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On the 2017/2018 drought at Jenolan Caves

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Abstract

A severe drought is currently (September 2018) affecting Jenolan Caves, NSW, both above and below ground. Rainfall data are analysed to show that this drought has surpassed the once-in-25 years level and is now a once-in-a-century event. This is the second-driest period since records began in 1895, and the driest in 115 years. The water levels observed in rivers, pools and sumps of selected caves are documented, revealing the driest subterranean conditions observed there to date. Underground river flow rates are at record lows. A warming climate is enhancing the severity of the present drought, compared to historical events of similarly low rainfall.

1 Introduction

The Jenolan Caves Limestone dates to the mid-Silurian (~430 Ma) and exists as a narrow belt that runs predominantly NNW-SSE with a perpendicular width ranging from 50 to 350 m (Branagan and others 2014). The geology has been described by Shannon (1976), with updates from Cooper (1990, 1998) and Branagan and others (2014). A map is provided in Figure 1. The road to Jenolan Caves cuts through the limestone at the natural Grand Arch, dividing the limestone into a southern area of 2.3 km and a northern area that outcrops nearly continuously for 4 km with isolated outcrops for a further 3 km. It is the Northern Limestone that contains the largest caves and has a much larger water catchment, hence is the focus of this paper.

To the north of the Grand Arch, the Jenolan River has carved a gorge into the limestone. This gorge transitions to alluvial flats around 1 km north up the valley at Playing Fields. The Jenolan River only flows during flood, but its dry bed can be followed north through gorges and across alluvial flats for up to 5 km, depending on recent rainfall, beyond which the river is on slate and always flowing. The Jenolan River and various minor tributaries divide the limestone into several bluffs.

Throughout the valley the limestone dips to the west, sometimes near-vertically, and is overturned in places. The full depth of the limestone is unknown, though dry sections of Mammoth Cave can be found 180 m below the surface. Slug Lake in Mammoth starts 65 m below ground, has been dived 96 m, and continues deeper out of sight (Vaughan-Taylor & Ryan 2000). Clearly, the near-vertical bedding allows large quantities of water to penetrate deep underground.

A hydrological model for Jenolan Caves was proposed by Shannon (1976) and Dunkley (1976). It includes three principal components: (i) the surface flow, derived mostly from the Jenolan River as it flows off the slate and into the U-shaped valley, supplemented by minor tributaries entering the valley from the east and west; (ii) the subsurface reservoir, consisting of alluvial storage located towards the northern end of the valley, being approximately 15 ha in area and ranging from 15 to 40 m in depth (Kelly 1988). This aquifer is usually assumed to have 20% porosity (Cooper & Staraj 1996) and it follows that its capacity is around 2.5 Gl (Cooper 2010); and (iii) the Jenolan Underground River (JUR) and underwater lakes that exist in voids in the limestone, some of which have been observed in drought for this work.

There are many stream sinks on the surface conducting water down to the subsurface, but with limited capacity (Figure 2). Hence under heavy rain conditions, or when the subsurface reservoir is full, the surface stream advances down the valley. In heavy flood, the surface stream flows all the way to the Grand Arch; in drought the low stream flow sinks into the alluvium as it leaves the slate. The latter describes the conditions observed at Jenolan Caves during this work (Apr – Aug 2018).

The exact path and location of the JUR are unknown north of Mammoth Cave. Given the dip of the limestone, it is expected that the river is located further west with depth beneath the surface, as seen clearly in the development of cave passage in Mammoth. It may therefore be expected that the

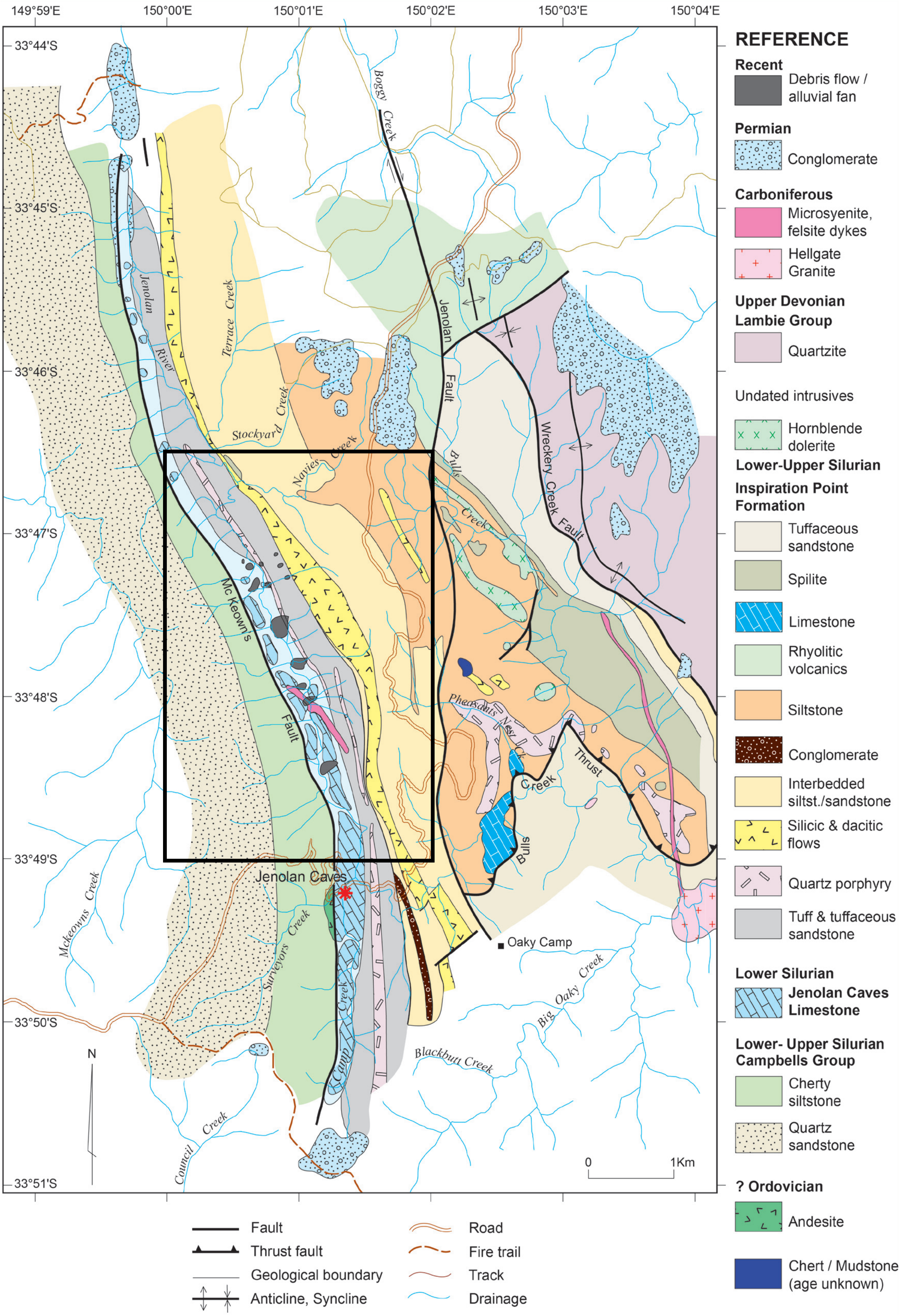

Figure 1: Geology of the Jenolan Valley, according to Branagan and others (2014). The unlabelled layer in the valley floor between the Jenolan Caves limestone bluffs is also debris flows / alluvial fans. The black outline shows the region that is annotated in Figure 2. *Reproduction by permission of author and journal.*

