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The Blue Waterholes, Cooleman Plain, N.S.W.

photograph by J.N. Jennings, December 1954

HELICTITE

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Cover Photograph: The Blue Waterholes, Cooleman Plain, N.S.W., is the perennial head of Cave Creek, tributary of the Goodradigbee River. Springs issue from the alluvial banks around the pool and through sand covering the bedrock limestone of the pool floor. See the paper by J.N. Jennings, p 3.

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FURTHER STUDIES AT THE BLUE WATERHOLES, COOLEMAN PLAIN, N.S.W., 1969-77

Part I CLIMATE AND HYDROLOGY

J.N. Jennings

Abstract

Previous study of the temporal and spatial distribution of limestone solution at Cooleman Plain rested on monthly discharges and water analyses of the Blue Waterholes over 4 years. For this study automatic recording of discharge (8 years), rainfall (8 years), evaporation (7 years) and temperature (4 years) was attended by variable success in the face of interference, rigorous climate and inaccessibility. The most important aspect of the climatic data was the support obtained for the earlier assumption of similar water balances in the forested igneous frame and the grassland limestone plain.

Runoff was again shown to be highly variable from year to year and to have an oceanic pluvial regime, with a summer-autumn minimum owing much to evapotranspiration. The flow duration curve from daily discharges puts this karst amongst those where neither extremely high nor low flows are important. The stream routing pattern offsets the effect of 71% of the catchment being on non-karst rocks, damping flood events. An inflection at 700 l/s in a flow duration plot based on discharge class means is interpreted as the threshold at which surface flow down North Branch reaches the Blue Waterholes.

Storages calculated from a generalised recession hydrograph parallel Mendip data where baseflow (fissure) storage provides most of the storage and quickflow (vadose) storage only a secondary part. Water-filled conduit storage (the phreas) could not be determined here but is considered small. The baseflow storage seems large, suggesting that it can develop independently of caves in some measure. A quickflow ratio for floods derived by Gunn's modification of the Hewlett and Hibbert separation line method appears relatively low for a mainly non-karst catchment and is again attributed to the routing pattern.

For analysis of variation of the solute load over time, estimates of daily discharge during gaps in the record were made for the author by Dr. A.J. Jakeman and Mr. M.A. Greenaway (see Appendix).

A small number of discharge measures of two contrasted allogenic catchments of the igneous frame shows a unit area yield close to that for the whole catchment. Together with a gauging of most of the allogenic inputs, this supports the idea that the water yield is much the same from the forested ranges and the grassland plain. This is important for the estimation of limestone removal rates.

INTRODUCTION

Previous study (Jennings 1972 a,b) of the solution regime of the Silurian limestone of the upland Cooleman Plain in southern New South Wales on the basis of monthly determinations of discharge and solutes from the Blue Waterholes was recognised to be inadequate. In the 4 years of observation (April 1965 - March 1969) there was much annual variation, rendering a longer record necessary; 8 further years go some way to satisfying that requirement. Since floods were found to be important in the solute load regime, the risk that high flows of short duration might not have been adequately sampled by monthly collections called for continuous monitoring of discharge. This was undertaken and also some meteorological observations were made to assist with the problem of estimating the input of allogenic drainage without measuring discharges of the many allogenic streams. Nevertheless, because of the difficulty of maintaining long term observations in a relatively inaccessible place, crude approximations still have to be incorporated in the calculations and the study remains unsophisticated compared, for example, with those of Atkinson (1977) in the Mendip Hills and of Mangin (1974-5) and Bakalowicz (1979) in the Pyrenees. Lesser experiments in support of the overall catchment study were also conducted, which have already been reported (Jennings 1977, 1978, 1979a, 1981).

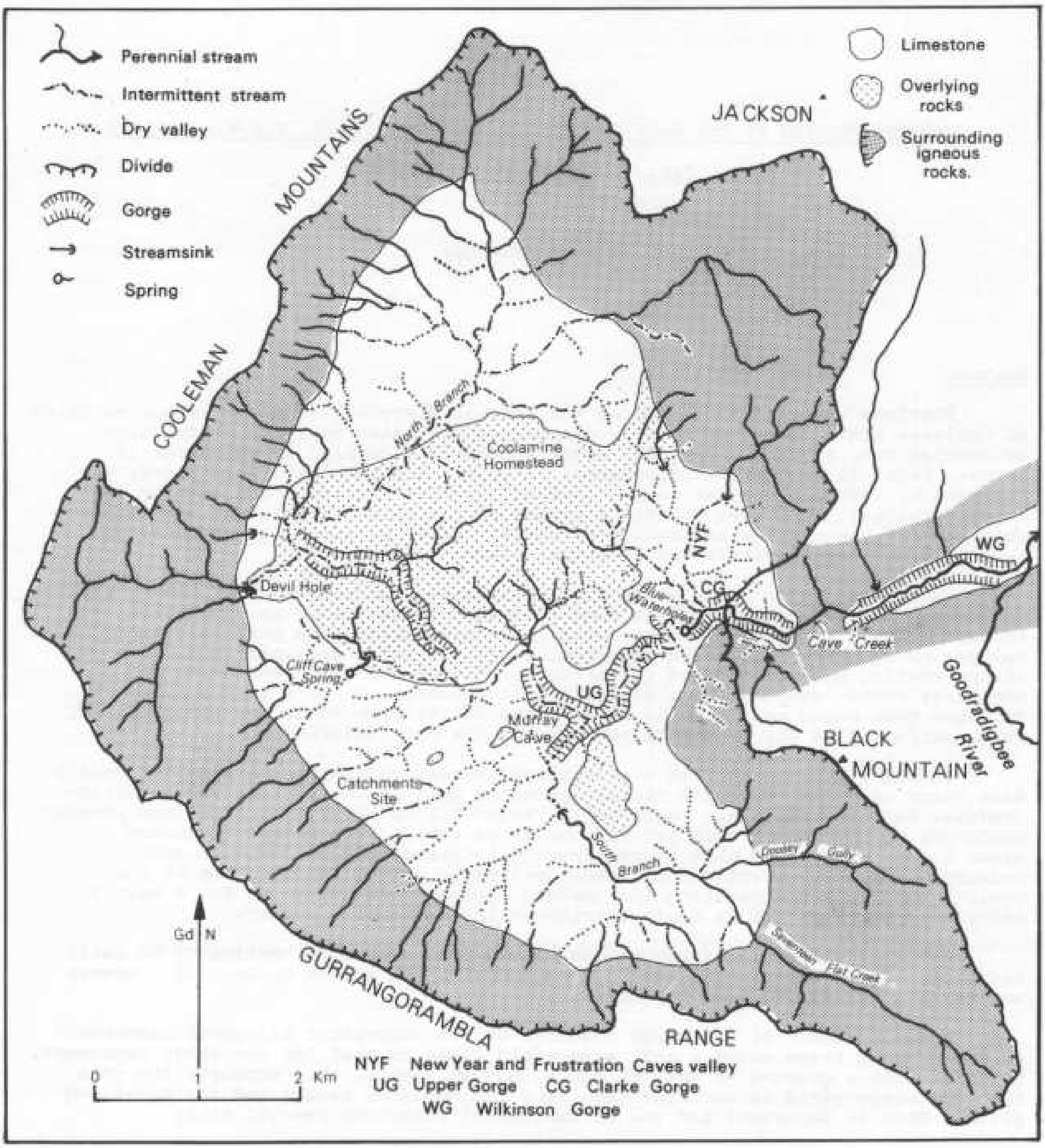

Figure 1. Selected geomorphological features of Cooleman Plain.

This paper will discuss the output of Cave Creek primarily. It will not recapitulate associated findings but refer to them so far as this is necessary for the study of the temporal and spatial distribution of limestone solution, which in this karst is the dominant geomorphic process.

For this study, Cooleman Plain has the distinct advantage that the common problem in karst of catchment definition does not arise because higher igneous ranges box in the limestone (Figure 1). Nearly all underground water from the Plain rises in the Blue Waterholes and when the North Branch of Cave Creek flows all the way down its surface course after more favourable water balances, it joins with the flow from these springs. Perennial from the Blue Waterholes, Cave Creek next enters Clarke Gorge, which is still in the limestone, but then crosses onto granite between Mt Jackson and Black Mt.

The earlier study employed three gauging sites at the Blue Waterholes. For this one only a single monitoring point was needed so the first site on Cave Creek downstream of the Blue Waterholes that was well suited for flow meter gauging was selected. This had the advantage of including the output of the New Year - Frustration Caves catchment (Rieder et al. 1977), the only area of the Plain not feeding the Blue Waterholes. Between the gauging site and the downstream granite, three small springs are known along Cave Creek - one from Black Range Cave, one from Barber Cave and one at the contact with the granite on the right bank of the stream. None of these discharges comes from the Plain. The channel at the gauging site was mainly floored by bedrock and the cross-section was not subject to significant change.

Shifting the gauging site downstream increased the catchment from 51.8 to 55.47 km^2 (maximum expected error less than ± 1%) and the area of exposed karst from 14.9 to 16.05 km^2 with a similar error. The area measurement was performed with a digitising table in place of the planimeter used in the original study.

Fresh geological mapping (Owen & Wyborn 1979) was also available. The exposed karst area was taken to include parts with thin covers of gravel and ferruginous sandstone of Tertiary age. The proportion of exposed karst in the catchment remained disadvantageously small, changing only from 28.8% to 28.9%. The subjacent karst where the limestone lies beneath younger silurian clastic sedimentary rocks and Devonian volcanic rocks increased from 6.6 km^2 (12.7%) to 9.0 km^2 (16.2%).

At the gauging site, a Sumner-Rimco automatic recorder operated two pens, the one linked to a float stage mechanism, and the other to a pluviograph, from 23 April 1969 to 24 April 1977. A similar recorder installed on the margin of the northern part of the limestone plain near Coolamine Homestead was linked to a pluviograph and a Type A plan evaporimeter from 14 October 1970 to 25 April 1977. It had been intended to install a second evaporimeter on the forested rim of the Plain but persistent difficulty with that at Coolamine Homestead discouraged this. Instead thermographs for evapotranspiration estimation were set up at the Coolamine Homestead site and on the Cooleman Mountains where the track from the Long Plain crosses the divide and were run from 7 March 1973 to 25 April 1977 in respect of the former and from 16 May 1973 to the same closedown for the latter. At the latter site a Snowdon large capacity raingauge was maintained and a standard raingauge was also in action from 11 April 1975 to 26 April 1977 at the site of two artificial small catchments on the western side of the southern part of the Plain.

All the automatic instruments were subject to failure of various kinds and some to repeated interference by men and other animals. The relative inaccessibility of Cooleman Plain from Canberra meant that these breakdowns often caused prolonged interruptions to records.

Water samples were collected at the gauging station for chemical analysis; at the time of collection, temperature, pH and conductivity were determined. Samples were usually analysed in Canberra within 2-3 days of collection. For most of the observation period, water samples were also collected from two input catchments on igneous rocks - allogenic streams (Williams & Dowling 1979), selected for contrasted behaviour (Jennings 1972b). Special sets of water samples in connection with particular experiments were also studied as well as samples of miscellaneous points of interest.

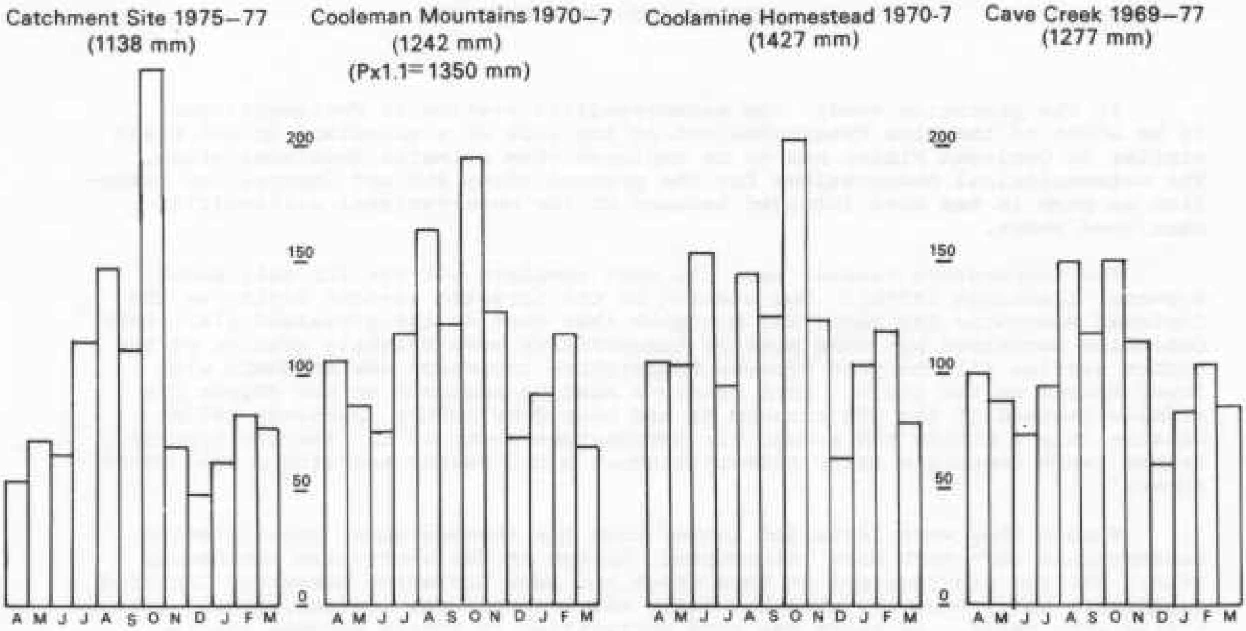

Figure 2. Seasonal distribution of precipitation at 4 sites on Cooleman Plain.

