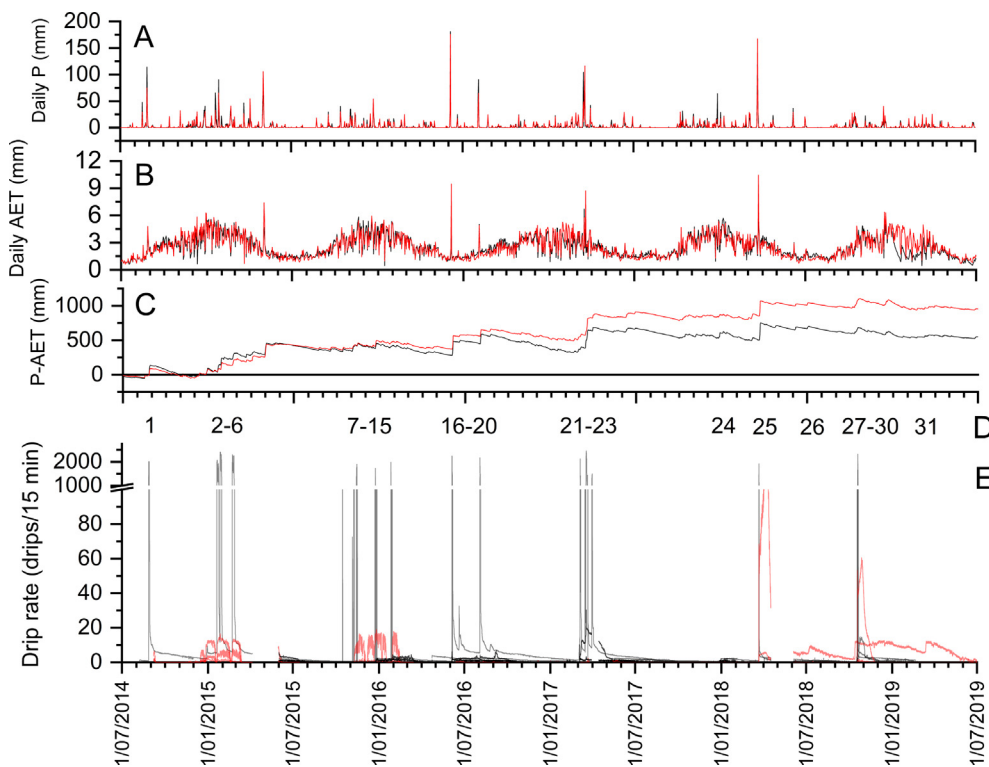
Fig. 3. (a) Daily precipitation from Lower Macleay (black) and Upper Macleay (red) from the AWRA-L. (b) Daily AET calculated using the AWRA-L. (c) Daily cumulative water balance (a water balance of 0 was assigned to 1/1/2014). (d) Event number. (e) All drip logger data for the Lower Macleay (red) and Upper Macleay (black).

time-series of model output in Supplemental Fig. S7. For the Upper Macleay, the optimal model configuration has a soil/epikarst overflow capacity of about 80 mm, with a drainage of 0.4 mm/day. The model correctly simulates recharge for 19 of the 27 observed recharge events. The optimum model configuration compared to a range of soil and karst storage capacities and drainage rates is shown in Fig. 4. Eight observed recharge events were not simulated by the model (shown in italics in Supplementary Table 1). These recharge events had 7-day antecedent precipitation < 81 mm/week and occurred in late spring and early summer: 20/01/2015 (49.5 mm/week), 5/11/2015 (60.7 mm/week), 8/11/2015 (75.7 mm/week), 26/01/2016 (45.1 mm/week), 27/01/2016 (50.7 mm/week), 29/01/2016 (50.8 mm/week), 30/12/2017 (54.4 mm/week), 17/12/2018 (81.0 mm/week). Six of these (in 01/2015, 11/2015 and 01/2016) were within three periods of consecutive recharge events, and in each case the water balance model failed to correctly estimate at least the first recharge event. The model simulates an additional three recharge events that were not observed (22/02/15 (86.7 mm), 05/04/15 (92.7 mm) and 31/03/17 (62.7 mm) and one during a period where no loggers were operational (03/05/15, 203.4 mm). The three simulated events where no recharge was

observed all occur in late summer and autumn.