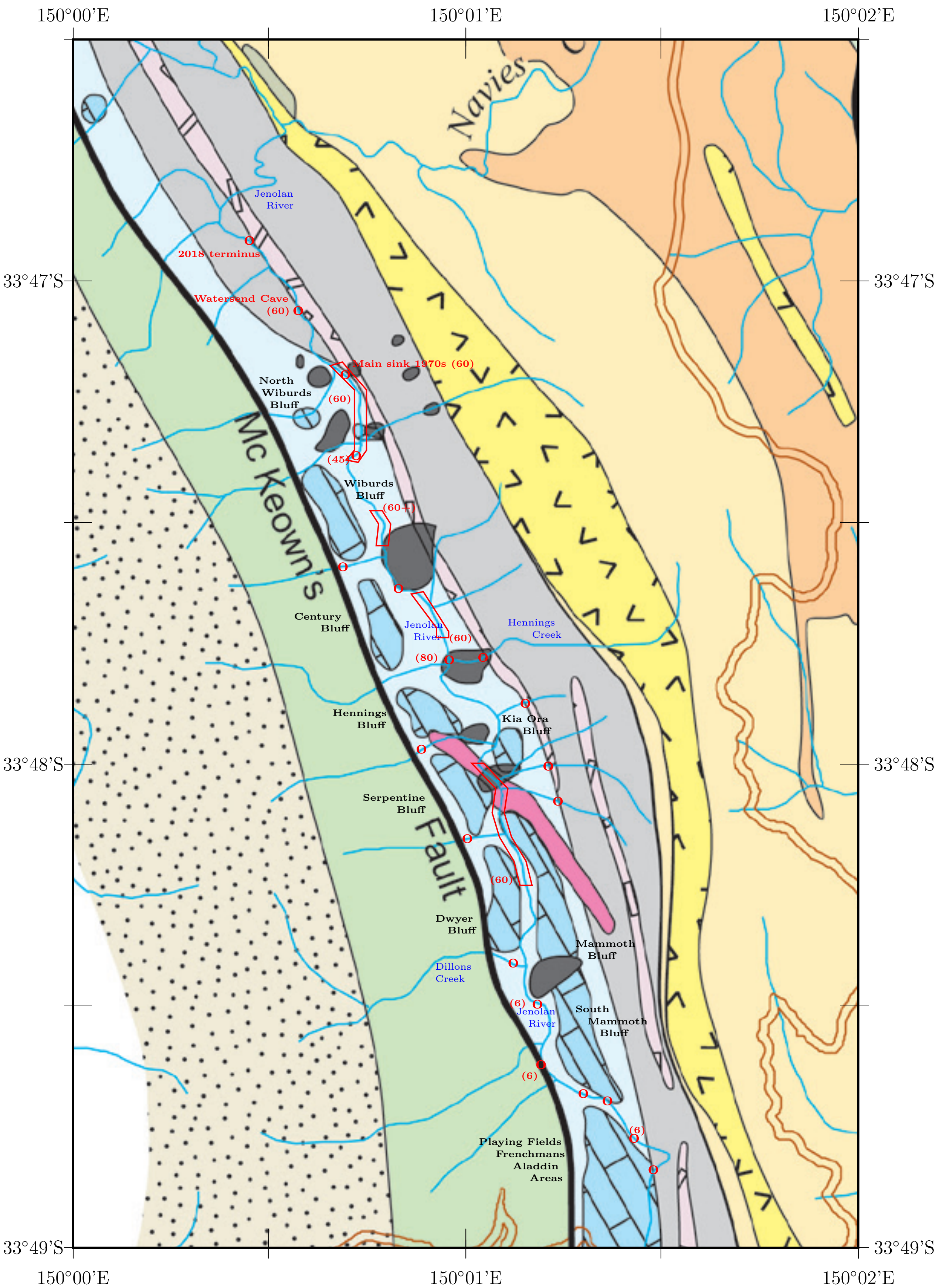

Figure 2: The Northern Limestone, enlarged from the map in Figure 1. See there for key. Stream sinks and their capacities from Shannon (1976) are highlighted in red, with several new additions, particularly sinks in side creeks from Cooper (pers. comm.). Sink positions are true with respect to the river, but some surface geology is in need of updating (Cooper, in prep.).

JUR lies under the limestone on the western side of the valley (Staraj & Cooper 1996). The JUR is first observed in the southern section of Mammoth Cave, where it is known as Lower River. It emerges from a hole in the western wall, is exposed for less than 20 m, then disappears again into a hole in the eastern wall. It later joins Slug Lake approximately 6 m below the lake's surface (or less in drought, when the water level is lower). It is audible or visible near the Lower River area of Mammoth Cave through slots or connected bodies of water such as Grinning Monster Lake. It was dived upstream to −50 m by Rod Obrien before becoming too dangerous to dive further (described by Johnston 2014). After becoming lost in Slug Lake, the JUR is next seen in Spider Cave, another kilometre downstream. Its path between Mammoth and Spider caves is unknown. However, once picked up at End Zone, at the northern end of Spider Cave, its path can be followed or dived south all the way through the show caves to the Blue Lake.

The subsurface reservoir appears capable of supplying water to the JUR even in extended droughts such as the present one. Cooper (2010) argued that the reservoir can supply 60 l/s for ~450 days. Lower River has never been observed to stop flowing, though its flow rate does change from around 60 l/s in drought to well over 500 l/s in flood,[1] with a normal flow rate of around 140 l/s.

Drought and flood each offer conditions that can further our understanding of karst landscapes. Hydrology based on flood events can shed light on potential connections between caves and thereby suggest opportunities for exploration and linking caves. At the same time, as flood waters recede, stream sinks become more obvious and their capacities can be measured. On the other hand, floods create sumps and can exclude large sections of cave from exploration for some time. During drought, sumps can dry out and allow for rare access.

Cooper (2010) noted that the northern catchment at Jenolan Caves is 25 km^2; the southern catchment is 2.7 km^2. Given that each mm of rain contributes 1 Ml of water per km^2, then a modest rainfall of 4 mm dumps 100 Ml into the northern catchment. Hence, downpours can bring volumes of the order of 1 Gl. While this is the approximate capacity of the alluvial reservoir, much of this water will be absorbed in topsoil before it can be channeled into the valley floor. Nonetheless, floods can occur very rapidly indeed when the alluvium is already charged. Droughts, on the other hand, develop on timescales of around a year.

In this article, rainfall data are analysed for evidence of a severe drought, accompanied by observations of changing conditions underground. While this drought has been developing since April 2017, it only came to media attention around April 2018. In the greater Sydney area, some major reservoirs such as the Cataract and Cordeaux dams are down on capacity by more than 50% compared with the same time last year. The largest of these reservoirs, the Warragamba Dam, lost 22% of its volume, corresponding to 450,000 Ml of water. State-wide the drought is having a devastating impact on farming. In Sect. 2 the rainfall data and processing of those data are described. Sect. 3 shows how these rainfall data indicate a severe and ongoing drought. In Sect. 4 it is shown that the climate has been warming over the past half-century and it is argued that this intensifies the drought. Sect. 5 documents observations of water levels and flow rates at Jenolan Caves.