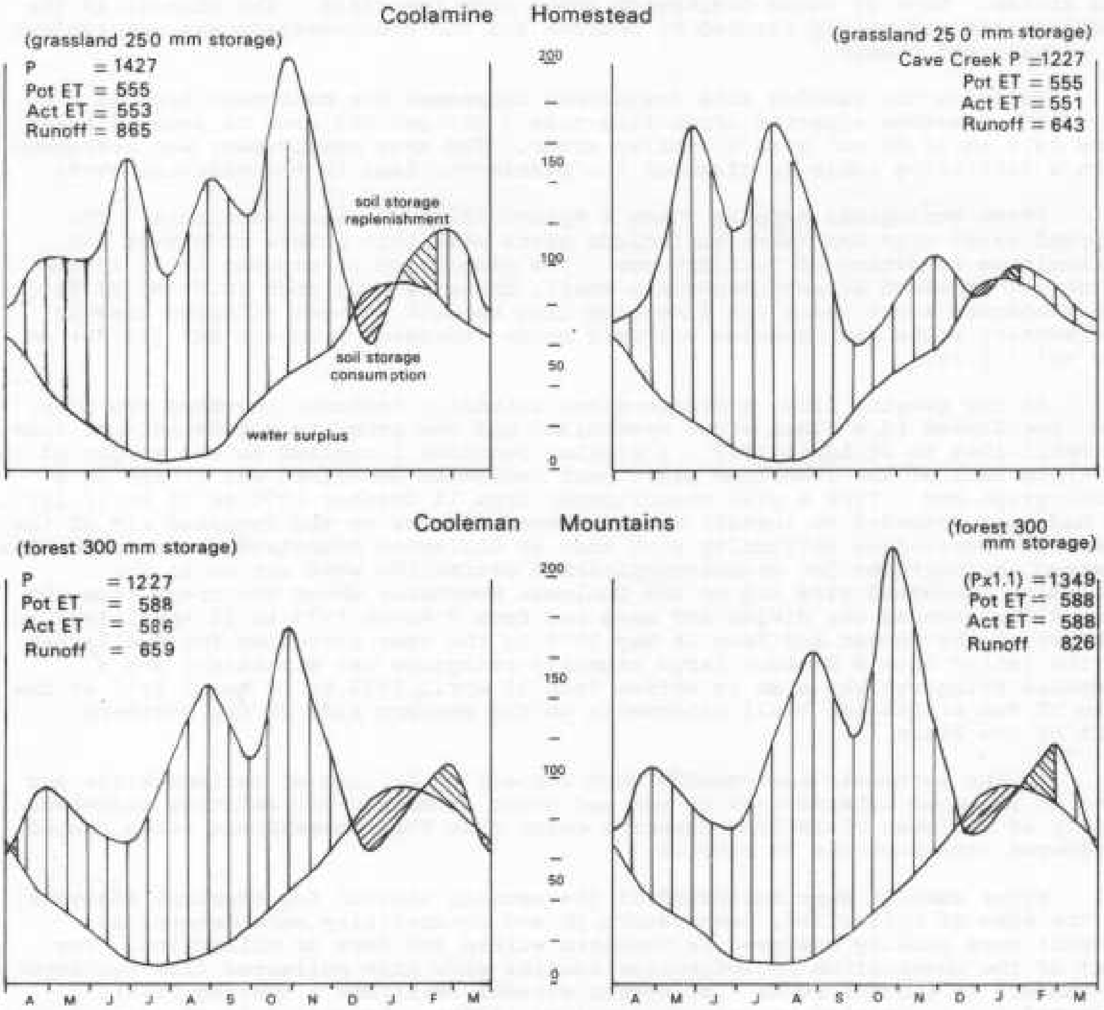

Figure 3. Thornthwaite water balance diagrams for Cooleman Plain based on thermograph records over 1973-7 at Coolamine Homestead and Cooleman Mountains and precipitation at Coolamine Homestead, Cave Creek and Cooleman Mountains.

CLIMATE AND WATER BALANCE

In the preceding study, the meteorological station at Tantangara Dam, 18 km south of the Blue Waterholes but at the side of a grassland upland plain similar to Cooleman Plain, had to be employed when climatic questions arose. The meteorological observations for the present study did not improve the situation as much as has been intended because of the observational difficulties mentioned above.

The temperature records were the most complete but ran for only about 4 years, (Jennings 1979b). The station on the forested western divide on the Cooleman Mountains lay about 143 m higher than that on the grassland plain near Coolamine Homestead but mean monthly temperatures were slightly greater at the higher station all the year because temperature inversion was frequent with lower minima on the plain. Both stations must be assigned to the Köppen Cfc climate instead of the Cfb climate as had been done before (Jennings 1972a) because only 4 months had a mean air temperature above 10°C. The Cfc type is termed 'warm temperate rainy climate without a dry season and with a cool short summer'.

Though they were installed longer than the thermographs, precipitation measurements were much more interrupted, except at the short-term catchments site. The two pluviographs at Cave Creek and near Coolamine Homestead included totalisers and frequently when the daily chart record was useless, totals between visits were valid. As there was good correlation in totals between visits between the two stations and between them and Tantangara Dam, it was feasible to arrive at monthly totals by allocating totals over irregular visit periods to calendar months proportionately on the basis of daily records elsewhere. This method was also used to determine monthly totals for the storage gauges on the Cooleman Mountains and at the small catchments site.

The Coolamine Homestead station was well sited for meteorological purposes but unfortunately its record for precipitation was the most broken. The Cave Creek station was perforce located in a narrow valley and there could well have been some sheltering from rain. The Cooleman Mountains site lay within the forest but beneath a canopy gap not large enough for recording rainfall. An interception of 10% is estimated and for some purposes this correction will be applied to obtain rainfall.

The available complete calendar years of precipitation are set out in Table I in comparison with those for Tantangara Dam; none was available from Coolamine Homestead.

Table I Calendar Year Precipitation (mm)

Year	Tantangara Dam	Cave Creek	Cooleman Mountains	Catchment Site
1970	1219	1438		
1971	1417		1223 (1345)	
1972	803		1021 (1123)	
1973	1121	1316	1296 (1426)	
1974	1571	1569	1554 (1709)	
1975	1388	1409	1378 (1516)	
1976	962	1005	952 (1047)	913

N.B. The figures in brackets for Cooleman Mountains include a 10% correction for interception.

The seasonal incidence of precipitation is displayed in Figure 2. It is well distributed through the year, with a weak late winter - spring maximum.

Annual precipitations for the 8 hydrological years were derived by meaning monthly totals available from all stations, employing in this case the Cooleman Mountains figure increased by the factor of 1.1 because of site characteristics (Table II). The stations were so poorly distributed over the catchment and the records so broken that there was no point in more representative handling such as by the use of Thiessen polygons. The rainiest year had nearly twice that of the driest year and even so no drought year was included. Although for Australia reliable, it is in reality quite variable in precipitation.

Table II Hydrological Year Precipitation (mm)

April 1969	- March 1970	1059
1970	1971	1518
1971	1972	1221
1972	1973	899
1973	1974	1303
1974	1975	1707
1975	1976	1393
1976	1977	1046

Although the Class A pan evaporimeter near Coolamine Homestead was mounted for 7½ years, for only a small proportion of months was a complete record obtained. These are meaned in Table III where the meagreness of the record is apparent; nevertheless the seasonal incidence is reliable enough for general argument, with high values in the summer half of the year and low values in the winter half. A potential evapotranspiration figure for the grassland can be approximated from this by applying to the pan evaporation the ratio found by McIlroy and Angus (1964) between results from a Class A pan and an irrigated grass lysimeter at Aspendale, Victoria. The result is 858 mm for the year.

Table III Pan Evaporation Mean Monthly Values (mm), Coolamine Homestead, 1970-7

	n	x	S.D.
January	7	135	35
February	6	109	15
March	6	76	34
April	4	70	
May	3	62	
June	2	49	
July	3	56	
August	2	49	
September	2	75	
October	4	85	
November	4	108	
December	5	151	31
Year		1022	

However, the main interest in evaporation arises from the need to compare runoff from the forested igneous rim with output from the grassland limestone plain (Jennings 1972a). Difficulty with the automatic pan evaporimeter at Coolamine Homestead led to the abandonment of a plan for a matching one on the Cooleman Mountains divide. A substitute is to calculate potential and actual evapotranspiration by the Thornthwaite method (Thornthwaite and Mather 1957) on a monthly basis from the 4 years of thermograph record.

The figure of 250 mm of soil storage per month was adopted for the grassland site and 300 mm for the forest site. At both stations (Figure 3) a condition of water surplus to soil requirements prevails through most of the year, with only a couple of summer months when soil moisture is being used up or recharged. Actual evapotranspiration calculated by this method very nearly equals potential evapotranspiration.

The theoretical runoff at Coolamine Homestead comes to 865 mm, whereas that of Cooleman Mountains on the basis of the measured precipitation is only 748 mm. However, this precipitation should be augmented to allow for the 10% interception estimate and then it becomes 826 mm. On this basis, the yield from the Plain is greater than that from the peripheral ranges by about 5%.

Table IV Water Balance (in mm)

	precipitation =	discharge +	evapotranspiration +	change +	error in groundwater storage
1907-7	1300 =	388	+ 858 (corrected pan evaporation)	+ 13	+ 31
1973-7	1362 =	363	580 (mean of Thornthwaite estimates for Cooleman Mountains and Coolamine Homestead)	+ 5	+ 414

It is convenient here to anticipate the overall result of discharge measurement and continue with consideration of water balance incorporating that result (Table IV). No estimate of change in soil storage has been made. It is likely to be in the same sense as the groundwater storage and also a small component. The largest likely source of error lies in the ET estimates, where it seems from this balance that the Thornthwaite formula has given a large underestimate (cf.Sellers 1965). Despite this there is no reason to think that the Thornthwaite ET estimates for the plain and the ranges will diverge drastically in their errors (separate water balance calculations give figures not far apart). Therefore the previous inference that the water balances of the two parts of the catchment are similar can continue to be made.

DISCHARGE

At the Cave Creek gauging station, discharge was measured with an Ott Type 'Arkansas' flow meter on 31 occasions following standard procedures. The error in the flow meter gauging is assumed to be ±5%. The range measured was from 194 l/s to 3370 l/s; this covers about 98% of flow duration. However, the upper value only approximates to bankfull discharge and the cross-section changes markedly above the banks. River stage was recorded to ±0.5 mm at each occasion of flowmeter gauging, recorder checking or water sampling occasion. A power curve fitted flow meter discharge to stage with $r^2 = 0.89$.

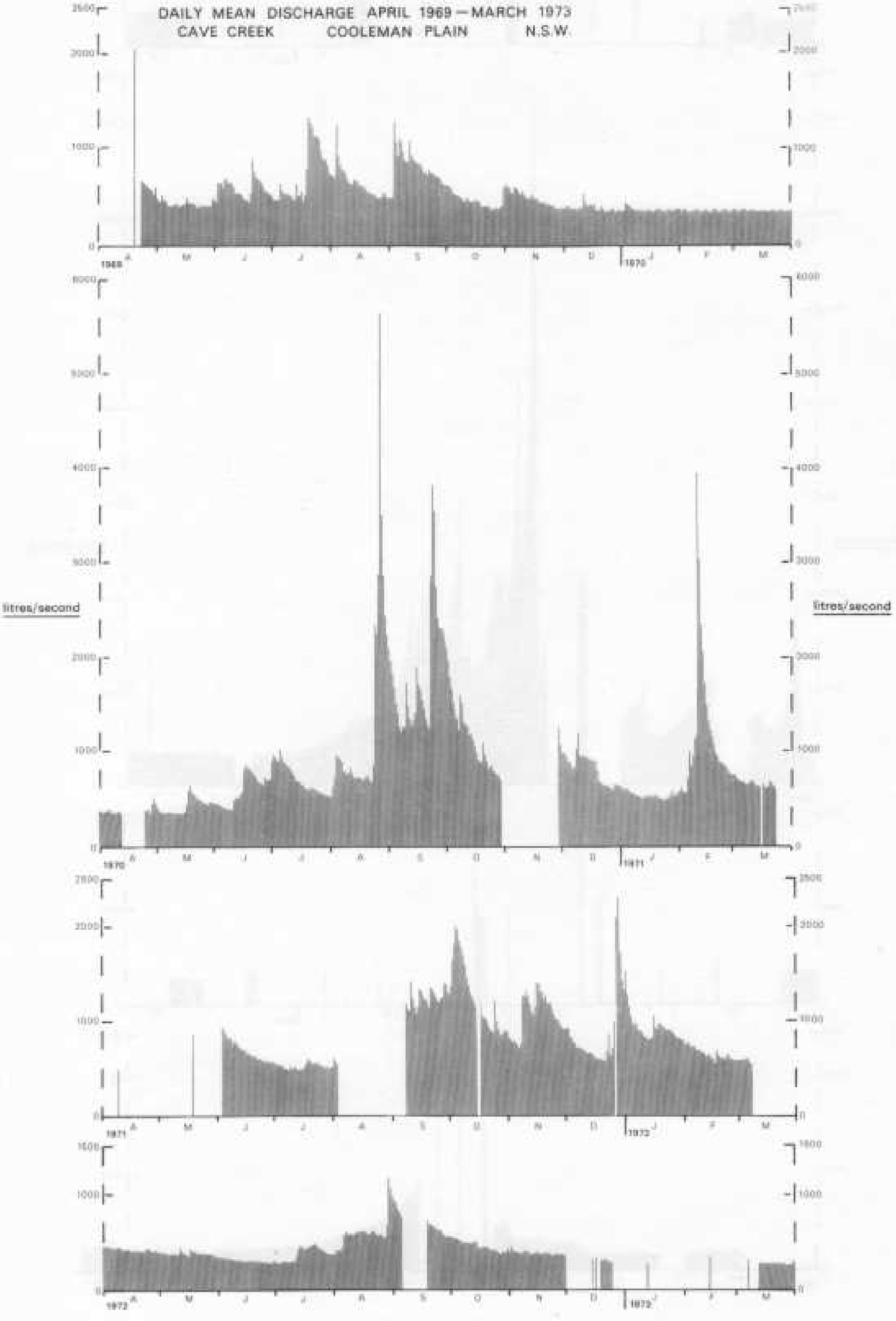

Figure 4. Daily discharge at Cave Creek, 1969-77.