For the Lower Macleay, the optimal model has a soil/epikarst overflow capacity of about 65.0 mm, with a drainage of 4.8 mm/day (Fig. 4). The model correctly simulates recharge for seven of the 14 observed recharge events (shown in Supplementary Table 1). The seven recharge events not simulated have 7-day antecedent precipitation < 83 mm, but otherwise have no relationship with season or periods of consecutive recharge events: 15/12/2014 (37.8 mm/week); 21/02/2015 (82.6 mm/week); 14/11/2015 (50.3 mm/week); 29/01/2016 (45.8 mm/week); 6/07/2018 (40.9 mm/week); 13/10/2018 (40.9 mm/week) and 14/03/2019 (33.3 mm/week). The model simulates an additional three recharge events, all of which were identified as potential recharge events from low volume drip responses at Deep Slide Cave: (05/06/16 (after 212.2 mm/week), 04/08/16 (after 149.5 mm/week) and 18/03/17 (after 283.7 mm/week). Two further recharge events were simulated for periods where no loggers were operational: (27/08/14 (157 mm/week), prior to site establishment and 02/05/15 (176.2 mm/week), due to no operational loggers. The misfits between modelled and observed recharge in the Lower Macleay, with seven recharge events not simulated after 7-day antecedent precipitation

Table 2

(a) Recharge threshold summary for the Upper and Lower Macleay (b) Water balance model summary.

| (a) Recharge thresholds (mm)								
	Lower Macleay				Upper Macleay			
	Antecedent precipitation				Antecedent precipitation			
		7-day	14-day	21-day		7-day	14-day	21-day
	MEAN	85.3	111.2	130.2	MEAN	97.6	124.5	153.4
	MEDIAN	76.2	98.6	127.1	MEDIAN	79.4	108.0	149.8
	MIN	33.3	43.1	43.4	MIN	30.1	32.6	47.9
(b) Water balance model								
	Lower Macleay				Upper Macleay			
Overflow Capacity (mm)	65				80			
Drainage (mm/d)	4.8				0.5			
Number of observed events	14 (+3 low volume events, with indistinct hydrographs)				27			
Number of observed events correctly simulated	7 (+3 low volume events with indistinct hydrographs)				19			
Number of observed events not simulated	7				9			
Number of simulated events not observed	0				3			
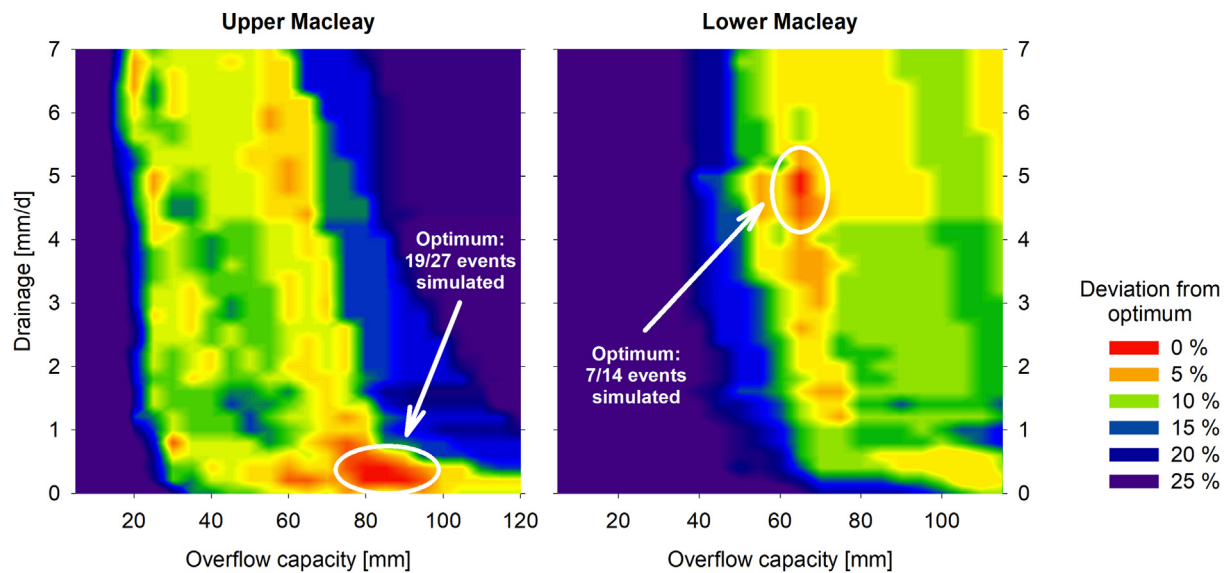
Fig. 4. Optimum model simulations shown for overflow capacity from 0 to 120 mm and drainage from 0 to 7 mm/d. The deviation from optimum is shown as a percentage of the optimum fit.