2 Rainfall observations

Rainfall data for Jenolan Caves (station number #063036) were downloaded from the Australian Bureau of Meteorology website.[2] Rainfall data were first collected for Jenolan Caves on 1 Apr 1895, and were taken daily almost uninterrupted until Mar 1976, when a hiatus of 10.8 yr began. Since the resumption of observations on 1 Jan 1987, there have been only minor interruptions to data collection (Figure 3).

In this paper the primary interest is in relative differences in rainfall as indicators of drought. While the absolute rainfall amounts are unquestionably important, there is some concern about the suitability of the Jenolan Caves station for this purpose, due to its location near a wall that would likely cause the rainfall to be underestimated. However, comparison with two nearby stations partially allays this concern. Little Hartley, 17.3 km to the north-east, and Oberon Springbank[3], 23.9 km to the north-west, each have annual mean rainfall totals *lower* than Jenolan Caves, at 777.0 and 837.2 mm, respectively, compared to Jenolan Caves' 961.4 mm. The higher rainfall at Jenolan Caves is likely because the station, at 792 m, is

1: It is not possible to observe the maximum flow rate of Lower River in flood, because this area becomes inaccessible.

2: http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_ display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=063036

3: This station appears to have changed name to Oberon Albion St. in 2018.

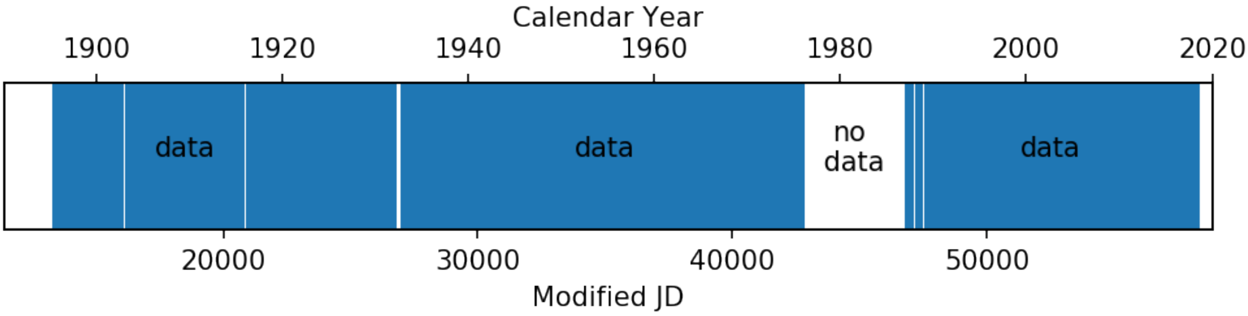

Figure 3: Coverage of rainfall data at Jenolan Caves, station #063036. Blue-shaded regions denote dates with rainfall coverage, while white regions have no data. The most recent blue shading extends to the time of writing (15 Sep 2018). The bottom axis is modified Julian date, defined as JD−2 400 000.5.

Table 1: Weather station data. The penultimate column gives linear distance from Jenolan Caves and the final column gives the mean annual rainfall. The Katoomba station is not used for rainfall analysis, but is used for temperature analysis in Sect. 4.

Name	Number	Lat. deg.	Long. deg.	Altitude m	Opened	Dist. km	Mean mm
Jenolan Caves	063036	−33.82	150.02	1792	1895	10.0	961.4
Little Hartley	063072	−33.70	150.13	1655	1951	17.3	777.0
Oberon Springbank	063063	−33.67	149.83	1053	1888	23.9	837.2
Katoomba Murri St	063039	−33.71	150.31	1015	1895	29.1	(1401.9)

surrounded on all sides by hills over 1100 m within a few kilometres. Details on the stations are given in Table 1. The large and unpopulated Kanangra-Boyd National Park lies to the south and east of Jenolan Caves, leading to a paucity of nearby weather stations in those directions.

Rainfall values are occasionally provided as accumulated totals, sometimes spanning a few days. Days within the accumulated interval are left with no data, giving the appearance of a gap in the data. On these days within the accumulated interval, the amount that fell is set to zero, thus treating the data as if all the rain over the interval fell in the final day. The interval is never greater than five days; only once in the entire record for Jenolan Caves is the interval five days, and only five times is the interval four days.

The nearby stations at Little Hartley and Oberon Springbank serve another useful purpose in filling gaps in data collection at Jenolan Caves. One of the summary statistics considered here is the cumulative rainfall over one-year periods (but not necessarily calendar years), which is unreliably computed when there are gaps in the data. For single-day gaps that are not due to accumulation of rainfall totals, such as 10 Sep 2016, and the occasional month-long gap such as Dec 1988, the use of data from nearby stations is useful and acceptable. Care is taken in quoting results from the 10.8-yr gap between 1976 and 1987, and throughout this article note is made of where this has been done.

To illustrate the validity of importing observations from nearby stations in this way, the correlation between rainfall totals is shown in Figure 4. The Spearman's Rank correlation coefficients between each station and Jenolan Caves are both 0.66. Outliers are likely due to thunderstorms affecting one station only.

When importing data from the two nearby stations, corrections are made for the difference in annual rainfall at these locations. The correction factor is the ratio of annual rainfall at the relevant locations. Thus when calculating the missing Jenolan Caves rainfall from the Oberon Springbank rainfall, the values are multiplied by (961.4/837.2 =) 1.148. Similarly, the factor for Little Hartley is 1.237. If both Little Hartley and Oberon Springbank have data available, the mean of their corrected values is used.

Note that Figure 4 suggests that rainfall at Jenolan Caves tends to be quite localised. This is consistent with field reports. In his article *Jenolan: Where it never rains but it floods!*, Staraj (1989) noted that on a seemingly dry Jenolan weekend[4], where it hadn't rained in Sydney for a few days prior, the surface creek was flowing in its usually dry bed and sinking as far south as Spider Cave.

4: The trip dates were 1–2 July 1989. Rainfall over the 5 days prior was [0.0, 0.8, 1.4, 1.6, 0.0] mm. While this is probably insufficient to cause the surface creek to flow, the week before that saw 53.6 mm, which is three quarters of the median June rainfall.