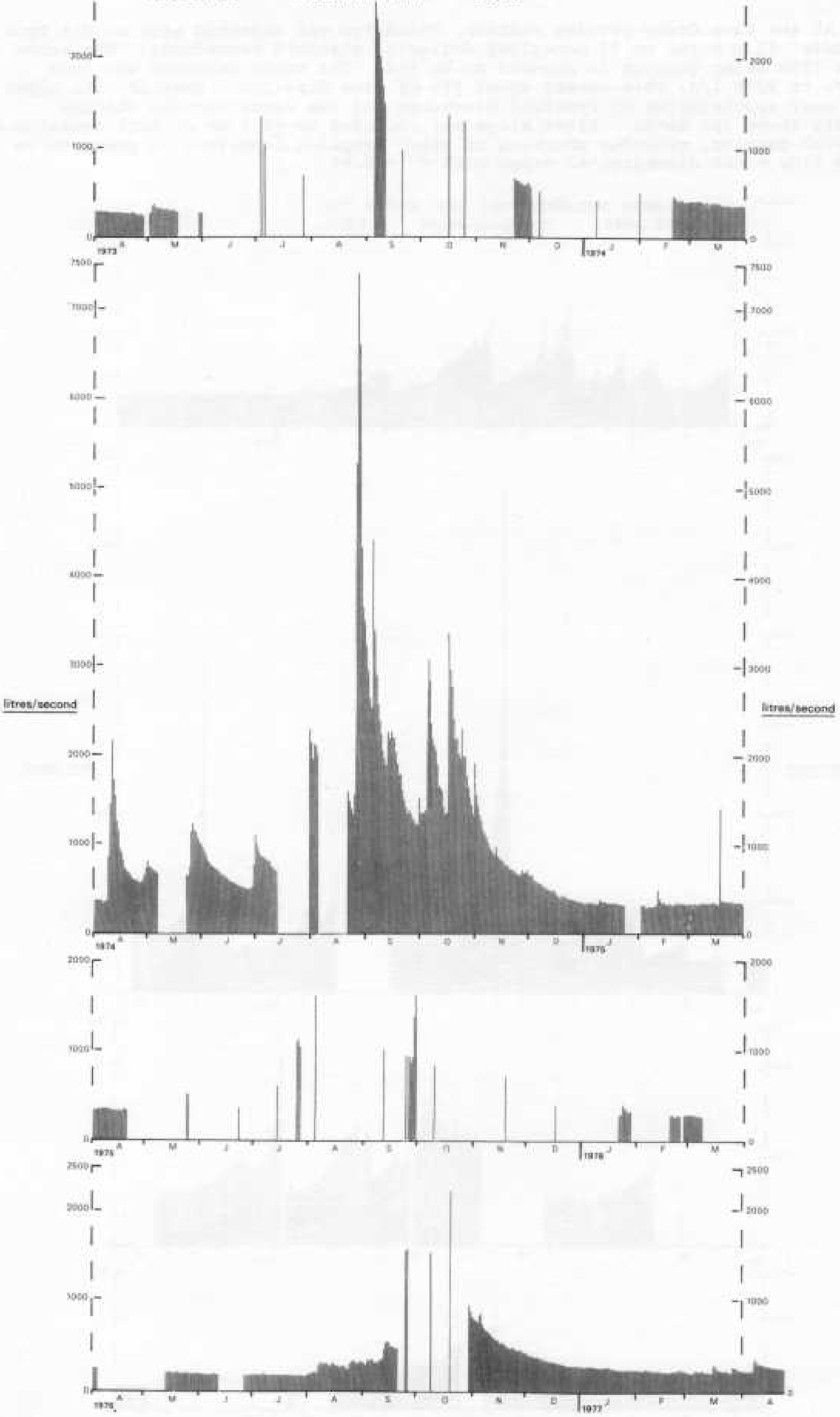

Figure 5. Daily discharge at Cave Creek, 1969-77.

$$Q = 0.0000176 \text{ river stage}^{4.238} \qquad (1)$$

with Q in l/s and river stage in mm.

Recorder chart height was taken off under a microscope with a precision of 0.01 mm but there was flutter in pen action of 0.1 mm, which would occasion an error of ±4%.

There were 3 different zeros in 8 years of recording because of interference, the instrument being damaged by rifle fire on two occasions. Adjustment to a common zero was made to about ± 0.1 mm. The best fit of flow meter discharge on chart height was a power curve with $r^2 = 0.83$ but a linear regression of river stage on chart height gave a better r^2 of 0.89.

$$\text{River stage} = 18.17 \text{ chart height} - 29.79 \qquad (2)$$

with river stage and chart height in cm.

Therefore chart heights were converted to discharges by (1) and (2). This was used to flow of 2240 l/s, a little below bankfull.

For higher stages, the Stevens method was used (Wilson 1974). From a surveyed cross-section at the site $A\sqrt{D}$ (where A = area and D = mean depth) was calculated for stages at 6 cm interval to 1.54 m which is above the limit of known floods from debris levels. A linear regression of discharge on $A\sqrt{D}$ gave $r^2 = 0.92$.

$$Q = 764.14\, A\sqrt{D} - 1323.49 \qquad (3)$$

where Q is in l/s and $A\sqrt{D}$ in m^2

The best fit between river stage and $A\sqrt{D}$ was a power curve obtained by least squares search, $r^2 = 0.999$.

$$A\sqrt{D} = 6.235\, (\text{river stage} + 0.02)^{1.87} \qquad (4)$$

with $A\sqrt{D}$ in m^2 and river stage in m.

This was combined with (2) and (3) to derive discharges above 2403 l/s from chart height.

A linear function was used to calculate discharges between 2240 and 2403 l/s to smooth a break between the use of the power curve (1) below bankfull and the Stevens method above it.

When stage was changing slowly, the midday chart reading was taken as the daily mean but during flood pulses from 4 to more than 30 discharges were calculated for each day, weighted for the time intervals between them and the means determined for the day from them.

The completeness of the record varied very much from year to year (Table V). As the results of the instrumental monitoring will be compared below with the monthly gauging methods employed in 1965-9, it is relevant to note here that Spearman rank correlation of completeness of annual record with maximum annual daily mean and with annual range of daily means failed to yield statistically significant results. This lack of correlation suggests that gaps were randomly distributed through the year.

Table V Cave Creek Discharge Record

Hydrological year	1969 -70	1970 -1	1971 -2	1972 -3	1973 -4	1974 -5	1975 -6	1976 -7
Completeness of record (%)	94.2	86.4	67.2	72.1	31.2	84.7	16.7	75.4
Maximum Q recorded (l/s)	1346	5615	2302	1170	2672	7822	1639	2244
Range of Q recorded (l/s)	997	5271	1806	897	2372	7523	1434	2077
Annual mean of recorded daily Q's (l/s)	549	902	811	404	743	1040	651	383
Annual mean calculated from weighted monthly flowmeter Q as a % of annual mean from recorded daily Q's	108%	121%	94%	109%	117%	89%	96%	123%

The daily means are graphed on Figures 4 and 5 on a linear scale; the fact that it is possible to use a linear scale is itself a measure of considerable damping of fluctuations by underground drainage (cf. White & Reich 1970).

The other striking point in these graphs is the demonstration once more of the great variation in discharge from year to year, including one year when 1000 l/s was exceeded on only 2 days of record out of a 72% complete record with most breaks in summer time. The annual variability (highest mean annual flow/lowest mean annual flow, Gygax 1948) was, however, 2.7, considerably less than the figure of 5.6 for the 1965-9 period; no drought year was included this time as it was in the first period.

This record and Figure 6 confirm the previous ascription of this stream's regime to Pardé's oceanic pluvial type, to which the Cfb type of Beckinsale (1969), i.e. all-the-year flow with slight warm season minimum, corresponds. September and October are the months when large floods occur most commonly, though in fact floods occur at any time. Thus a peak of 3940 l/s was reached in February 1971 in the low flow season. The fresh data confirm the earlier adoption of April for the beginning of the hydrological year; it is the month when summer-autumn low flow is most likely to end. However this start can be delayed till August in a dry year.

In Table V the annual mean flows for 1969-77 calculated from the gaugings at roughly monthly intervals, weighted for the intervals between as was done for 1965-9 (Jennings 1972a), are expressed as a percentage of the annual mean flows calculated from the daily record neglecting gaps. However, the records for 1973-4 and 1975-6 are so poor that they are best left out of consideration. For the other years, this percentage ranges from 89% to 123%. Given the assumption of linear change between the monthly visits, positive errors will arise from the concave nature of the hydrograph in the long recession periods. Negative errors will arise from floods being missed by monthly measures. The overall mean of the annual means from the daily records for the 6 hydrological years for which the record is reasonably complete is 686 l/s and by extrapolation from the monthly visits is 722 l/s, giving an error of 5%. As an error of this order is involved in the flowmeter gauging on which both rest, there has been no gain by adoption of the more elaborate methods in the second period of observation as far as this overall figure is concerned, though this stricture does not apply to other aspects of this study, of course.

For consideration of the temporal aspect of solute loads it was desirable to complete the daily discharge record. Estimates for the missing daily discharges were made for me by Dr. A.J. Jakeman and Mr. M.A. Greenaway from the daily record (completed where necessary from Tantangara Dam station). A transfer function model was set up for this single input - single output system by means of a recursive instrumental variable - approximate maximum likelihood technique developed by P.C. Young and his colleagues and implemented with the programme CAPTAIN. The present application of the method will be discussed in Jakeman, Greenaway and Jennings (in prep.) but a brief explanation is given in an Appendix below.

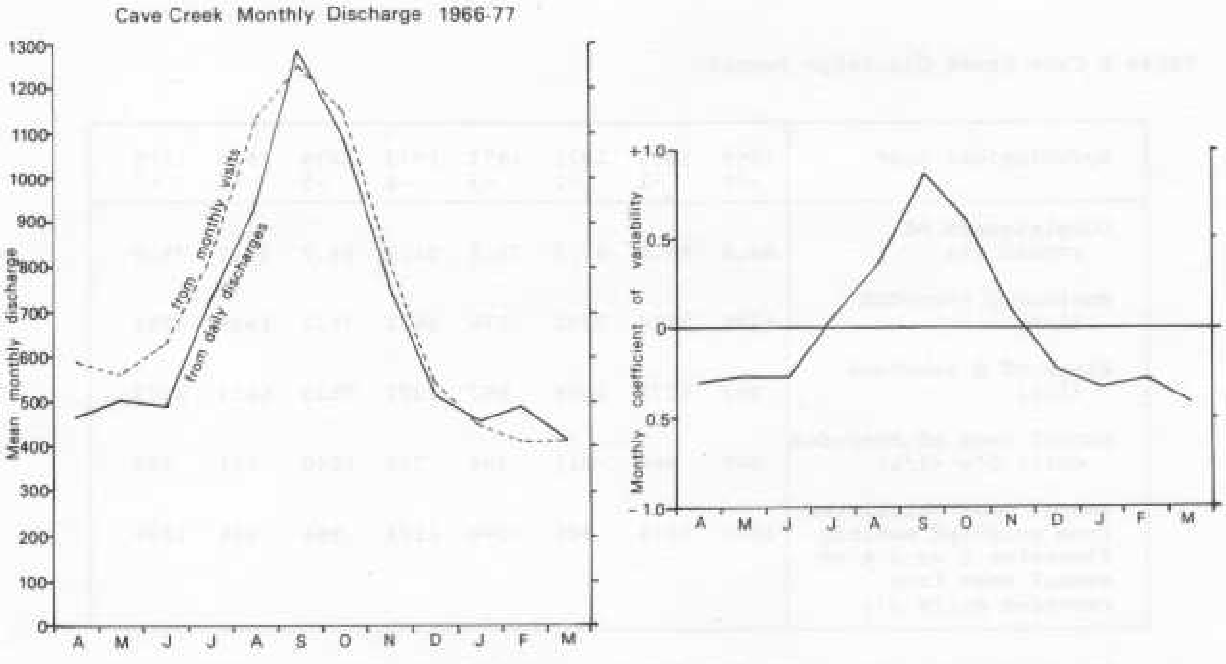

Figure 6. Runoff regime of Cave Creek, (a) monthly means, (b) coefficient of variability.

FLOW DURATION, STORAGES AND HYDROGRAPH SEPARATION

Figure 7 is a flow duration curve derived from the daily flows. For comparison are included the flow duration curves of the Riwaka South Branch in the Pikikiruna Range, New Zealand, a largely marble catchment (Williams & Dowling 1979), and Cheddar Spring, Mendip, England (Smith & Newson 1974). The most important difference between Cave Creek and the Riwaka is the lesser importance of high flows at Cooleman Plain. Factors explaining this are the greater and steeper relief, and the more intensive storms of the Southern Alps basin, but in addition there is the factor of difference of river pattern. There are many more streamsinks at Cooleman Plain; as their streams have different underground transit times, the flood peaks are blunted and recession curves prolonged.

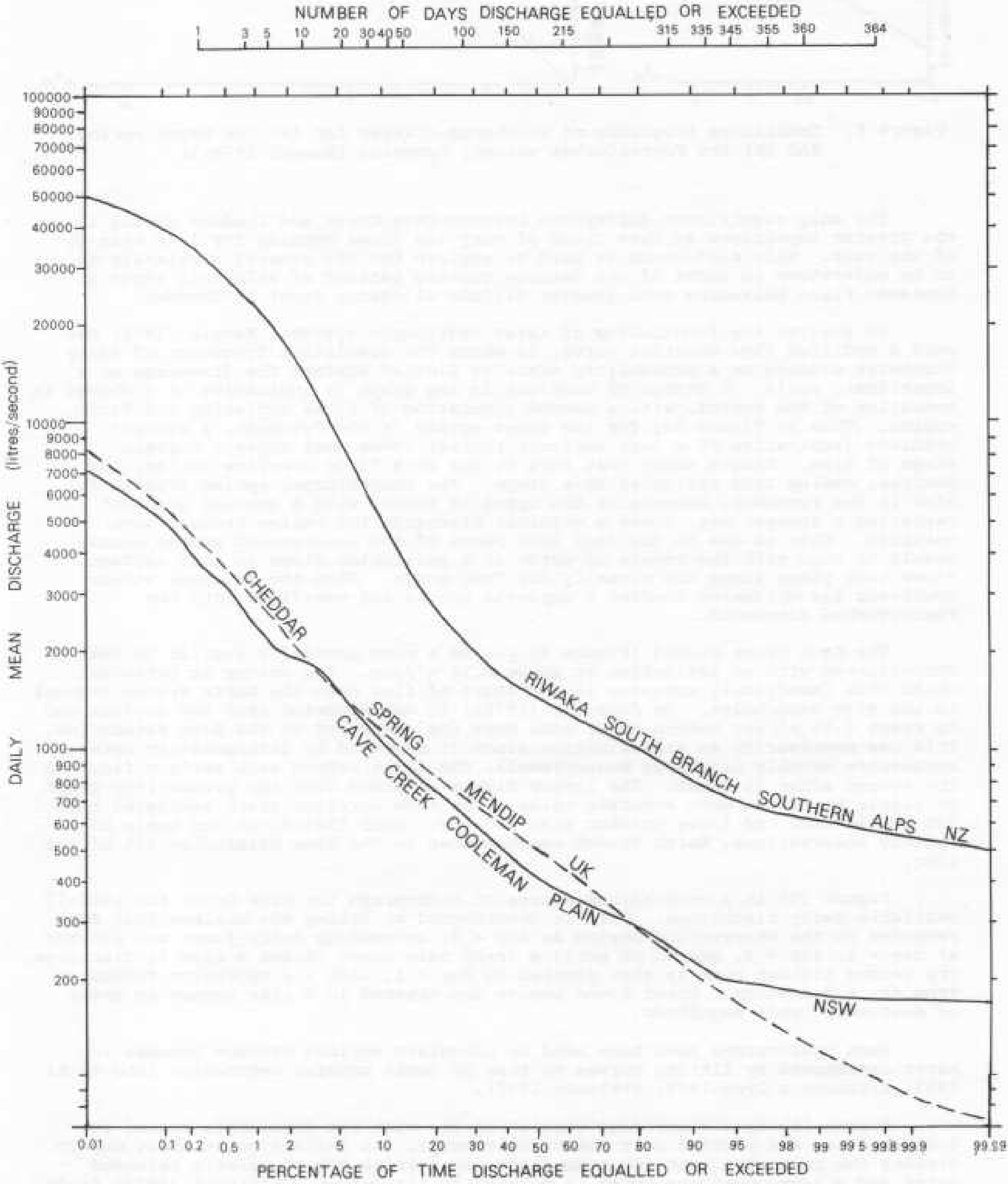

Figure 7. Flow duration graph for Cave Creek, Riwaka R. (Williams & Dowling 1979), and Cheddar Spring (Smith & Newson 1974).