of < 83 mm, and only two out of nine recharge events correctly simulated for the same 7-day antecedent precipitation, suggests that the soil/epikarst store is bypassed before storage capacity is reached. This can be conceptualised as focussed recharge into fractures from bare limestone surfaces.

4. Discussion

4.1. Comparison of observed rainfall recharge thresholds and modelled soil/karst storage capacity

We observe a median rainfall recharge threshold of 76 mm/week (Lower Macleay) and 79 mm/week (Upper Macleay), with recharge at lower antecedent precipitation possible, to a minimum of 30 mm/week. More recharge events are observed in Upper Macleay than the Lower Macleay. The observed median rainfall recharge thresholds are consistent with our simple soil/karst water balance model, which simulates soil/karst storage capacities of about 80 mm/day with 0.4 mm/day drainage (Upper Macleay) and 65 mm/day with 4.8 mm/day drainage (Lower Macleay). The combination of observational data and modelling helps further elucidate groundwater recharge processes in the karst limestones of the Macleay region.

In the Upper Macleay, observed recharge events with relatively low seven-day precipitation amounts in late spring/early summer months were not successfully simulated using our simple soil/karst model. Furthermore, additional recharge events were simulated by the model in late summer months which were not observed. These discrepancies between model and observation lead us to hypothesise that either (1) AWRA-L AET is overestimating the actual AET at the sites, (2) a significant proportion of AET is taken from deeper in the profile than the modelled soil/epikarst store, or (3) the model assumption of a constant soil/karst storage volume is not constant over time. For the former two hypotheses, we run additional model simulations using arbitrarily decreased values of daily AET (75%, 50%) Figure S8). These demonstrate that decreasing AET improves the fit between observed and simulated recharge only at the Upper Macleay, with the best agreement when AET is reduced to 55–60% of its actual value, resulting in the model correctly simulating 23 or 24 of 27 recharge events, with 6 additional events simulated (Figure S8 gives examples for 75% and 50% of actual AET values). With subtropical rainforest cover at these sites and tree roots systems that can penetrate beyond the depth of the caves, we infer from this result that either AWRA-L is an overestimate of total AET for

this site, and/or up to 50% of the actual AET is from tree water use from the root network below the elevation of the caves. For the third hypothesis, a soil/karst storage volume that increases over the summer season would explain the discrepancy between model and observations. This is most simply conceptualised as multiple bucket model, with two connected stores, one of which may represent the deeper regions of the epikarst or karst vadose zone, which drain over the summer season, increasing the overall storage volume (Fig. 5a).

At the Lower Macleay, seven out of eight observed recharge events which had antecedent 7-day precipitation below the median recharge threshold were not successful simulated by the soil/karst model. There were no temporal trends or patterns in these unsimulated recharge events, suggesting no relationship with seasonal changes in soil or karst water storage capacities. Given the discrepancy occurs for periods where antecedent precipitation amounts were low, we hypothesise that there is also focussed recharge at these sites which bypasses the soil/karst store and which is not captured by the soil/karst model. This can be conceptualised as runoff over exposed limestone surfaces which is routed directly to the karst via solutionally widened fractures (Fig. 5b). We also have a lower overflow capacity in the Lower Macleay model, indicating there is on average less soil/epikarst storage compared to the Upper Macleay. In addition, the relatively higher drainage term (4.5 mm/day) in the soil/karst model at this site helps explain the lower number of recharge events observed at the Lower Macleay sites compared to the Upper Macleay sites. For precipitation events of equal magnitude at both sites, which have similar soil/karst storage thresholds, the model simulations would generate fewer recharge events for the higher draining soil/karst store at the Lower Macleay sites. We infer that at the Lower Macleay, the higher drainage term represents recharge which was not observed by the drip loggers. For example, this may occur via higher volume flows to cave streams and seeps, as well as via drips not included in our monitoring network.