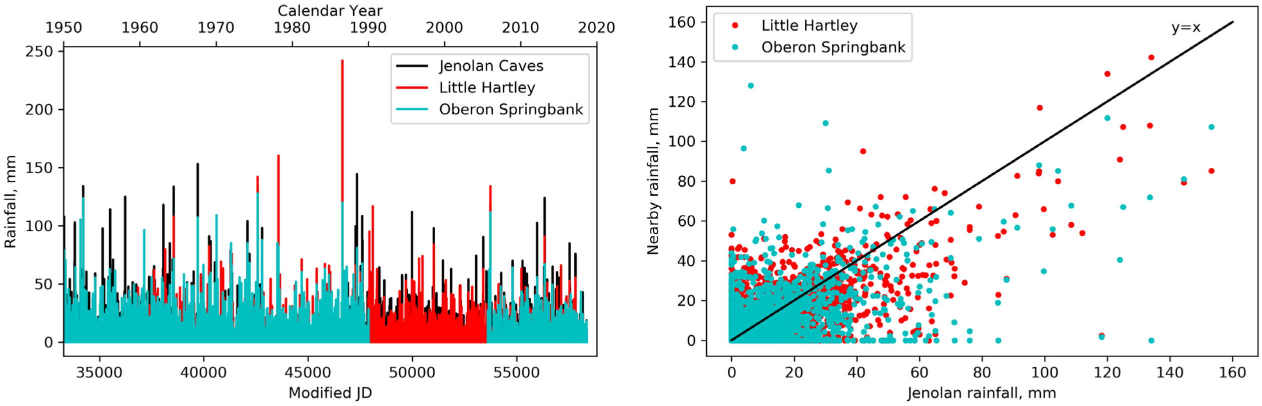

Figure 4: *Left:* Rainfall at the three sites since 1950, indicating correlation between sites at least for the larger rainfall events, though Jenolan Caves generally receives more rain in such events. For better visibility, lines have thicknesses greater than one day, giving the false impression that the rainfall never reaches zero. *Right:* The *y* axis shows how much rain fell at nearby sites on occasions where *x* mm fell at Jenolan Caves. Data are shown for each day on which data overlap between Jenolan Caves and another station. The diagonal line is not a fit to the data, it is the line *y*=*x* to guide the eye. This panel also shows that Jenolan Caves receives more rain than nearby sites.

3 Evidence for drought in rainfall data

Comparison of rainfall totals year-by-year reveals that 2017 was the driest year of the decade so far, and 2018 is the driest start to a year this decade as well. In fact, at no time in the past 30 years has a year started with anywhere near as little rainfall as 2018 has to-date (analysis fixed at 15 Sep 2018). Comparisons for the past 30 years are shown in Figure 5. Note that 1965, 1940 and 1902 are the only three years to have started drier (to 15 Sep) than 2018 (not shown in the figure, and excluding the hiatus years). Only 346 mm fell to 15 Sep in 2018.

The end of 2017 was dry and the start of 2018 was dry, hence the total rainfall over the 365-day interval ("1-year cumulative rainfall") was extremely low – much lower than any time in the previous 30 years (Figure 6). This way of analysing rainfall data makes droughts much clearer in the data, and better highlights their duration and severity. It is also more meaningful than plotting calendar years, since the levels of lakes and flow rates of rivers are insensitive to our choice of calendar.

The same data also reveal changes in rainfall on time-scales of decades. The period c.1895–1940 was generally dry, with a particularly dry period in the late-1930s to 1940. From the mid-1940s to the mid-1950s rainfall increased dramatically and was quite erratic from one year to the next. Then a generally wet period followed, lasting until the late 1970s, which included the largest flood to affect the Northern Catchment on record, in 1975 (Welch 1975). For the period around 1980 caution must be exercised because data are only available by importing from nearby weather stations, but the late-1970s and early-1980s were dry, consistent with field reports. The late 1980s and 1990 were particularly wet years, with 1990 being the last year in which a lake was observed in Wiburds Lake Cave (Cooper 2010). Since the early-1990s, Jenolan Caves has been relatively dry, except for a blip in 2010. This might be identified as the "Millennium Drought" which stretched from the mid-1990s until the terminating La Niña in 2010-2011. However, after the La Niña, the rainfall appears to have returned to "Millennium Drought" levels that are comparable to rainfall before the 1950s. The data do not go far back enough in time to establish a particular periodicity to this variability, nor to assess whether anthropogenic effects are at play.

It is difficult to compare the relative rarity of floods and droughts, partly because the timescales involved are different: droughts take time to develop but last a long time, whereas floods are more frequent but shorter lived. One can make comparisons against over-simplified scenarios, though, to see how rare extreme-weather events of each type are.

A downpour of 50 mm supplies around 1.25 Gl of water to the northern catchment, which is half of the reservoir volume. Thus, if the reservoir is more than half full, there will be a flood. Of course, if the reservoir is already full, much smaller amounts can cause flood, but the reservoir might also be less than partially filled when the hypothetical 50-mm downpour occurs, so let us take that as a first estimate. That gives us 177 such events in the rainfall record since records began in 1895. That seems approximately correct for this location: around two flood events occur per year, even if

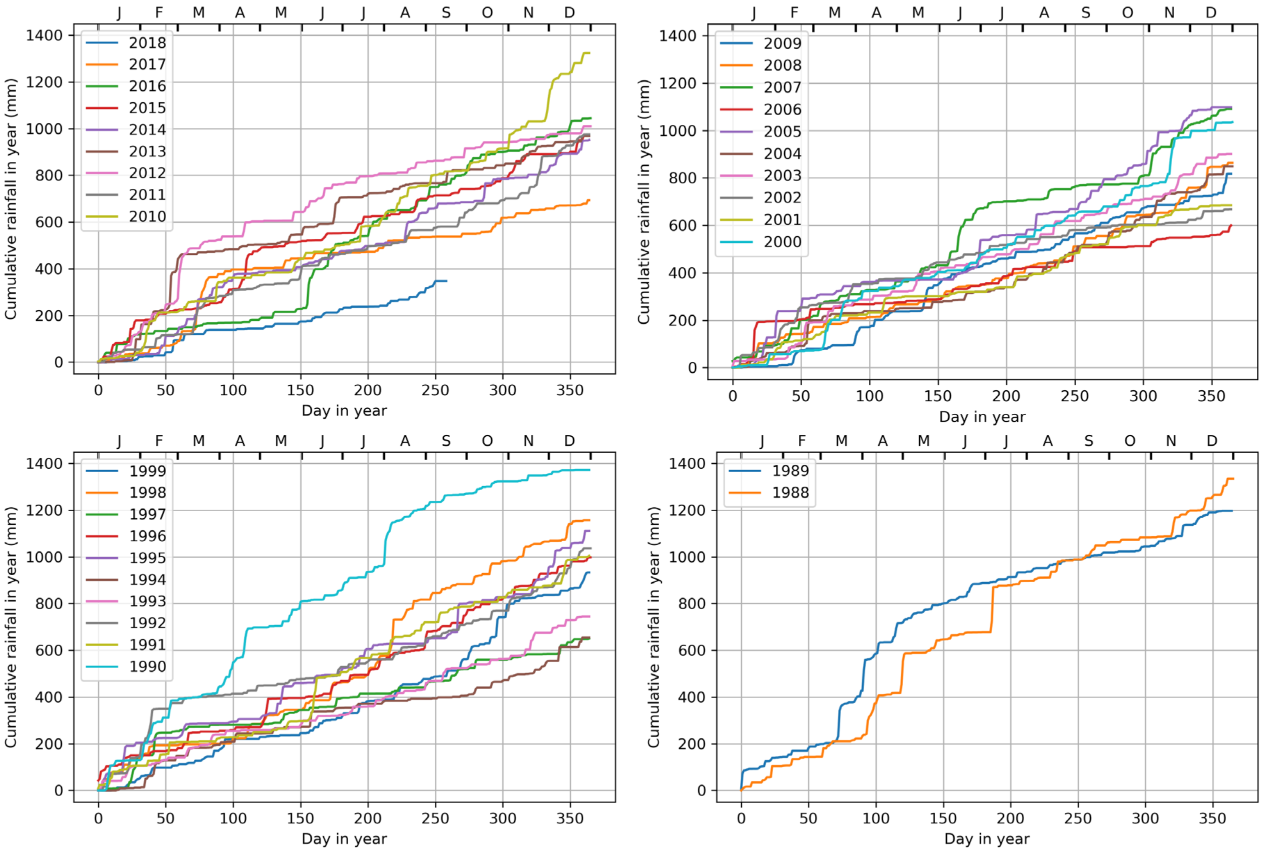

Figure 5: Year-by-year cumulative rainfall comparisons for the past 30 years, separated by decade. Rainfall data for the Jenolan Caves station are unavailable for the rest of the 1980s (Sect. 2). The mean annual rainfall at this location is 961 mm. Panels all have the same vertical scale.