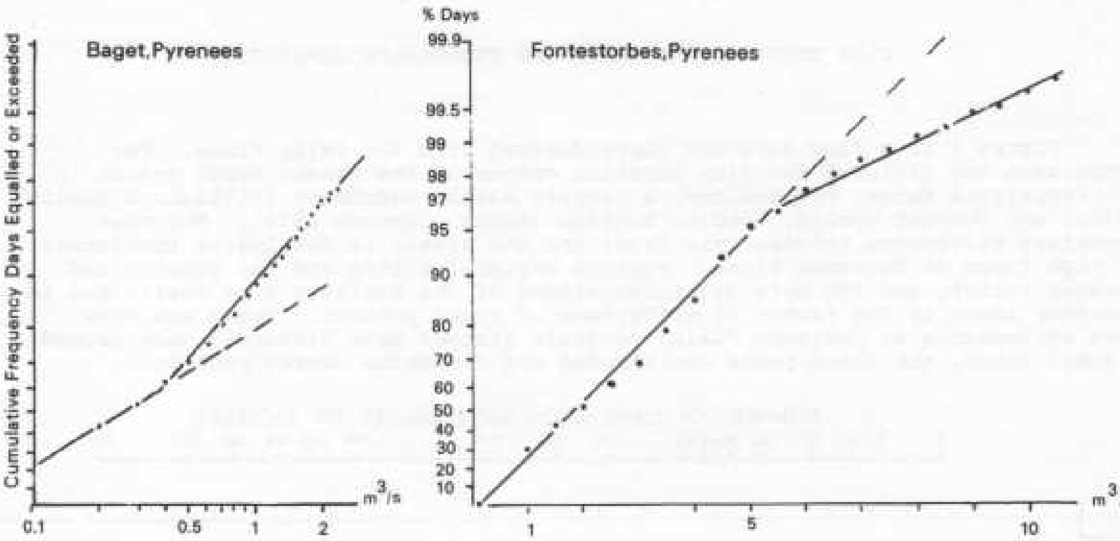

Figure 8. Cumulative frequency of discharge classes for (a) the Baget spring and (b) the Fontestorbes spring, Pyrenees (Mangin 1974-5).

The only significant difference between Cave Creek and Cheddar Spring is the greater importance at Cave Creek of very low flows running for less than 5% of the year. This difference is hard to explain but the general similarity is to be understood in terms of the damping routing pattern of allogenic input at Cooleman Plain balancing much greater diffuse allogenic input at Cheddar.

To analyse the functioning of karst hydrologic systems, Mangin (1975) has used a modified flow duration curve, in which the cumulative frequency of daily discharge classes on a probability scale is plotted against the discharge on a logarithmic scale. A change of gradient in the graph is indicative of a change in operation of the system, with a second population of flows replacing the first regime. Thus in Figure 8a, for the Baget spring in the Pyrenees, a steeper gradient (indicative of a less variable regime) takes over above a certain stage of flow. Mangin shows that this is due to a flood overflow spring, Las Hountas, coming into action at this stage. The Fontestorbes spring (Figure 8b), also in the Pyrenees, behaves in the opposite sense, with a gentler gradient replacing a steeper one; above a critical discharge the regime becomes more variable. This is due to the fact that parts of the underground system become unable to cope with the inputs of water at a particular stage so that surface flows take place along the normally dry Frau gorge. Also the Balagues stream overloads its streamsink feeding a separate spring and overflows into the Fontestorbes catchment.

The Cave Creek record (Figure 9) yields a plot basically similar to that of Fontestorbes with an inflection at about 0.70 m^3/sec. The change in behaviour which this immediately suggests is the start of flow down the North Branch channel to the Blue Waterholes. In Jennings (1972a) it was reported that the springs had to reach 0.55 m^3/sec before water came down the creek bed to the Blue Waterholes. This was necessarily an approximation since it depended on interpolating between successive monthly discharge measurements, the first before such surface flow and the second after it began. The larger figure obtained from the probability graph is likely to be the more accurate value. The flow duration graph indicates that 22% of the time had flows greater than 700 l/s. Over 1965-9, on the basis of monthly observations, North Branch reached down to the Blue Waterholes 35% of the time.

Figure 10a is a generalised recession hydrograph for Cave Creek for 1969-77 available daily discharges. This is constructed by taking the maximum peak flow recorded in the observation period as day = 0; succeeding daily flows are plotted at day = 1, day = 2, and so on until a fresh rain event causes a rise in discharge. The second highest peak is then plotted on day = 1, with its recession following from day = 2 onwards. Other flood events are treated in a like manner in order of descending peak magnitude.

Such hydrographs have been used to calculate various storage volumes in karst catchments by fitting curves to them by least squares regression (Abd-el-Al 1953; Atkinson & Drew 1974; Atkinson 1977).

Figure 10b is a simplified version of it, with the discharges meaned in 5 day classes and plotted on a logarithmic scale. An inflection at about day 20 divides the recession into two components, an initial one of quickly released water and a subsequent one which is delayed in its output. Atkinson (1977) finds this behaviour characteristic of Mendip karst catchments and labels the two regimes, quickflow and baseflow, by analogy with surface streams. The quickflow comprises allogenic streamsink water passing through caves and also percolation water descending quickly through widely opened joints from closed depressions and feeding small inlets into the cave streams; its storage is labelled vadose storage. The flow will be dominantly turbulent and governed by the Darcy-Weisbach equation. The baseflow is considered to derive from groundwater stored in joints and fissures in which flow is thought to conform to Darcy's Law for diffuse flow. Atkinson and Drew (1974) termed its storage 'fissure storage' and Atkinson et al. (1973) showed that as a flood event passed along cave passages, it could on the rising limb feed water into this baseflow storage, which on the falling limb returned it to sustain the recession in the later stages.

To define this baseflow, an exponential function of the form

$$q = a.e^{-bt}$$

where q = baseflow, t = days, and a and b are constants derived from the curve fitting, is fitted. From field experience in the Mendip, Atkinson (1977) fitted the curve to the data from t = 40 onwards, since after such a time most water supply points have dried up in the caves. This curve could then be projected back to day 0 to separate the baseflow and by integration to calculate the total baseflow storage above the level of the spring outflow level. For Cooleman Plain, 40 days seems too long on the basis of monthly visits to Murray Cave over 2 years for drip collection.

The inflection in Figure 10b suggests instead about 20 days. The discharge at 20 days on the flow duration curve is 1100 l/s, which corresponds with 11% of the time on the flow duration curve (Figure 7). The difference between this value and that of 20% of flow down North Branch to the Blue Waterholes is in part explained by the fact that the latter flow is sustained by delayed flow.

This limit of 20 days was employed to calculate the baseflow equation for Cave Creek

$$q = 1962\ e^{-0.0255\ t} \qquad r^2 = 0.828 \qquad (5)$$

with q in l/s

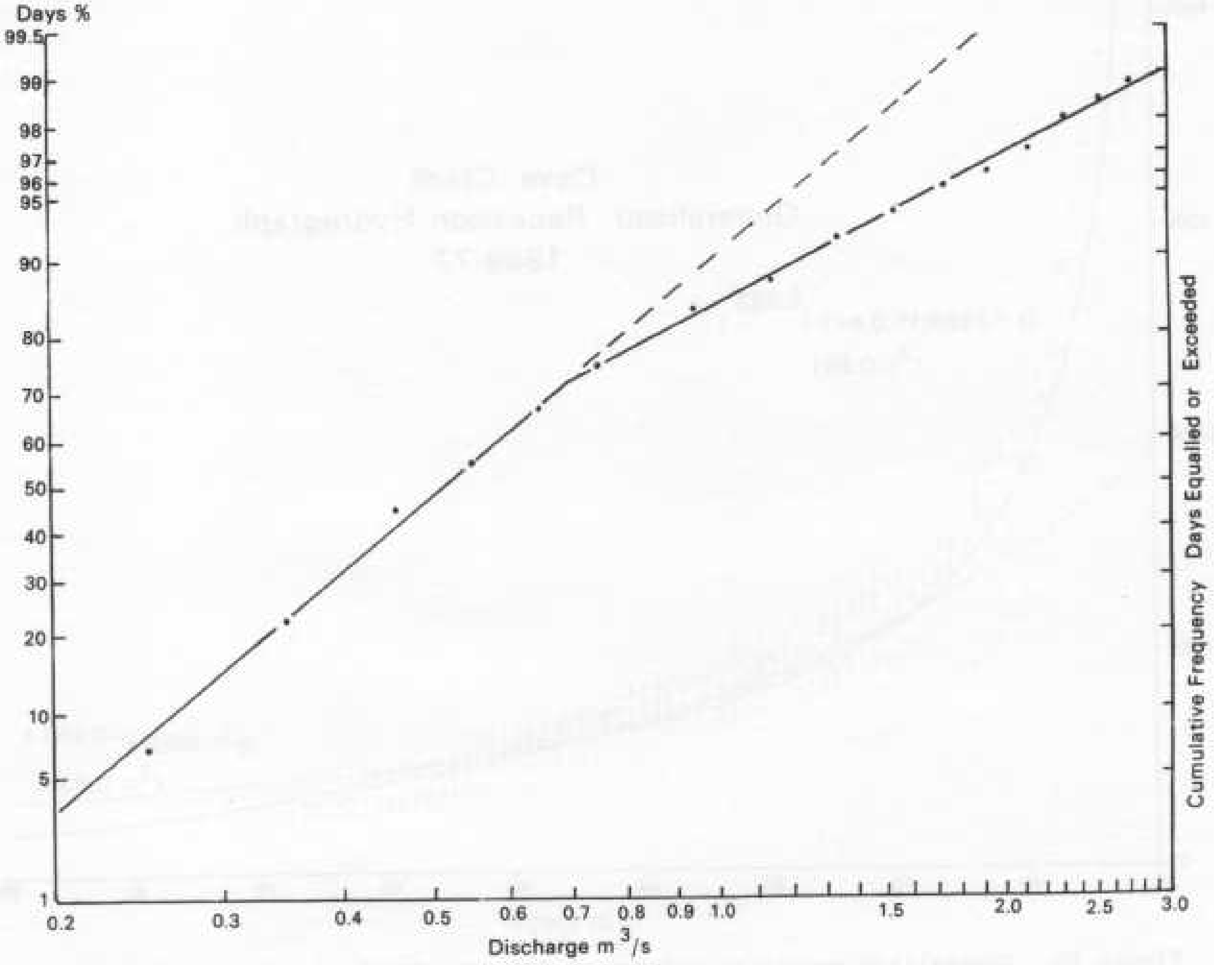

Figure 9. Cumulative frequency of discharge for Cave Creek.