The AWRA-L model produces a 'deep drainage' output, which is an estimate of the water that drains from the bottom of the modelled deep soil layer (6 m) into the groundwater and is used to generally describe diffuse groundwater recharge. The deep drainage output is compared to long-term national groundwater recharge products (Frost et al., 2018) and is of low confidence due to the poor availability of quality data to define the soil properties of the deep soil layer (BOM, 2019). AWRA-L modelled deep drainage at both the Upper Macleay and Lower Macleay sites varied seasonally from 0.05 to 0.15 mm/day, with an annual winter maximum. Modelled AWRA-L deep drainage therefore has no
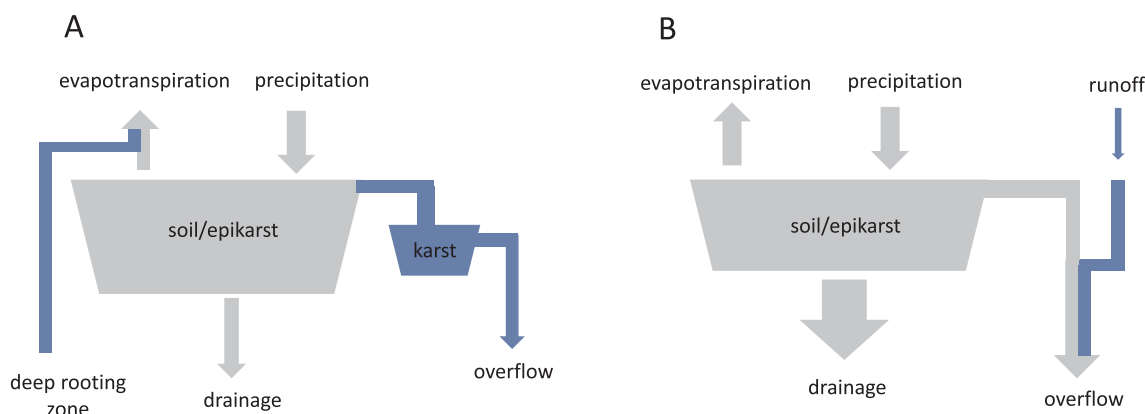
A

B

Fig. 5. Conceptual water balance models with model refinements in blue. (a) Upper Macleay, with a possible second karst store that increasingly holds no water through the summer and a contribution to evapotranspiration from below cave depth. (b) Lower Macleay, with a large drainage volume and a contribution to the overflow from a bypass flow from the surface runoff.

relationship to the observed timing of groundwater recharge at both sites, and confirms low confidence of its use for these sites.

4.2. Comparison with other recharge threshold and soil storage estimates

The recharge thresholds of 76 mm/week and 79 mm/week determined here using a direct physical method, for an environment where P/PET ~ 0.8, compare favourably to monthly-resolution recharge threshold estimates for Australia using isotope techniques (Hollins et al., 2018). To the south, in the sandstones of the Sydney region, with a temperate climate and P/PET = 0.88, Cendón et al. (2014) show that monthly precipitation > 100 mm leads to recharge. To the north, in the arid (P/PET = 0.18) Lawn Hill karst of Mount Iza, Hollins et al (2018) show that groundwater isotope composition reflects the large rainfall events which are associated with cyclonic and monsoonal activity in the summer months, and recharge of groundwater occurs only after intense rainfall events of > 150 mm/month. In the Ti Tree Basin of the arid central Australia (P/PET = 0.18), Harrington et al. (2002) similarly demonstrated that recharge throughout the basin occurs only after intense rainfall events of at least 150 to 200 mm/month. That monthly rainfall recharge estimates are consistently higher than our 7-day rainfall recharge measurements could suggest that the some of the monthly rainfall does not contribute to recharge. Our observed recharge thresholds are also consistent with those modelled at an annual resolution for Australia by Barron et al. (2012), who found the best correlation between recharge and annual precipitation parameters was with those related to rainfall intensity (for example, the aggregated annual precipitation for > 20 mm precipitation days) and not annual rainfall amount.