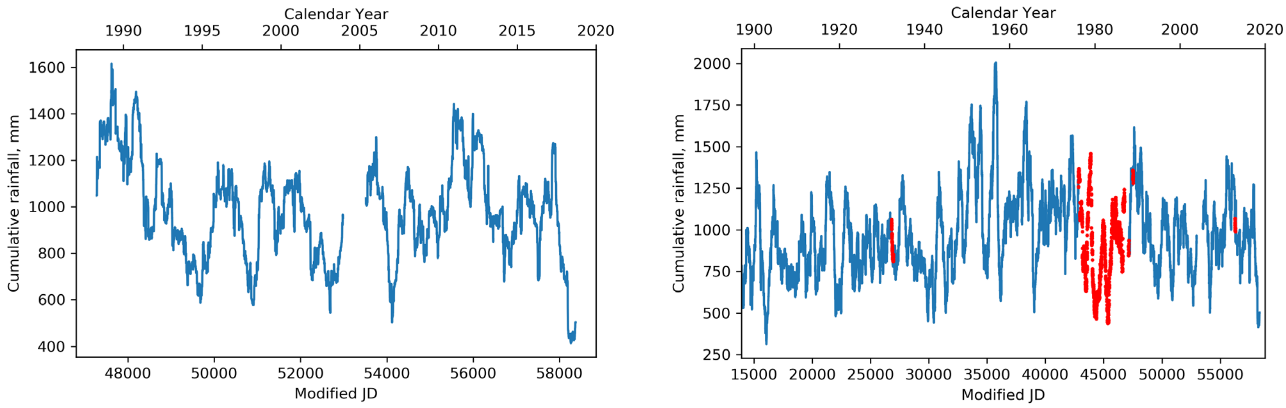

Figure 6: *Left:* 1-year cumulative rainfall, calculated on each day since the resumption of observations in 1988. *Right:* As in left panel, extended back to 1898. Red points indicate where two or more consecutive dates were filled in using nearby station data.

Table 2: Significant drought events with 1-year rainfall below 500 mm, since records began. The third column gives the lowest 1-year cumulative rainfall total received in the period, and the second column is the Julian Date (JD) on which it occurred.

Calendar dates	JD	1-y cumu. rainfall mm	Name
1902 Aug – 1903 Apr	16072	313.3	Federation Drought
1919 Feb – 1919 May[1]	22013	481.0	
1940 Oct – 1940 Nov	29933	450.3	WW II Drought
1942 Jan – 1942 Mar	30440	442.5	WW II Drought
1980 Jun – 1980 Jun[2]	44367	496.0	
1983 Jan – 1983 Mar[2]	45354	466.4	
2018 Mar – 2018 Sep	58268	413.4[3]	

Table notes: [1]The dry spell continued for some months afterwards and dipped below 500 mm again a year later. [2]These observations are based on data imported from nearby stations, so should be treated with caution. They are consistent with contemporary accounts of low rainfall. [3]The final row is the present and continuing drought, with its deepest low on 30 May 2018.

those floods realistically develop or last over a period of about one week, perhaps supplemented by lesser amounts of rain over the same period.

For drought, we might institute a definition of less than half the annual rainfall to have fallen in any given 1-yr period. Only 4 such droughts have occurred, perhaps suggesting our definition is too extreme. Drought events are recorded in Table 2, where this definition is relaxed to 500 mm per year, resulting in two more such droughts. The most extreme of the six was by far the 1902–1903 "Federation Drought", not only in duration but also in its severity. Now, Jenolan Caves finds itself in a similar situation. The 2017-2018 drought is the second driest in recorded history for this location. Careful inspection of Figure 6 shows it has surpassed the once-in-25-years level and is a once-a-century drought. It has been 99 years since a drought has persisted for more than three months at this level. The present drought has not only persisted for longer, but is 15% drier than that event.

Under the definition above (<500 mm/yr), the 11 mm that fell on 8 Sep 2018 brought the present drought to an end with a 1-year cumulative rainfall of 503 mm, but in the absence of significant and frequent rainfall, drought conditions still persist at Jenolan Caves. The *in-situ* observations presented in Sect. 5 can still be expected at Jenolan Caves. In the next section, I investigate how recent climate change may have intensified the drought.

4 The role of temperature

Rainfall data do not tell the whole story. Increases in evaporation and transpiration, whatever the cause, intensify droughts. Since the global land-ocean temperature index has climbed markedly over the past 50 yr (Hansen and others 2010, GISTEMP Team 2018), corresponding increases in evaporation and transpiration will make droughts more severe in the modern era. In this section it is shown that the temperature at Jenolan Caves has increased significantly in recent decades.

Temperature data from the Jenolan Caves weather station are not available after 1973, and are often patchy before then. The nearby stations used for rainfall analysis in Sect. 3 also do not have adequate temperature data, so instead temperature data from the Katoomba Murri St station were used (see Table 1), as the nearest station with complete temperature records for the past half-century. The Jenolan Caves station is lower lying than the Katoomba station, so the stations are not expected to have the same temperature. Nonetheless, it is assumed that they have responded similarly to climate change and that decadal increases in temperature at Katoomba are representative of those at Jenolan Caves.

Figure 7 shows decadal changes in temperature since 1960 at Katoomba as a proxy for Jenolan Caves. For this, the average daily maximum for each day in each calendar month was taken, and averaged over the decade. Hence for the point at January for the 1960 decade, I took all (31x10=) 310 January days from the years 1960-1969, and calculated the mean temperature. The data for the 2010s show warming of 2°C compared to the next-warmest decade, and nearly 4°C compared to the 1960s. We show that average daily maximum temperatures this decade are at least 2 C warmer than in the previous century.

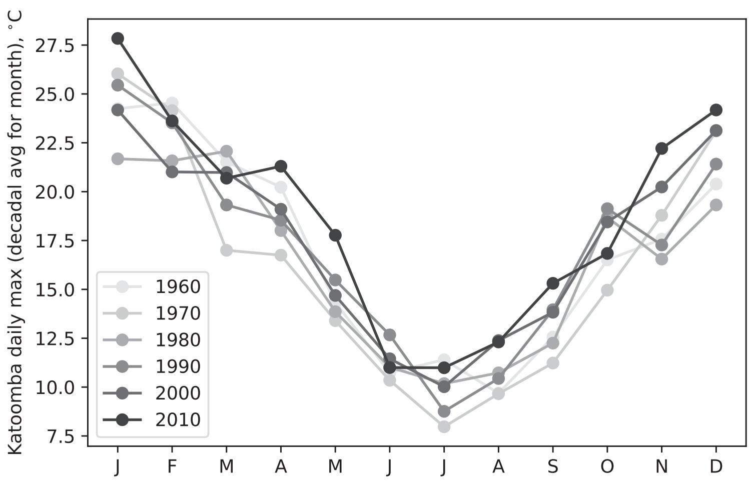

Figure 7: Decadal temperature comparisons for Katoomba, 29 km from Jenolan Caves, 'as the crow flies' . The data show a warming, particularly in the last two decades, that can be expected to exacerbate drought conditions.