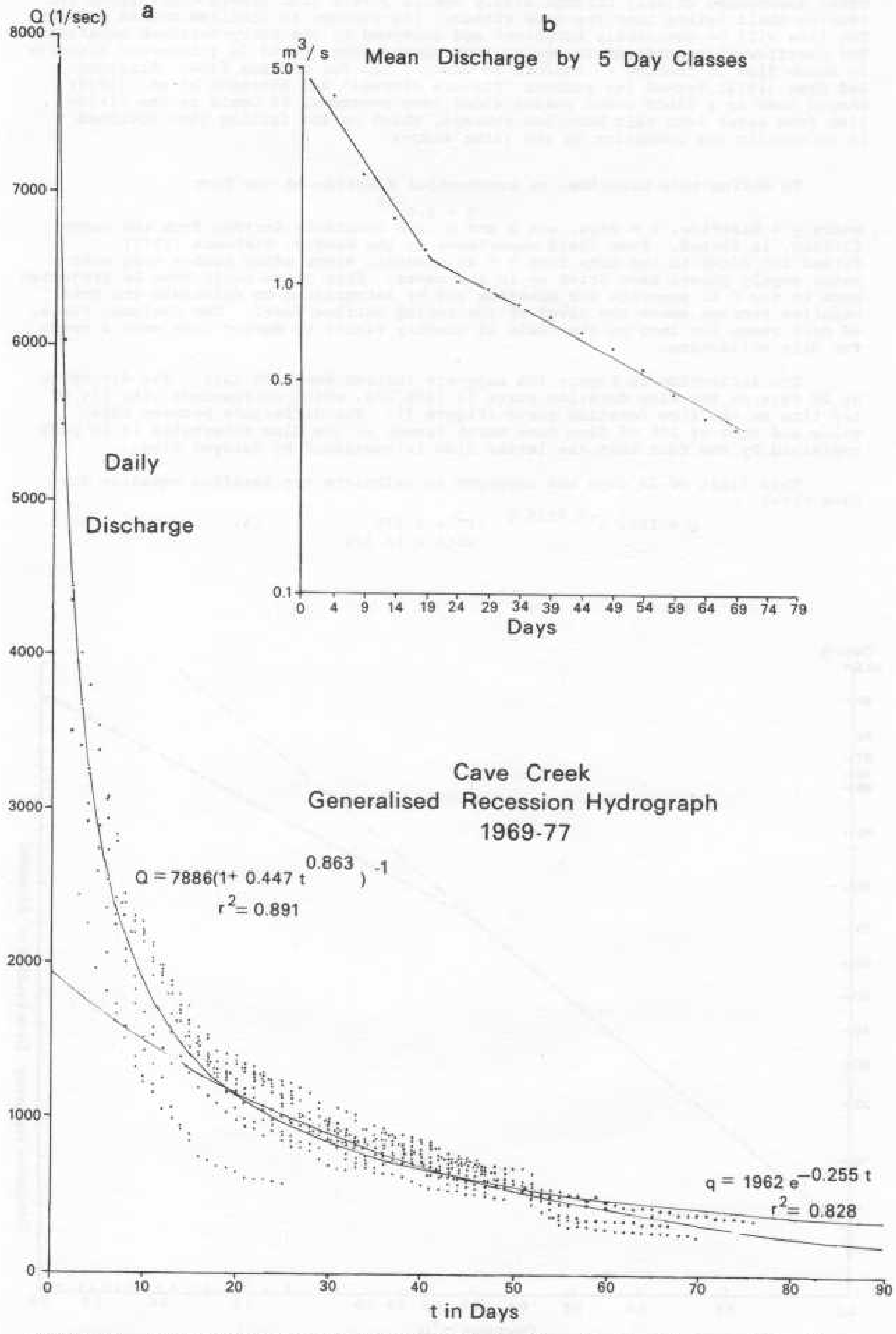

Figure 10. Generalised recession hydrograph for Cave Creek, (a) from daily flows, (b) from 5 day class means.

A hyperbolic curve is fitted to include the quickflow of the form

$$Q = Q_0(1 + a.t^b)^{-1}$$

where Q = total discharge at day t, Q_0 = total discharge at day 0, and b are constants from the curve fitting. By integration, the total storage over the quickflow period (40 days for the Mendip, 20 days for Cooleman Plain) is calculated from this equation and the vadose storage obtained by subtracting the baseflow storage over the same period. This vadose storage is essentially the volume of emptiable cave above spring level.

The hyperbolic for Cave Creek was

$$Q = 7886\ (1 + 0.4466\ t^{0.8632})^{-1} \qquad r^2 = 0.891 \qquad (6)$$

with Q in l/s

The total storage above spring level is calculated from day 0 to day 20 (40 at Mendip) by integration with the hyperbolic equation and from day 20 onwards with the exponential equation. Results are set out in Table VI, along with Atkinson's results from two Mendip catchments. For comparison, they are standardised by dividing the storage volumes by the area of the karst aquifer, namely the limestone area concerned.

Table VI Storages Calculated from Generalised Recession Hydrograph

	Cave Creek	Cheddar	Wookey Hole
Catchment area	55.7	39.4	30.6
Percentage in limestone	28.9	81.7	60.0
Total storage (m^3/km^2)	4.7×10^5	1.1×10^5	2.5×10^5
Baseflow storage (m^3/km^2)	3.9×10^5	1.0×10^5	2.0×10^5
Vadose storage (m^3/km^2)	8.0×10^4	1.2×10^4	5.3×10^4

The Cooleman Plain figures are in basic agreement with the Mendip results in that baseflow storage is much greater than vadose storage; this is another indication of a strongly damped system. This is a comparable conclusion to that of Wigley (1976) in respect of Mullamullang Cave in the Nullarbor Plain from study of its meteorology. From its 'breathing', he calculated a much greater volume for small voids of an impenetrable nature than for the cave proper.

However, there are differences from the Mendip catchments which need to be explained. The vadose storage per unit area is greater for Cooleman Plain proportionately to the baseflow storage as well as absolutely. In absolute terms, this may be in some degree fictitious as regards the Wookey Hole catchment. The Rodney Stoke springs are also fed from the catchment supplying Wookey Hole; if their output was brought into the calculation, the unit area storages would rise for the Wookey catchment. The higher proportion of quickflow at Cooleman Plain will be partly due to the component of surface flow coming down North Branch, which is necessarily included in this figure. In 1965-9, about 20% of the total output came down North Branch, though not all of this is quickflow, of course. On the other hand, the cave systems at Cooleman Plain are smaller and simpler than in the Mendip. The Cooleman karst is surrounded by higher country and is only being developed hydrologically from one outlet virtually. In contrast the Mendip is a limestone plateau surrounding its non-karst cores, with many springs around its upstanding periphery. This plateau stands up about 180 m whereas the dissection of Cooleman Plain is only about 90 m deep and the peripheral parts of its karst are at an early stage of karst development.

This geomorphological comparison makes the greater baseflow storage of Cooleman Plain compared with the Mendip catchments all the more surprising. It suggests that the development of fissure or baseflow storage is not closely dependent on cave development.

It is unfortunate in this circumstance that data are not available to calculate other hydrological elements in the system as Atkinson (1977) does for the Cheddar catchment. Thus the volume of water-filled conduits can be calculated through the difference in time of arrival at a spring of the mechanical effect of a flood and of the floodwaters themselves. This separation is a result of the hydraulic ram effect of the water-filled passages (the saturated zone of Mangin (1974-5), the phreas of Anglo-American literature). As soon as a flood pulse reaches the upstream end of the water-filled cave section, it causes an increase in discharge at the downstream end of that section, usually a spring. It is also possible to tag the floodwater with dye. The arrival of the floodwater as distinct from this mechanical effect is marked by a drop in solute content and an increase in turbidity. The total discharge between the two events is the measure of the volume of the water-filled passages. For Cheddar and other Mendip systems, it has been shown that the total is much smaller than the vadose storage, only 30% of it in the case of Cheddar. So far at Cooleman Plain water tracing has only been employed to elucidate drainage connections, not for quantitative purposes. As yet there are no indications of much development at depth below the Blue Waterholes. River Cave, Murray Cave and Cooleman - Right Cooleman Caves, nearly horizontal caves with only occasional small downward loops, point to epiphreatic development (Jennings 1969, 1970). A large, deeply looping, water-filled cave zone is not likely at Cooleman Plain. So only a small water-filled cave storage is to be expected.

An automatic conductivity meter was installed at the Cave Creek site for several months but the length of successful record was very short and the sensitivity not great enough for the small changes in conductivity experienced in flood events there. Thus it was not possible to employ this record for unit hydrograph separation by a method especially appropriate for solute-rich water. Instead the more arbitrary but practical method of Hewlett and Hibbert (1967) was adopted (Figure 11); this employs a line at a gradient of 0.55 l/s/km^2/h to separate quick flow from delayed flow. Following Gunn (1978), the index of catchment behaviour calculated was the ratio of quickflow to total flow during the duration of the quickflow (R_v). For Cave Creek, summing the quickflows and the total flows for 51 events (mainly multi-peaked) gave a percentage of quickflow of 33.1%. This is much greater than the values Gunn (1978) obtained from two small catchments of limestone bedrock in the Waitomo region of New Zealand, namely 16.7 and 8%. (The value of quickflow/total flow percentage of 50% by Atkinson (1977) for Mendip catchments is not comparable, being calculated in a different way). Nevertheless the Cave Creek R_v value appears to be comparatively low for a catchment with 71% impervious rocks. Part of the explanation of this value must reside in the routing pattern. All the water is routed through the limestone outcrop, most of it underground. In addition, the streamsinks are numerous and the inputs mainly small. They have different routes through the limestone and different transit times. The multiplicity of underground routes results in the output of the Blue Waterholes being smoothed and peaks blunted. The Cooleman Plain hydrological system is well damped, particularly because of routing.

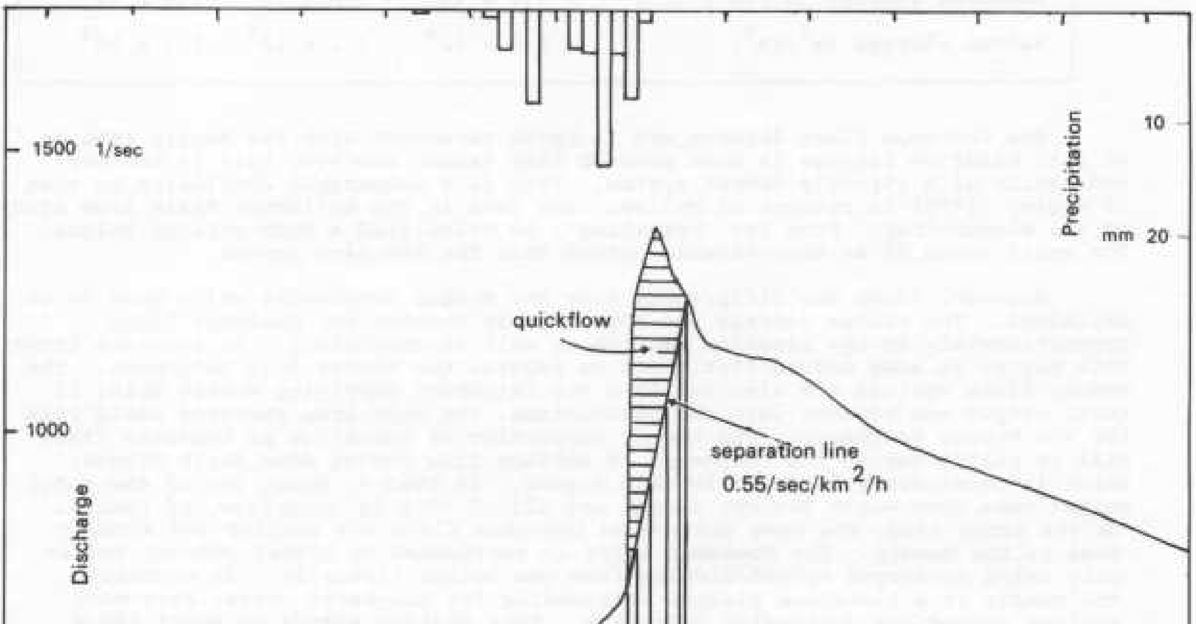

Figure 11. Hydrograph of a selected event to show use of (a) Hewlett and Hibbert separation line, (b) Gunn's quickflow/delayed flow ratio.

ALLOGENIC DRAINAGE

In Jennings (1972a), it was inferred on theoretical grounds that there would not be much difference in water yield per unit area between the limestone plain on the one hand and the surrounding ranges and central hills on impervious rocks on the other. The discussion of water balance above suggests this cannot be far removed from reality. Some direct discharge evidence was collected in this connection.

The discharges of two contrasted peripheral catchments, Devil Hole and Doosey Gully (named Six by the Fence in Jennings 1972a), were measured on 9 occasions through the year at the igneous rock - limestone contact and compared in terms of runoff per unit area with Cave Creek discharge for the same day. There is, of course lag between the inputs and the output, but the measures were variable in stage and season so the effects of lags may have largely cancelled out in the means. For Devil Hole, the mean water yield was 106 l/s/km^2, for Doosey Gully 90 and for Cave Creek 102. Such close agreements from inadequate data must be regarded to a degree as fortuitous; nevertheless it is reasonable to take them as supporting the assumption previously made.

On 9-11 November 1982 in a period of steady weather following prolonged drought, 26 peripheral catchments were gauged, mainly by the time and volume method so that the measures were good. However, many of the sites (fortunately for lesser inputs) rendered the determinations dubious in their meaning. They were located on swampy fans transgressing the impervious rock - limestone contact. The swamps caused distributary channel patterns and high evapotranspiration. At the same time their peats constituted important storages at this time of water dearth and were augmenting the surface flow. However they were also providing percolation water to the underground. Errors in determining input are inevitable in such circumstances whatever the state of the water balance.

The total discharge of these input streams amounted to 45 l/s when Cave Creek was carrying 240.6 l/s. However, this total is from only 22.1 kml^2 of the 39.4 km^2 of the impervious rock component of Cave Creek catchment. If it is assumed that the ungauged portion was yielding at the same rate as the gauged, the total input at this time would have been 80.4 l/s (33.4% of Cave Creek discharge). In addition, the measures were taken in an extreme condition, well inside the lowest decile of flow duration, when Cave Creek is bound to depend more on autogenic water (Williams & Dowling 1979). On this occasion, Doosey Gully and Devil Hole contributed only 3.5% of the Cave Creek volume whereas on the average of the 9 occasions discussed above, they yielded 6.3%. This permits the calculation of a total input of $(33.4 \times (6.3/3.5)) = 60.1\%$ as an estimate for the more representative collection of 9 occasions. This falls not far short of the 71% it should be if in fact the limestone and the other rocks were yielding equally.

(Acknowledgements and references will be included in consolidated form at the end of Part II).

APPENDIX

MODELLING A COMPLEX HYDROLOGICAL SYSTEM

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Australian National University

A cursory inspection of the rainfall - flow data over the years 1969 to 1977 reveals that the Cave Creek hydrological system exhibits significant changing facets of behaviour. Perhaps the simplest example of this is given by the steady state gain of the system. The property is the amount of flow produced per unit of rainfall input and this quantity was found to vary from 8 for the January to November period of 1972 to as much as 280 for the January to November period of 1970. Quite clearly, such variations are the result of complex storage and retention processes within the system and are not just due to some simple soil moisture effects.

On this basis, the use of any mechanistic model trying to detail the physical behaviour of the system was deemed inappropriate. Appeal was therefore made to a statistical approach incorporating the only significant mechanism known to be operating - an exponential-type decay in flow following rainfall events. The advantage of the approach is that it is capable of identifying the time intervals of consistent hydrologic behaviour. Thus different periods in the data set produced different statistical models with parameter values relevant to the period of interest. As we shall see, the basic structure of these models is similar and it is the values of the parameters in the structure which vary. What is important to note here is that the modelling exercise yields criteria for judging the validity of each model. Basically, these criteria are related to how well the model predicts known data and the reliability or confidence level of those predictions.