We observe a maximum of thirty-one recharge events over a five-year period, with a median recharge threshold of 76–79 mm/week. We use this threshold to investigate the frequency of such precipitation amounts occurring. Only fourteen calendar weeks over the five-year period have 76 mm or more precipitation at both the Upper and Lower Macleay sites (5% of all weeks). The majority of weeks with > 76 mm cumulative precipitation occurs in November – March (ten of fourteen weeks in the Lower Macleay, nine of fourteen weeks in the Upper Macleay), suggesting that groundwater recharge is more likely in these months. This aligns with results from the meta-analysis of global groundwater recharge data by Jasechko and Taylor (2015) and Jasechko (2019), where water stable isotopic evidence suggests that high-intensity rainfall months contribute disproportionally to recharge in tropical and sub-tropical regions.

Finally, we can compare our calibrated storage capacities of about 65 mm and 80 mm of our simple soil and karst water balance model to other applications of simple bucket type models. In Spain, Hartmann

et al. (2013) found soil storage capacities of 82 to 98 mm. In temperate semi-arid Australia, Cuthbert et al (2014) found a maximum soil moisture deficit of 87 mm needed to be overcome prior to cave drip water recharge. Schmidt et al. (2014) found 70–190 mm at the Jordan Valley for their soil storage reservoir. Heilman et al. (2014) measured 70 mm of soil storage capacity at a ~20 cm woodland soil at the Edwards Plateau, Texas, USA. We therefore note a broad agreement of storage capacities across these sites. However, this storage capacity might not just be located in the soil, but as demonstrated for our Macleay sites which can have limited or no soil cover, also be located in the epikarst. Refinements to the simple model structure proposed in Fig. 5, incorporating multiple reservoirs and soil by-pass flows to better explain water recharge processes in karst, are also in agreement with previous conceptualisations (e.g. Hartmann and Baker, 2017) and modelling studies of karst unsaturated zone hydrology. For example, water movement to individual drips has required a by-pass flow to explain drip water and speleothem geochemistry time series at a cave in NW Scotland (Baker et al., 2012) and multiple reservoirs were necessary to model drip water chemistry in a Western Australia cave (Treble et al., 2019).

5. Conclusions

We demonstrate the utility of a network of drip loggers to determine rainfall recharge thresholds in karst environments. By making direct physical measurements of water movement through the unsaturated zone, the method can unambiguously determine rainfall recharge thresholds from other recharge mechanisms. As a physical technique that does not require water isotope measurements, it can be applied to any karst region globally, and in particular in regions where there is no isotope amount effect. The high-temporal frequency of data collection allows the investigation of antecedent conditions at higher resolution than isotopic techniques, which typically are monthly resolved. By combining observed recharge thresholds and simple hydrological models, further insights into the recharge process can be elucidated.

Our approach has the potential to better understand a range of groundwater recharge processes in karst systems. Use of drip loggers can have limitations. For example, loggers are best deployed where there is a single, fixed drip source; at very high discharges, the loggers are unable to resolve discrete drips; not all drip sites fall from a height sufficient to be detected by the pressure transducer; drip volumes may not be constant with respect to drip rates (Collister and Mattey, 2008). Despite these limitations, quantification of the spatial and temporal heterogeneity of recharge in karst would be possible using a larger network of drip loggers. Loggers deployed in vertical transects can be used to identify the depth of the zero flux plane and its variability,

potentially including the identification of tree water use through diurnal drip rate variations (Coleborn et al., 2016). Analysis of recharge at paired sites with different vegetation types can be used to better quantify the transpiration control on recharge thresholds. Although we have limited our analysis to recharge thresholds, our approach leads the way to recharge volume estimates that can be made when coupling drip logger data with upscaling approaches that include catchment scale modelling and in-cave lidar mapping of recharge sources (Mahmud et al., 2016).

CRediT authorship contribution statement

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2020.125001.

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