5 In situ inspection

This article was prompted by visits to Jenolan Caves, where it was noted that several trips had gone by with little to no rain and the caves were getting drier between each visit. This section describes flow rates and water levels at points of interest in the hydrology of Jenolan Caves.

Volumetric flow rate observations were carried out by (i) selecting a length of stream where the cross-section is uniform, or as close to it as possible; (ii) estimating that cross-section; and (iii) measuring water flow speed. Where possible, the latter was done by dropping a floating object (e.g. a leaf) into the water and timing its passage between the ends of the identified length of stream. With the cross-section and velocity, one obtains a volumetric flow rate. The nature of the measurement means that these flow rates should be considered as broad estimates only.

5.1 Watersend

Ordinarily the Jenolan River sinks into gravel to the north of Wiburds Bluff (Shannon 1976). Just to the north of the ruined Rowe Hut at the northern end of Rowe Flat (the largest alluvial flat, lying to the east of Wiburds Lake Cave), the gravel is capable of taking 45-60 l/s in each of three sinks. The northernmost of these was the main sink in the 1970s, but those were wetter times, as was shown in Figure 6. For most of the past ~25 yr, the main sink has been a pool opposite J244-245 Watersend Cave that is capable of draining 60 l/s.

On 2 Jun 2018 the stream had a very small flow near its terminus, no greater than 5 l/s, and was sinking at 33°46’56.15”S, 150°00’26.19”E in the middle of the flat that lies north of Rowe Flat (labelled ‘2018 terminus’ in Figure 2). This is 600 m away from the 1970s main sink on a bearing of 325°, and it is 370 m on a bearing of 324° from the sink at Watersend Cave, both measured ‘as the crow flies’. The stream lost its flow into the gravel over approximately 10–15 m of creek bed. The following month, on 12 Jul 2018, the stream was sinking 10 m down the valley from there with no noticeable change in creek flow rate further to the north. However, on this occasion, a very minor flow of ≲0.1 l/s was observed over a short section of creek bed where the creek first flows against the eastern edge of the valley floor (33°46’56.5’S, 150°00’29.3”E). The latter was not connected to the main stream via surface flow and the change in altitude of these creek sections is only 1 m over a horizontal separation of 70–100 m, suggesting that a resurgence is an unlikely explanation. The area was revisited on 7 Oct 2018 and the flow rates estimated again. They are compared on a map in Figure 8.

5.2 Imperial Streamway and Far Country

Between the third upstream sump and the second upstream sump, as labelled in the 1979 map by Lewis & Allum (Figure 9), I estimated the flow rate to be 50±20 l/s. While the second upstream sump is a duck-under, the third upstream sump (and the fourth, beyond it) require dive gear. The fifth upstream sump lies in a passage to the north-east of the Imperial Streamway, in Far Country. On 3 Jun 2018 it was observed to be a pool, rather than a sump, with a depth of 20 cm and a further 20 cm of airspace at the roof’s lowest point. There was no flow between this ‘sump’ and the Imperial Streamway.

Following the passage further in the same north-easterly direction, two dive lines are encountered. The first passes through an area that is clearly sumped in wet conditions, as evidenced by high water marks on the walls and the installation of a dive line, but on 3 Jun 2018 was found to be mostly dry, with no pooled water though damp sediment lined the floor. The 6th upstream sump begins shortly beyond here, in the same location as indicated on the map, suggesting no substantial retreat in the present drought.

5.3 Mammoth Cave

Mammoth Cave has been thoroughly surveyed by Sydney University Speleological Society (SUSS), the maps from which can be found in *SUSS Bull*, 52(1), 52(3), 53(3) and 55(2) (Maynard 2013a,b, 2014, 2016). The cave has several watercourses including two rivers (Central River and Lower River), two major lakes (Ice Pick Lake and Slug Lake), and several pools and sumps. Together these offer a window into the hydrology of the Jenolan Caves system. The following observations have been made during the present drought.

- The southern part of Railway Tunnel, between Horseshoe Cavern and Skull and Crossbones, has dried considerably. Usually dominated by slippery wet mud and the occasional small puddle, the mud here is now firm.
- Central Lake is dry, with a sandy bed.
- Southbound (downstream), Central River usually sumps shortly after Central Lake. The river passage is currently dry and accessible for some 30 m south of the large Central Lake chamber, right until its southernmost surveyed location at station lake.cld14 (Maynard 2014), located at MGA (56H) 224128, 6255441, altitude 769 m. Immediately before the sump the sediment changes from sand to a fine-grained mud/sand mixture (Figures 10 and 11). It seems this area is accessible in moderately dry conditions, occasionally via a duck-under (Staraj 2004).
- Central River north of Central Lake and south of First Crossing is dry, and the river bed has thin calcite residue.
- Central River north of First Crossing is also completely dry with calcite deposition. There is no trickle from the Ninety Foot, down from Railway Tunnel.