Satisfactory statistical models were found to exist for six monthly periods - December to May and June to November - over most of the data. In general, there were enough rainfall - flow data in each period to perform the modelling exercise from which the flow gaps for that period could be inferred. Unfortunately, two of these periods contained almost no flow records for modelling. In these cases, the most similar rainfall period with comprehensive flow records was sought. This was the January to November 1969 period and the model obtained for this was used on these other data sets.

A brief description of the model structure and its properties is now given but the reader can find more detail in Young (1978), Jakeman (1981) and Maherdrarajah et al. (1982). The form is a linear systems input (rainfall) - output (flow) model.

$$(1)\quad x_k = -a_1x_{k-1} - a_2x_{k-2} - \dots - a_nx_{k-n} + b_ou_k + b_1u_{k-1} + \dots + b_mu_{k-m}$$

which expresses that flow on day K, say, is a linear combination of flows on the n preceding days, and of rainfall on the current day and the past m days. In fact, this is equivalent to the unit hydrograph form since the above equation is a very good approximation of

$$(2)\quad x_k = g_ou_k + g_1u_{k-1} + g_2u_{k-2} + \dots + g_\infty u_{k-\infty}$$

However, the linear system model (1) has distinct advantages. The number of parameters (m+n+1) to be estimated is always much smaller than the number of non-zero g coefficients in (2). In the modelling exercises on Cave Creek, it was found that n=1 always and m varied from 0 to 2. A lower number of parameters yields lower variance on the statistical parameters and hence on the model predictions.

In practice, allowance must be made for errors in the data. The most general methods then for identifying the orders n and m and estimating the parameters a_i (i=1...,n) and b_j (j=0,1,...m) is known as the instrumental variable technique. The methodology has been computer packaged and is described in Jakeman et al. (1982).

The salient properties of the linear systems model (1) are the steady state gain, which has already been described, and the system time constants. With n=1, there is only one time constant and it can be defined as the time taken for the peak flow response to an impulse of rain to decay to about one-third of its peak value. It is a measure of the period of influence of previous rainfall. The time constant was reasonably consistent across most of the data sets, being around 9 days but it did vary down to 2-1/2 days on the December to May 1975 period.

Jakeman et al. (in preparation) provide the complete modelling results for all periods from 1969 to 1977. These include the models used to predict the gaps in flow data and computer plots of the rainfall, measured flow and predicted flow.

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MECHANICAL TESTING AND EVALUATION OF SCREW-LINKS

D.J. Martin

Abstract

Screw links (maillon rapides) are an item of equipment which may be used as an alternative to karabiners in some caving situations. The gate design of a screw link gives it several advantages over the karabiner. The results of testing of some screw links which are sold in Australia are presented. Some recommendations as to their suitability for caving use are given.

INTRODUCTION

Screw links are similar to karabiners in both function and shape. The main structural difference between screw links and karabiners is in the construction of the gate. Screw links are threaded on both sides of the gate gap. The gate is opened by screwing back the sleeve or nut to reveal a gap. This type of gate design eliminates the pinned spring loaded gate of the karabiner.

The gate design of screw links allows a small but strong link to be made as the sleeve physically connects the two sides of the gate together. It does, however, place more reliance on the caver to ensure the gate is properly screwed up. A karabiner will form a closed link of reduced strength when the gate springs shut by itself and is not tightened.

Martin (1981) discussed the uses, advantages and disadvantages of both oval and delta shaped screw links. For the Australian caver the only readily available screw links are the oval chain links sold in many hardware stores. A number of these links were purchased by the author and subjected to tensile and hardness testing and chemical analysis. The links tested were the Zenith brand quick links which are made in Taiwan. These are described as zinc plated.

METHODS

One set of links was subjected to destructive tensile testing. The Rockwell B surface hardness was determined for each link prior to tensile testing. Link sizes which were tested were 5, 6 and 8 mm ovals. Chains were used to mount each link in the jaws of a tensile test machine such that the link would be loaded along its long axis. Each link was progressively loaded to allow determination of yield and tensile forces.

A second set of links (4, 6 and 8 mm) was subjected to Vickers surface hardness testing. Each link was then chemically analysed to determine the alloying elements present. The grades of steel were then determined.

The sleeves of an 8 mm and a 6 mm link were removed by cutting them into several pieces. The thread length on both sides of the gate was measured for each of the two links. The outside diameter of the sleeve screw thread for each link was determined by removing the thread with a file and measuring the resulting diameter. The metal cross sectional area of the sleeve was determined for both links and compared to the cross sectional area of the link bar sizes. A micrometer was used to check the nominal diameters (i.e. size) of each link.

RESULTS

Yield forces and ultimate tensile forces for lengthwise loading of the first set of links are given in Table I. The manner in which each link failed is also given. The yield stresses and ultimate tensile stresses have been calculated and are based on the original underformed cross sectional area. The Rockwell B hardness of all three link sleeves was 88. This converts to a Vickers hardness of approximately 180. Plate 1 shows the broken links.

The Vickers hardness numbers for the second set of links ranged from 207 to 220 for the links and from 225 to 248 for their sleeves. Table II gives the results of the chemical analyses for this set of links. Determinations for nickel, chromium, molybdenum, copper, aluminium and tin contents were also carried out but are not presented here. The results for the 4 mm and 8 mm links correspond to AS1442-1979 Grade R1008 whilst the higher manganese content in the 6 mm link indicates a grade of AS1442-1979 K1008.

Table III compares the metal cross sectional areas of the 6 and 8 mm link bores and the sleeves. Thread length on either side of the gate is also given. The nominal diameters were found to be correct to +/- 0.15 mm. Plate 2 shows an 8 mm link with its sleeve removed to reveal the hidden thread. The cross section of the sleeve is shown with its thread removed.

NOMINAL SIZE (mm)	ULTIMATE TENSILE FORCE (kN)	ULTIMATE TENSILE STRESS (MPa)	YIELD FORCE (kN)	YIELD STRESS (MPa)	DESCRIPTION OF FAILURE
5	10.2	520	6.2	320	GATE THREAD PULLED APART
6	18.2	640	NO DEFINITE YIELD POINT		NECK AND SHEAR AT ONE END
8	43.6	870	15.6	310	NECK AND SHEAR AT ONE END

Table I Tensile Test Result.

LINK SIZE (mm)	Carbon	Phosphorus	Manganese	Silicon	Sulphur
4	0.035	0.018	0.31	0.005	0.015
6	0.075	0.015	0.59	0.13	0.021
8	0.055	0.019	0.35	0.005	0.032

Table II Chemical Analysis of Links - Principal Alloying Element.

NOMINAL LINK SIZE	CROSS SECTIONAL AREA OF BAR	CROSS SECTIONAL AREA OF SLEEVE	EXPOSED THREAD LENGTH	HIDDEN THREAD LENGTH
6 mm	28 mm^2	41 mm^2	4.5 mm	3.5 mm
8 mm	50 mm^2	75 mm^2	6.5 mm	5.5 mm

Table III Metal Cross Sectional Areas and Gate Thread Lengths.

DISCUSSION OF RESULTS

The human body is able to withstand a force of about 10 kN in a good harness and a dynamic fall situation (Eavis, 1981). Other system components should therefore be at least as strong as the human body. The test results indicate that both the 6 mm and 8 mm links satisfy this criterion. The 8 mm link tested yielded at a force higher than 10 kN. It will generally be considerations other than strength that will determine the suitability or otherwise of links of the 8 mm size in caving applications.

In normal use of a link the yield force should not be exceeded. Safe working loads are often presented as a percentage of the yield load. Some links have safe working loads stamped on them. These are 5.9 kN and 8.7 kN (on conversion from lbf) respectively for Zenith 6 mm and 8 mm links. The ultimate strength is of interest for situations such as falls. The 8 mm link withstood 10 kN without yielding. Unfortunately the yield point could not be determined on the load elongation curve for the 6 mm link. This link failed at 18.2 kN.

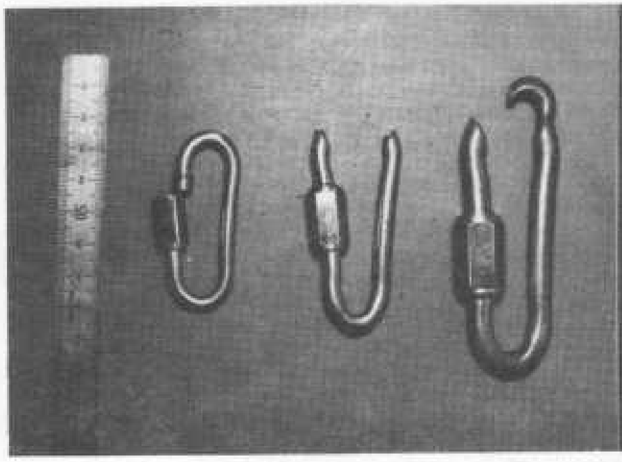

Plate 1. Tensile failures of 5, 6 and 8 mm links.

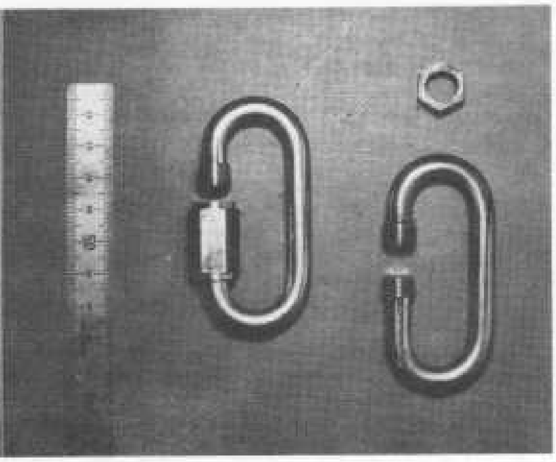

Plate 2. Hidden thread section on an 8 mm link and gate sleeve cross section.

Both the 8 mm and the 6 mm links sustained neck and shear failures at the radius at one end of the link. The sleeve threads were still operable on both links. The radius is the point where failure would be expected if the screw threads are properly designed.

By way of comparison the ultimate tensile test results compare to within 10% of 'strengths' of links as quoted in the Caving Supplies catalogue (1980). This reference quotes values of (when converted to kN) 19.6 kN for 6 mm and 39.2 kN for 8 mm links.

The 5 mm link failed when the gate thread was pulled apart. This is an undesirable feature and may indicate that the thread is underdesigned. The thread length should be such that the thread is at least as strong as the unthreaded bar section in the rest of the length. For the 5 mm link, two possibilities exist. Either the thread length is insufficient or the manufacturing tolerances are excessive, resulting in a reduction of thread strength. The yield stress for the 5 mm link has been determined on the assumption that the link was yielding and not the thread.

In an ideal situation the length of the thread on each side of the gate should be the same. With reference to Figure 1, dimension X should equal dimension Z. In the case where dimension X is greater than Z full strength should be developed when the sleeve covers a length equal to Z on the exposed thread side.

A number of links inspected by the author appeared to have 'sloppy' sleeves. Loose tolerances on the screw thread may be of assistance in the manufacturing process as it makes it easier to align the threads when the link is bent to shape. The threads would be rolled before the link is bent.

The exposed thread length on both the 6 mm and 8 mm links were found to be greater than the hidden thread length. The results given in Table III pertain specifically to those links which were measured. It is expected some variation would be found if more links were checked. In the case of the 6 mm link the thread height on the first and last turns of the hidden thread were less than on the middle section of the thread. These features are indicative of the manufacturing tolerances.

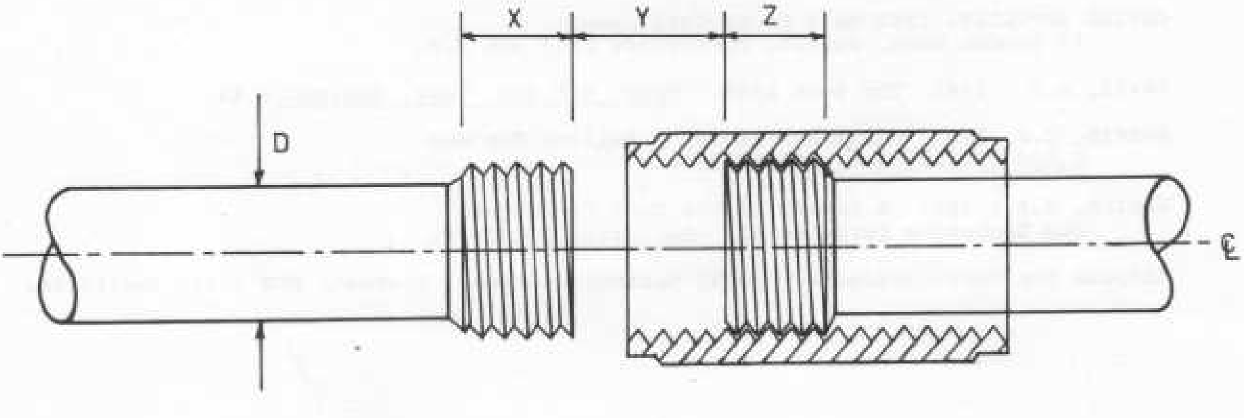

Figure 1. Screw thread details of a screw link.

The metal cross sectional areas of the sleeves appears to be just adequate when allowing for stress concentration and the case of the axial tension. For the 8 mm link the sleeve cross sectional area is 1.5 times the bar cross sectional area. The effect of bending or shear due to crosswise loading has not been investigated. Further work may be warranted in this area.

The hardness tests conducted on the two sets of links were to check all links were made from a similar grade of steel. All hardness results indicate the use of a low strength soft steel. This is verified by the chemical analysis results. The steels used have very low carbon contents and are hence cheap, suitable for cold forming and of relatively low strength. They are not suitable for heat treatment unless carburised.

Karabiners and screw links are both very strong when loaded along their long axis with their gates closed. Typically screw links will be smaller than karabiners for similar maximum safe working loads. There is no weight advantage in using smaller steel screw links instead of aluminium alloy karabiners. The karabiner is probably easier to use in many situations due to the larger gate opening (Martin, 1981). When using screw links in rigging applications, the loss of rope strength due to bending through a tight radius needs to be considered.

The strength of a karabiner loaded across the long axis is typically less than 5 kN (Eavis, 1981). The gate design of screw links eliminates some of the undesirable structural features of the karabiner. Sideways loading or three-way loading is probably most likely to occur in seat hardness attachment applications. Delta-shaped screw links should be used for this application rather than the oval shape.