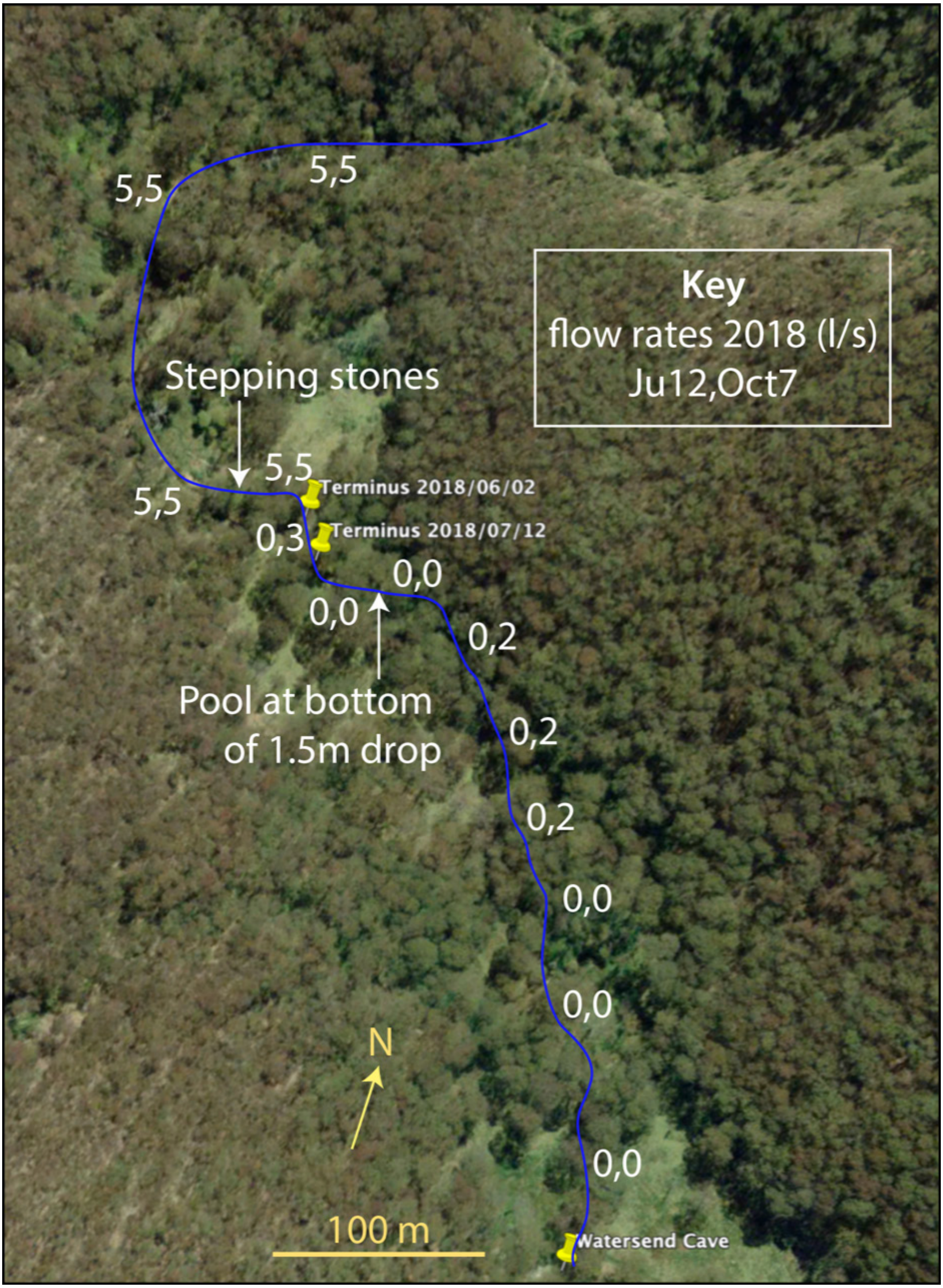

Figure 8: Map of the northern end of McKeowns Valley. The approximate river course is illustrated with a blue line, with the direction of flow being generally south. Flow rates along its course in l/s are written in white for two dates: 12 Jul 2018 and 7 Oct 2018. The two termini mentioned in-text are pinned with their corresponding dates, as is Watersend Cave in the south. The river leaves the slate at the position of the first flow estimate. Map imagery from NSW Globe, which is copyright of Department of Finance, Services & Innovation 2018.

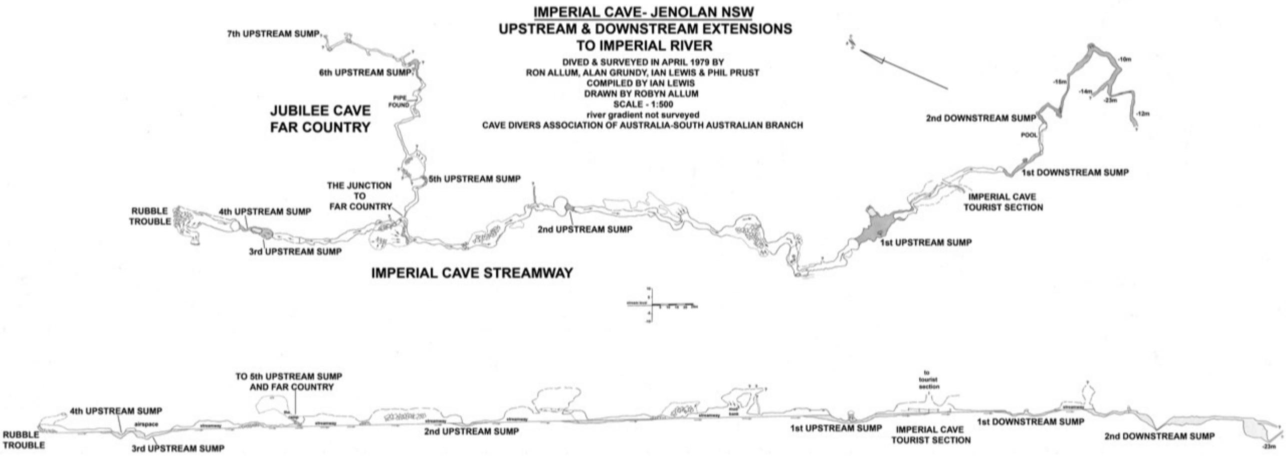

Figure 9: Map of the Imperial Streamway by Lewis & Allum from the SUSS map library.

Figure 10. Central River southern sump. The underwater photo (left) shows that the river passage continues in a tight phreatic tube. Photo credit: Rafid Morshedi. Date: 12 May 2018.

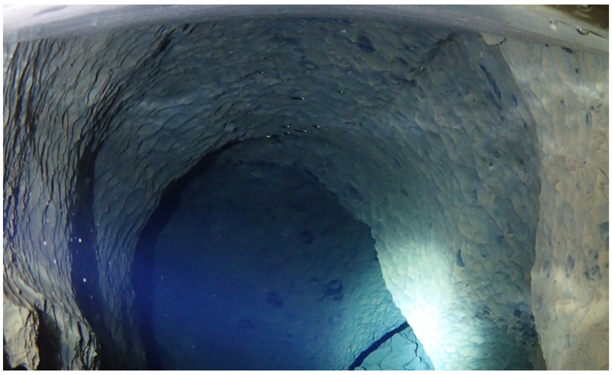

Figure 11. Central River southern sump, two months later. The water level is not visibly different from the photo in May. Photo credit: Rafid Morshedi. Date: 14 July 2018.

- The sump of Central River, just north of the First Crossing rockpile is also completely dry (Figure 12). Here, there is a 30 cm layer of sand, beneath which is some damp mud. The mud may dry if exposed to air.
- The Overflow Sump, which is the lowest part of Mammoth Cave except from Ice Pick Lake and Slug Lake, is dry and passable. Gravel is abundant either side and through the (dry) sump (Figure 13).

Figure 12. Central River, first sump north of First Crossing. No water was evident. Sand transitions to mud about 30 cm below the surface. Subject: Simon Murphy. Photo credit: Rafid Morshedi. Date: 12 May 2018.

- Between The Overflow and The Junction, south of Northwest Passage, there is normally a resurgence of Central River in a narrow hole in bedrock beneath a 3 m climb. This is also

Figure 13. The Overflow sump on Central River. No water was evident. Ample stream gravel was found and had to be removed to pass under the bedrock. Subject: Joshua Parker. Photo credit: Rafid Morshedi. Date: 12 May 2018.

dry. Gravel covers the floor. There are no new exploration opportunities here since the bedrock hole is too tight for humans (Figure 14).

Figure 14. The resurgence of Central River (impassable hole to lower right) contained no water. The ground is covered with gravel. Glove for scale. The dark area in the upper left is a shadow. Photo credit: Rafid Morshedi. Date: 10 Aug 2018.

- The Overflow is a tight phreatic tube with minor vadose modification. Stream gravel lines the floor, and water can drain through occasional fissures. There is no flow here at present (Figure 15). This only flows during floods.
- There is no water in The Liquidator, as far as this passage can be accessed by normal-sized humans (Murphy & Morshedi 2018). Progress here is hampered both by the twisting shape of the rift and its narrow size, before it descends steeply at similar dimensions (Figure 16). Since that visit, I have learned of an obscure but ‘easier’ route into The Liquidator which apparently leads to a ‘squalid sump’ (Staraj 2004) but I have not yet had the opportunity to revisit.

Figure 15. The Overflow also contained no water. Stream gravel in the floor was dry, but water can drain to lower levels through small fissures. Subject: Simon Murphy. Photo credit: Rafid Morshedi. Date: 14 Apr 2018.

Figure 16. The Liquidator contained no water. Central River was not flowing into this part of the cave. This passage could not be investigated much beyond the entrance of the rift. Subject: Rafid Morshedi. Photo credit: Rafid Morshedi. Date: 14 Apr 2018.

- Ordinarily Central River would flow from Risky Business to The Liquidator, but there is no flow at present.

- Risky Business is surprisingly wet, given the appearance of other areas of the cave. There are several small pools of clean water in the rock floor, filled to their brims. These appear to be supplied by water dripping from the roof, probably arriving via the nearby shale contact.
- Unlike Risky Business nearby, Damocles Lake is dry, with a sandy bed. The "muddy sump" described on the survey (Maynard 2016) is also dry, and this was pushed on a recent trip to a newly-entered sand-floored chamber (Murphy 2018).
- Waterfall Passage still carries its permanent trickle. This has never been observed to cease flowing.
- Dry Syphon is dry except for water emanating from Waterfall Passage, which then all exits Dry Syphon through a narrow slot in rock in the western wall. No water is flowing south out of Dry Syphon.
- No water is flowing or pooled in any significant quantities in Northwest Passage. Mud in the Guzaround area is still damp and soft.
- Sewerslide in Northwest Passage is the exception, still looking wet and uninviting as it must have when first named.
- Debouchment Detour usually contains one long muddy puddle and a smaller one to its southwest that sits in a constriction on a corner. The larger of the puddles still has its main body where the passage turns north, but it is narrower and shallower than usual. The northern end of this puddle is now heavily fragmented and most of the depth is soft mud, rather than water. The south-western puddle no longer exists.
- The small man-made dam just north-east of First Crossing was initially constructed for the Easter Camp of 1961 to collect drinking water where it constantly drips down here. It is now so empty that it cannot be relied upon as a source of drinking water. In normal conditions this overflows the dam.
- The "hole to water" heading down and north from Snakes Gut (just before Gravel Grovel) still contains water, at least 1 m deep (Figure 17). However, it has receded enough from its usual levels to reveal a passage leading off it to the south-east (towards Ice Pick Lake) that is usually submerged (Figure 18). This is probably a fossil level of Central River.

Figure 17. The hole to water in Snakes Gut, believed to be part of the sumped Central River. Approximate depth 1 m. The white wire may be old dive line. Photo credit: Stephanie Murphy. Date: 13 May 2018.

Figure 18. The newly exposed tube leading south-east from the hole to water in Snakes Gut. Dimensions are approximately 30 cm high by 30 cm wide. Photo credit: Stephanie Murphy. Date: 13 May 2018.

- Ice Pick Lake is well down on normal levels, but this lake can have quite a variable surface height and "normal" levels have not been precisely recorded, so a direct comparison is difficult. The surface is presently 1.5 m below the dive-line tie-off in the middle of the chamber. This tie-off is submerged in wet years and in flood. The lake is partially covered in calcite rafts (Figure 19).
- At the confluence of Central River and Ice Pick Lake, the lake is now low enough that the river and lake are disconnected by a mud bank. Central River is also covered in calcite rafts and sumps

5–10 m upstream of the lake (Figure 20), as indicated on the survey (Maynard 2014).

Figure 19. Ice Pick Lake is presently about 1.5 m below the dive-line tie-off. Subject: Jen Evans. Photo credit: Lisa Vitaris. Date: 13 May 2018.

Figure 20. Looking approximately west at the Central River sump. Ice Pick Lake lies just out of frame to the left (south). Photo credit: Simon Murphy. Date: 13 May 2018.

- The survey indicates two pools at the start of World of Mud (i.e. the low western part). From the top of the 4 m pitch that precedes them, the western of the two appears dry and the floor muddy. The eastern pool could not be assessed due to permit restrictions.* At least one of these pools has been entered during a previous dry period and no way on was found (Staraj 2004).
- Lower River is flowing, with very reduced flow (Figs. 21 and 22). Only the southern of the two holes in the western wall is conducting any water. A gravel bank blocks flow from the northern hole (Figure 21). The flow here is an upwelling from a sump under pressure that ordinarily delivers ~140 l/s. At the time of writing, the flow is down to 40±10 l/s – the lowest flow ever recorded.
- At the far side of Lower River, after the first climb down towards Slug Lake but before the second, there is a sump on the east, beyond an 8-m climb down. This is considered a linked backwater of Lower River, which when dived by Rick Grundy was found to continue in passage too tight for a diver (Grundy 2014). It was not re-inspected for this work.

Figure 21. Upper: Looking approximately north, a gravel bank separates the northern outflow from the main southern outflow from the western wall at Lower River.
Lower: As above, looking approximately south.
Subjects: Pete Baxter, Miriam Noble. Photo credit: Shaleen Patel. Date: 7 July 2018.

Figure 22. Upper: Looking approximately north-east, a further 5 m downstream, flow is low enough to observe cascades.
Lower: Looking approximately south-east, after the small cascades at the deeper part of Lower River.
Photo credit: Shaleen Patel. Date: 7 July 2018.

* Note added in proof: during Jan 2019 the eastern 'pool' was observed to be completely dry and the hole ~8m deep.

- A similar sump between Lower River and Slug Lake exists in rockpile and was dived by Brian Hebden with the same conclusion, that it is a backwater of the river (Cooper, pers. comm.). It was not re-inspected for this work, either.
- Slug Lake is well down on normal levels, with "Arse Rock" now protruding above the surface. Dave Apperley has observed that the restriction at -30 m is silting up. It is not clear if this is a direct result of lower flow in Lower River. Similar observations were made during Ron Allum's record -96 m dive (Ryan 2001).
- Grinning Monster Lake (altitude of ~775 m) is usually at the same level as Lower River, except in flood, so I have declined to inspect it.

5.4 J340 Enigma Cave

While this article is concerned with the Northern Limestone, it is worth reporting a fleeting observation of J340 Enigma Cave. This diveable cave was discovered in 2013, with an entrance 10 m above the dry Camp Creek riverbed. The start of the dive is just a couple of metres below the entrance and hence some metres above Camp Creek level (Anon. 2013). The water was found to persist for quite some time and its depth is at least 11 m with open leads (Larkins 2014). Explanations for the cave have been put forward by Cooper in the same article (Larkins 2014), that this is either a resurgence or an old flood swallet. We checked on the water level during the present drought. On 7 Jul 2018, J340 was found to be full of water, still.

6 Conclusions

Archival data have been used here to study rainfall at Jenolan Caves. The years 2017 and 2018 have seen a once-in-a-century drought, which is the second-driest period since rainfall observations began in 1895. It is also apparent that Jenolan Caves undergoes variations in rainfall on time-scales of decades: the period 1895–1940 was much drier than 1950–1975, and 1991–2018 was comparatively dry again. Temperatures this century are shown to be, on average, approximately 2°C warmer than the mid-20th Century, and through increased evaporation and transpiration rates this will exacerbate droughts, now and in the future.

Observations are presented on the water levels at Jenolan Caves, including the location of the surface stream sink, flow rates of underground rivers, and the levels of pools and sumps. There are marked changes consistent with the low rainfall. Lower River, the centrepiece of Jenolan Caves hydrology, is at its lowest flow ever recorded.

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