CONCLUSIONS

Whilst a statistically significant number of links was not tested, the tensile test results are in reasonable agreement with the ultimate strengths quoted in the Caving Supplies catalogue (1980). The safe working loads claimed by Zenith would appear to be approximately 50% of the yield force.

The links which were tested were made from a cheap material and to what appeared to be relatively loose manufacturing tolerances. These are, however, significant factors in producing a link which is only a fraction of the cost of a karabiner.

The test also revealed a possible design problem with the screw threads on the brand tested. The thread failure exhibited by the 5 mm link and the variation in thread lengths in the larger links suggests that the larger links may also be capable of failing at the thread. It is unfortunate that one of the main factors determining link strength is a thread length which is always hidden.

The 8 mm links would appear to be strong enough for general caving use such as rigging pitches or use with the Cord Technique (Warild, 1981). Further work could be carried out into the strengths of links under crosswise loading.

ACKNOWLEDGEMENTS

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TAYLOR CREEK SILCRETE CAVE, NORTH OF MELBOURNE, CENTRAL VICTORIA

J.A. Webb and E.B. Joyce

Abstract

Taylor Creek Cave is formed within sediments of the Red Bluff Sand, a Pliocene unit overlain by Newer Volcanics. The cave consists of a single low chamber, 12 m long and 5 m wide, that has been excavated in friable sandstone under a resistant silcrete roof; it has formed by an unusual combination of piping and stream erosion. Taylor Creek initially exposed the silcrete surface, then piping below the silcrete caused tunnel formation in the sandstone. Collapse of overlying material into this tunnel captured Taylor Creek, causing it to flow beneath the silcrete and thereby enlarge the cave to its present size.

INTRODUCTION

Silcrete is a brittle, indurated rock composed mainly of quartz grains in a silica matrix. It forms as subhorizontal layers in the zone of weathering, as a result of silica accumulation in a parent rock (usually a sand or sandstone), and is of widespread occurrence in Australia (Langford-Smith, 1978; Ollier, 1978). Because of its texture and composition, silcrete is very resistant to erosion and forms an ideal caprock, giving rise to distinctive topographic features ranging from small cliff lines to mesas and buttes (Goudie, 1973). Small caves occasionally develop under silcrete horizons by weathering and removal of the unsilicified parent rock, and examples have been described from several localities in Queensland (Joyce, 1969; Grimes, 1974; Shannon, 1975). Taylor Creek Cave, a small but rather unusual silcrete cave in Victoria, forms the subject of this paper.

LOCATION

Taylor Creek Cave is located approximately 15 km NNW of Melbourne, Victoria, and 2 km NW of Keilor (Figure 1), at grid reference 07332408 on the Darley 2,500/32.20 sheet (M.M.B.W. map series). The cave is in the bed of Taylor Creek, which begins as a shallow swale on the basalt plain, but downstream cuts through the basalt to expose the strata beneath, including the silcrete in which the cave has developed. The creek flows into the cave entrance, which faces upstream.

The cave is on Melbourne and Metropolitan Board of Works land, and is approximately 2 km upstream from the Green Gully section of the Brimbank Metropolitan Park.

GENERAL GEOLOGY

Taylor Creek Cave is formed within sediments of the Red Bluff Sand (Figure 2), which is the upper formation of the Brighton Group (VandenBerg, 1973). The Brighton Group forms an extensive cover over the southern and southeastern parts of Melbourne, but thins markedly to the north and west. The lower formation of the Brighton Group, the Black Rock Sandstone, comprises predominantly marine fossiliferous sandstones of uppermost Miocene age. This unit lenses out approximately 6 km SE of Keilor. The overlying Red Bluff Sand is 24 m thick at the type locality to the south of Melbourne, and consists of poorly consolidated sands, silts, clays and gravels, often with cross-bedding and rapid changes in grain size. A predominantly fluviatile environment of deposition is likely, and the sparse flora and fauna indicate a Middle-Late Pliocene age (VandenBerg, 1973).

Northwest of Melbourne the Red Bluff Sand becomes a thin, discontinuous deposit of fluviatile silty sand and sandy gravel, often partly silicified. Taylor Creek Cave itself is formed within these sediments, which are regarded as Pliocene, although definite evidence of their age has yet to be found (VandenBerg, 1973). Strata under- and overlying the Red Bluff Sand near Keilor (see below) restrict the age of this unit to Middle Miocene - Middle Pliocene.

Approximately 300 m downstream of Taylor Creek Cave, the Red Bluff Sand overlies "ferruginous and earthy Trap", as it is designated on the Victorian Geological Quarter

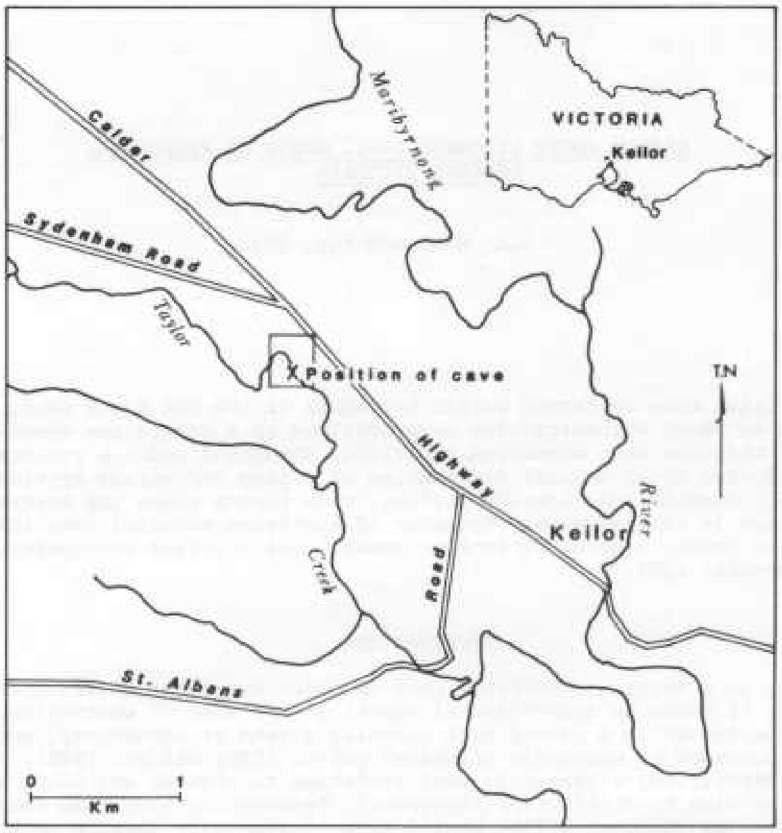

Figure 1. Location of Taylor Creek Cave.

Sheet 1 N.W.(c. 1860). This material apparently represents very weathered basalt of the Older Volcanics, a stratigraphic unit which outcrops in several discrete areas in the Melbourne district. In the Tullamarine-Keilor area the dominant lithology is a fine-grained olivine basalt, which has been radiometrically dated as 20-22 My old (Early Miocene; Bowen, 1975).

Two kilometres downstream, a thin unit assigned to the Fyansford Formation separates the Older Volcanics and Red Bluff Sand. This unit comprises a lower bryozoal calcarenite, containing forams of late Early Miocene age, overlain by fossiliferous ferruginous grits with early Middle Miocene fossils (Abele et al., 1976).

Stratigraphically overlying the Red Bluff Sand throughout the Melbourne district are the Newer Volcanics, basalt flows interbedded with occasional pyroclastic, sand and soil horizons. Most of the lavas are varieties of olivine basalts. The basalt plain south of the Maribyrnong River and west of Melbourne, including the Keilor area, has given several radiometric dates of 2.5-2.7 My (Late Pliocene; McDougall et al., 1966).

Along Taylor Creek, alluvium in the creek bed and on river terraces forms the youngest deposit present, together with some patches of colluvium on the hill-sides. Where the creek enters the Maribyrnong River (Figure 1) it is known as Green Gully, and terrace deposits in this area have yielded an aboriginal burial (Bowler, 1970) and numerous artefacts, including some of silcrete. A lower terrace along the creek is composed largely of blocks and boulders of basalt and silcrete, and carries a grey to black soil. An upper terrace has a red clay soil.

CAVE MORPHOLOGY

Taylor Creek Cave consists of a single low chamber, approximately 12 m long and 5m wide (Figure 3). The entrance is 8 m wide, but is partially choked by boulders and logs. Inside the entrance the rubble floor of the cave slopes down to a pool of water, with a gravel bank at its edge. The water depth increases toward the rear of the cave, reaching 0.6 m, and the bottom of the pool is covered with logs and boulders, separated by occasional patches of silt.

The walls of the cave are composed of white, friable sandstone, and a low shelf of the same material runs along the base of the northeastern wall. The roof is made entirely of silcrete, and slopes gradually from the entrance of the cave towards the rear, eventually disappearing beneath the water surface (section A-A', Figure 3). The maximum roof height of 1.2 m is just inside the entrance. The silcrete layer forming the roof is only 0.75-1.5 m thick, and is pierced by three small daylight holes. These are 15-25 cm in diameter, and lie more or less in a straight line.

To the east of the entrance the cave roof is only 0.1 m above the floor, which is dry and covered with dust, twigs and rubble.

The cave faces upstream, and when Taylor Creek is flowing the water in the creek runs directly into the cave, washing in rocks, logs and other debris. The cave has not been blocked with this material because there is a downstream exit, an underwater hole in the silcrete about 1 m wide and over 1 m long, which connects the pools of water inside and outside the cave (Figures 3, 4). This opening is sufficiently constricted that when Taylor Creek is running strongly, the water level in the cave may rise enough for water to flow out of the lowermost hole in the roof (arrowed on Figure 3). Presumably in flood times the whole cave may fill with water, and the stream flow over the top of the silcrete pavement. The water level in the cave in 1982 and early 1983 was unusually low because of the drought, and Taylor Creek rarely had running water in it.

DESCRIPTION OF THE SILCRETE OUTCROP

The silcrete layer which forms the roof of Taylor Creek Cave extends well beyond the bounds of the cave itself (Figure 4). To the south and west of the cave entrance the silcrete is exposed as a gently sloping pavement, rising towards the northeast. This pavement is approximately 25 m wide and 45 m long in maximum dimensions; to the west it disappears under basalt rubble, but in the east bank of the creek a 2 m cliff exposes basalt of the Newer Volcanics overlying the silcrete. A stratigraphic section at this locality (Figure 5) shows that the basalt is separated from the silcrete by a thin unit of yellowish unconsolidated sand, but the upper surface of the silcrete layer still seems to be a good approximation of the pre-basalt surface.

In the east bank of the creek, to the north of the cave entrance, there are several discontinuous outcrops of the silcrete pavement, separated from one another by soil and rubble creeping down from the overlying volcanics. These silcrete outcrops show that the pavement continues rising towards the northeast, reaching a high point about 59 m above sea level (Figure 4). To the northwest the silcrete surface appears to

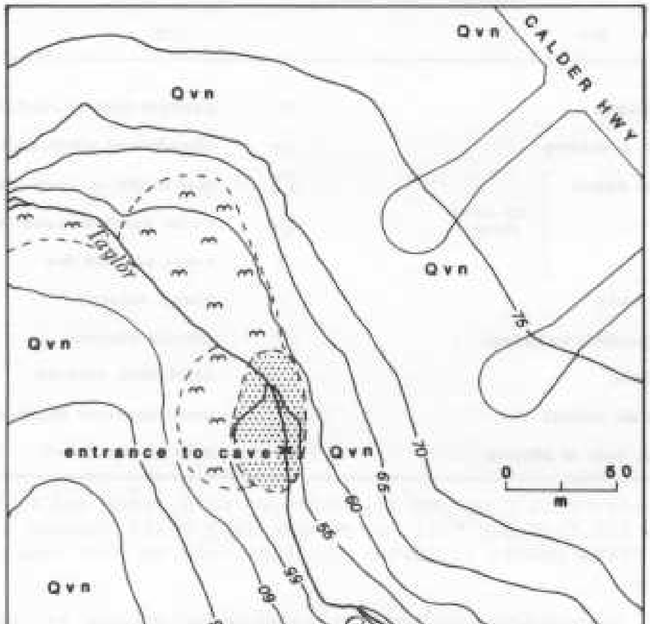

Figure 2. Geology and topography of area surrounding Taylor Creek Cave. Due to poor exposure, boundary of south-eastern outcrop of Red Bluff Sand is only approximate. Possible access roads shown.

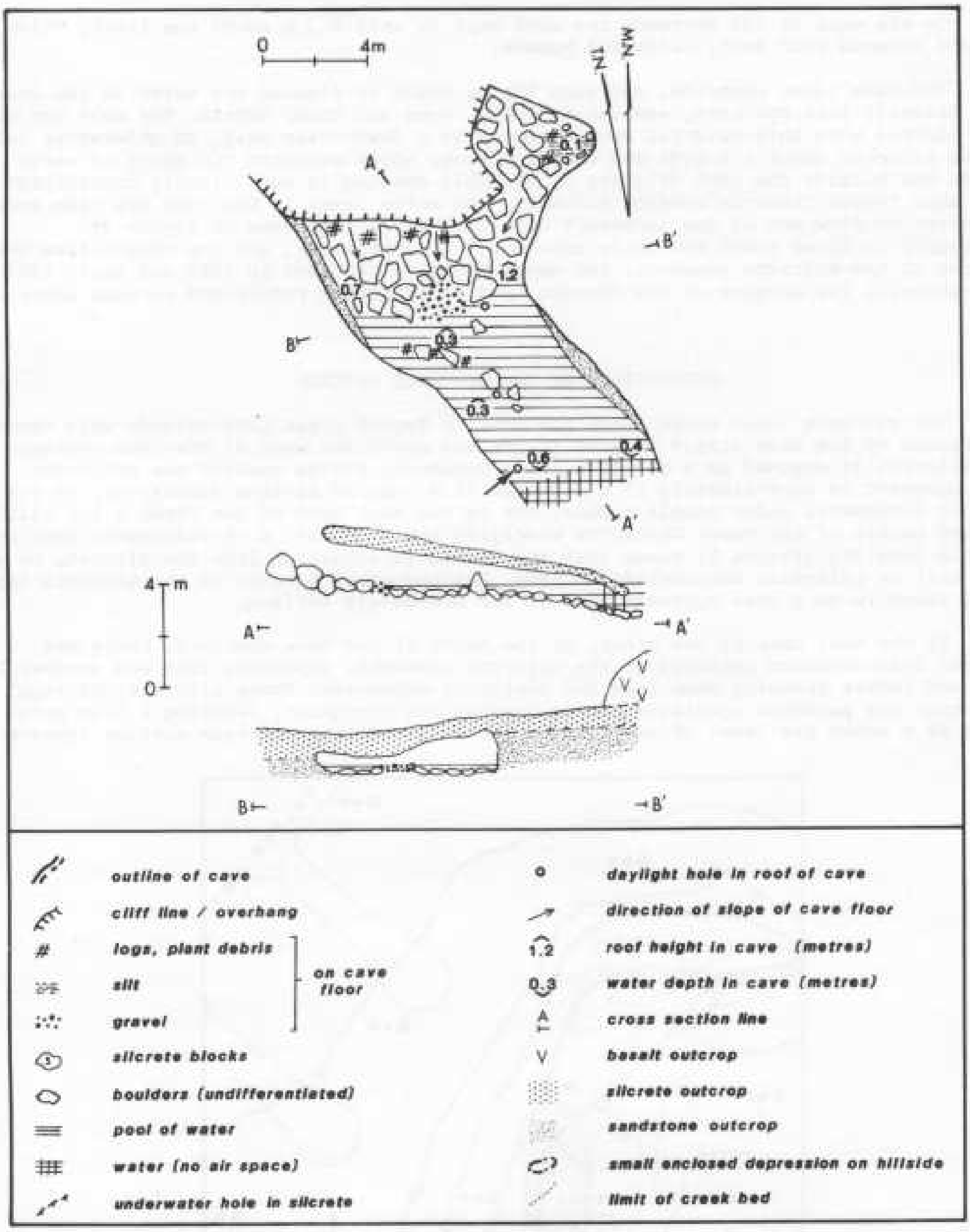

Figure 3. Map of Taylor Creek Cave (NW-2). Surveyed by J. Webb and B. Carter on 18.7.1982; A.S.F. Grade 5.5; map number 3NW2.VSA87. Legend also applies to Figure 4. Arrow points to lowest daylight hole in cave roof.

slope down gradually, disappearing under a river terrace (Figure 2). Although the terrace rises slightly to the north (upstream), it is at much the same topographic height as the silcrete outcrop, and is raised some 2-3 m above the present creek bed.

Thus the overall shape of the silcrete pavement appears to resemble a large hummock, with its crest about 59 m a.s.l. On the northern side, relief must have been over 1 m, as basalt outcrops at a topographic height of about 58 m in the creek bed 150 m northwest of the cave. On the southern side there must have been at least 8 m of relief, as basalt in the creek 75 m downstream of the cave is at a level of about 51 m.

Further downstream, the pre-basalt surface (i.e. Red Bluff Sand) reappears, and rises quite rapidly towards the south, displaying local relief of 8-9 m (Figure 2). This outcrop of Red Bluff Sand consists largely of sandstone, and contains only localized, discontinuous lenses of silcrete, which always occur less than 0.5 m underneath the basalt.

The bed of Taylor Creek immediately upstream of the cave contains mainly basalt rubble with some silcrete scree, and occasional outcrops of sandstone and silcrete (Figure 4). These silcrete outcrops are not part of the pavement described above, but represent small vertical or inclined bodies of silcrete, up to 2 m wide, that penetrate down into the sandstone.

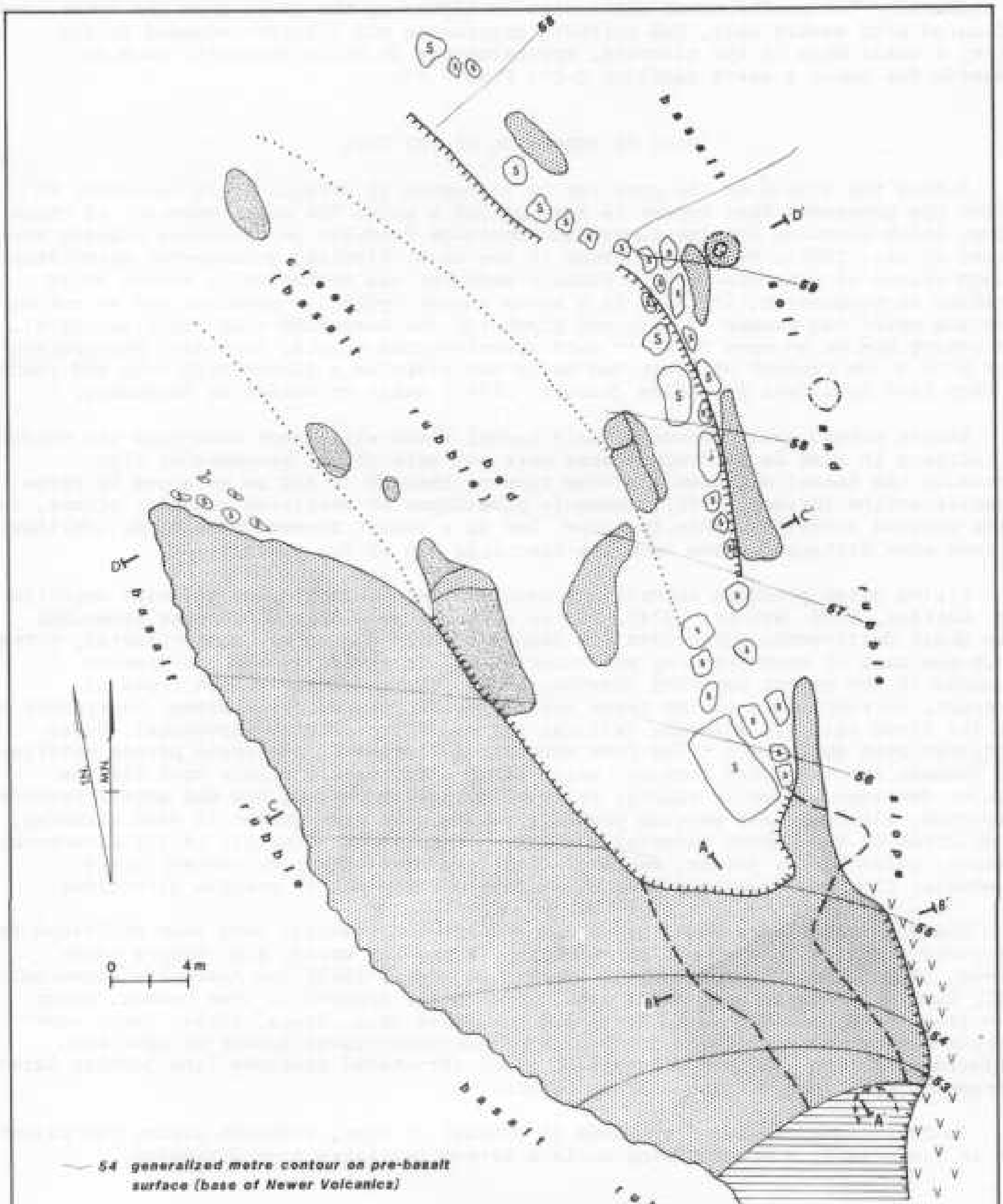

Figure 4. Detailed map of silcrete outcrop containing Taylor Creek Cave; for legend, see Figure 3. Basalt rubble shown only in cross-sections. Contours on pre-basalt (silcrete) surface are to Australian Height Datum; they have been generalized from spot heights surveyed using level and staff, and have an accuracy of ± 0.5 m. Note that the outcrops of silcrete in and immediately adjacent to the creek bed do not represent the pre-basalt surface (see text for details).

Above the silcrete outcrops in the east bank of the creek are two small enclosed depressions (Figure 4). Both are in basalt soil overlying the silcrete, and are about 2 m in diameter. The southernmost depression is higher up the slope than the other, and is floored with basalt soil. The northern depression has silcrete exposed in the centre; a small hole in the silcrete, approximately 30 cm in diameter, extends downwards for about a metre (section D-D', Figure 4).

MODE OF FORMATION OF THE CAVE

Before the origin of the cave can be discussed in detail, it is necessary to outline the processes that appear to have played a part. The most important of these is piping, which produces tubular subsurface drainage conduits in insoluble clastic rocks (Parker et al., 1964). Piping may occur in two ways. Firstly, groundwater percolating through cracks or pore spaces in a clastic sediment can mechanically remove solid particles in suspension, if there is a steep enough hydraulic gradient and an outlet where the water can escape readily and discharge its suspended load (Löffler, 1974). This outlet can be an open space or more open-textured strata. Secondly, percolating water with a low content of dissolved salts can disperse a flocculated clay and remove the very fine resultant particles (Warner, 1974); again an outlet is necessary.

Either method will produce a small tunnel which will erode back from the outlet and increase in size as it concentrates more and more of the groundwater flow. Eventually the tunnel may have a stream running through it and be enlarged by normal corrasive action (Grimes, 1975). Commonly subsidence of overlying material occurs, due to the erosive activity within the pipe, and as a result closed depressions (dolines) may form some distance upflow from the discharge end of the tunnel.

Piping often produces tunnels and cavities in unconsolidated alluvial deposits (e.g. Löffler, 1974; Warner, 1974), and is also the main erosive process producing caves under duricrusts. Duricrusts are indurated horizons, often subhorizontal, formed within the zone of weathering by accumulation of, or replacement by, different compounds in the parent material (Goudie, 1973). There are three main types of duricrust, corresponding to the three most important compounds involved; ferricrete or laterite (iron oxides), silcrete (silica) and calcrete (calcium carbonate). Caves associated with duricrusts arise from mechanical removal of unaltered parent material from beneath the indurated capping, which forms a relatively stable roof for the cavities developed. Usually piping, followed by stream action, are the active processes of erosion, although salt wedging probably causes cave enlargement in arid climates, and solution of the parent material may play a minor role (Renault, 1953). Structural elements, particularly joints, may influence cave development by concentrating groundwater flow and causing preferential cave development in certain directions.

Closed depressions, small caves and underground drainage have been described from ferricrete terrains in a number of countries around the world, e.g. Sierra Leone (Bowden, 1980), India (Goudie, 1973), Brazil (Simmons, 1963) and Australia (Robertson, 1982). Similar features associated with silcrete are apparently less common, being known from the Sahara (Renault, 1953) and Australia (e.g. Joyce, 1969). Caves under calcrete duricrusts are almost unknown. Most duricrust caves appear to have been initiated by piping, sometimes localized along structural features like joints; later enlargement by stream corrasion often occurs.

In comparison, Taylor Creek Cave is unusual in that, although piping has played a part in its origin, a pre-existing surface stream initiated cave formation.

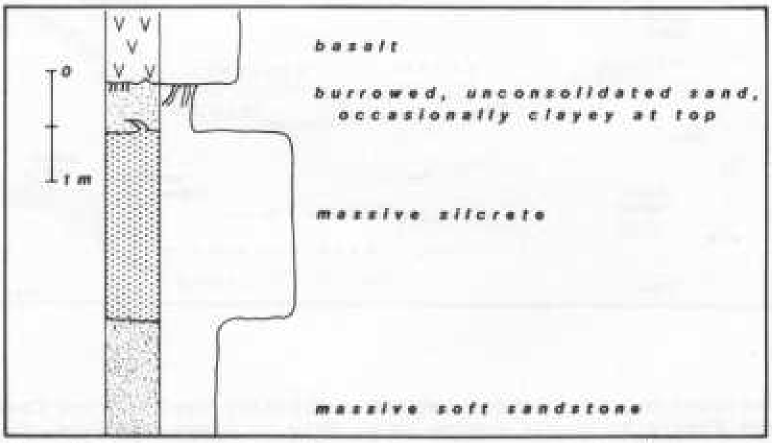

Figure 5 Generalized stratigraphic section of units exposed in the east bank of Taylor Creek, immediately to the south of the cave entrance. Left hand column shows lithologies, right hand column shows sedimentary structures and idealized outcrop profile.

During the Quaternary, Taylor Creek cut down through the Newer Volcanics to expose the pre-basalt topography beneath. At the cave site this erosion revealed a hummock of very resistant silcrete; the crest of this hummock served as a local base level of erosion until it was breached by Taylor Creek. That this took some time is shown by the presence of a small river terrace immediately upstream of the silcrete hummock and at approximately the same topographic level as its crest (Figure 2).

Prior to development of the cave, Taylor Creek must have uncovered the downstream-sloping section of the silcrete pavement, much of which is still preserved (Figure 4). There are several holes in this silcrete surface (Figure 3), and piping probably began behind the lowermost of these, and perhaps behind some of the others as well. Percolating ground water would have eroded a small tunnel in the sandstone underlying the silcrete, the hole in the silcrete serving as the outlet. Mechanical removal of clastic grains would have been the main process in operation; dispersion of flocculated clay was probably a minor factor, as the sandstone contains very little clay.

Water sinking in the bed of Taylor Creek probably supplied the groundwater which was eroding the tunnel. Eventually enlargement and headward erosion of the pipe under the silcrete were sufficient for it to capture all of the water in Taylor Creek, probably as the result of a collapse into the tunnel, upstream of the crest of the silcrete hummock. The collapse may have occurred where the silcrete was thin, penetrated by holes, or absent altogether.

Taylor Creek was thus diverted beneath the silcrete pavement, instead of flowing over it, and the corrasive action of the stream enlarged what was probably once a small tunnel into the larger cave now present. The downstream exit of the stream from the cave is sufficiently restricted that in times of flood the creek probably fills the cave and flows over the top of the silcrete pavement. The river terrace upstream of the cave now lies abandoned above the present stream level (Figure 2).

Thus, the cave has formed largely because of the fortuitous shape of the silcrete surface. Further downstream Taylor Creek eroded through the pre-basalt surface easily because the silcrete there is present only as small, discontinuous lenses. Approximately 500 m southwest of Taylor Creek Cave a silcrete pavement has been exposed by a tributary of Taylor Creek, but this pavement is almost flat-lying and no caves have developed.

The small enclosed depressions in the basalt soil on the hillside above the cave (Figure 4) have resulted from the downward movement of soil particles into cracks in the silcrete. Presumably piping in the underlying sandstone removes the clay once it has passed through the silcrete. The occurrence of only two small dolines suggests either that there are few open cracks in the silcrete, or that piping in the underlying sandstone develops only rarely.

ACKNOWLEDGEMENTS

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