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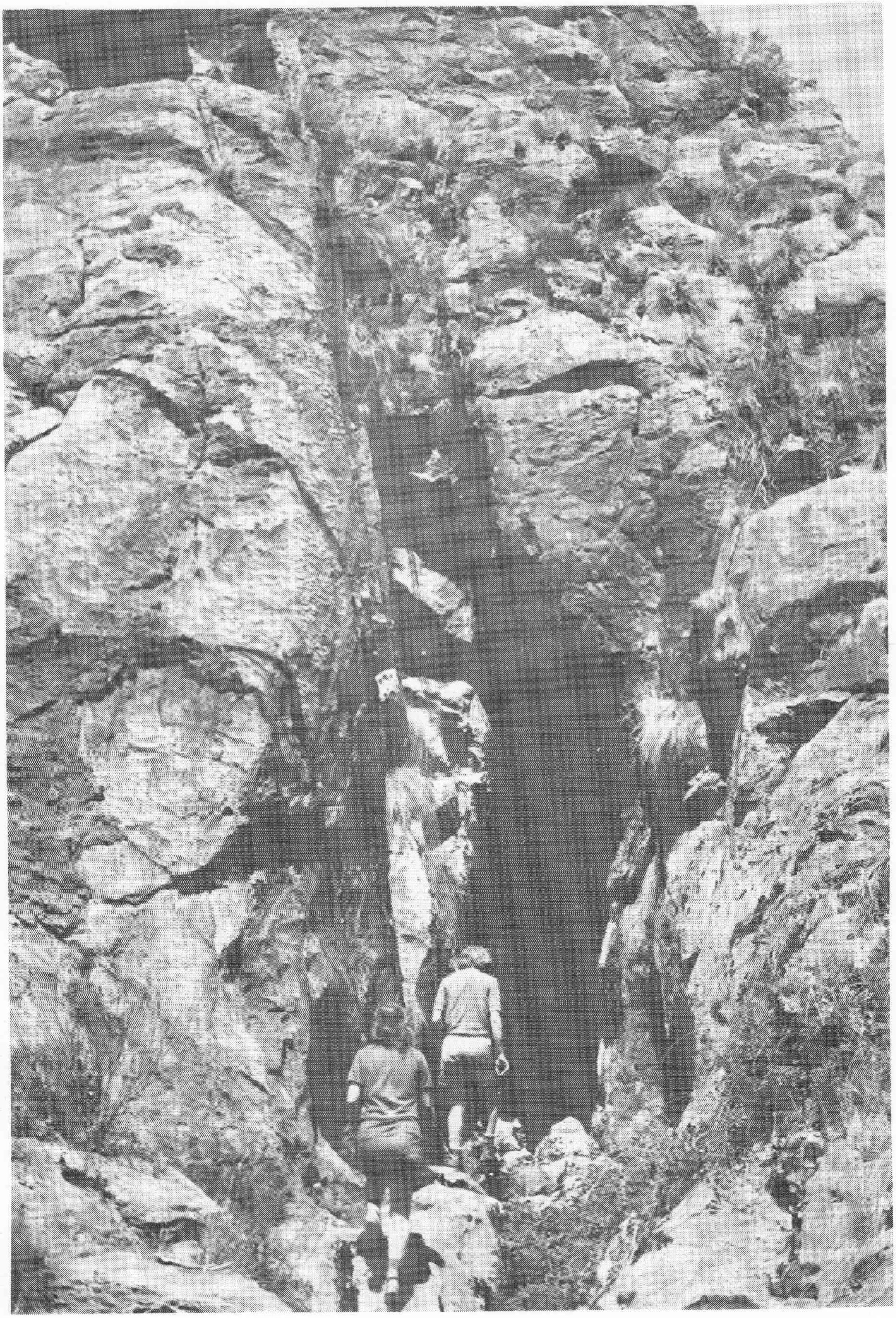
Helictite

JOURNAL OF AUSTRALASIAN CAVE RESEARCH



Murray Cave, Cooleman Plain, N.S.W.

Photograph by Guy Cox

HELICTITE

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This Journal was (and is) intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia in the truest sense— Australia, New Zealand, the near Pacific Islands, New Guinea and surrounding areas, Indonesia and Borneo.

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CONTENTS

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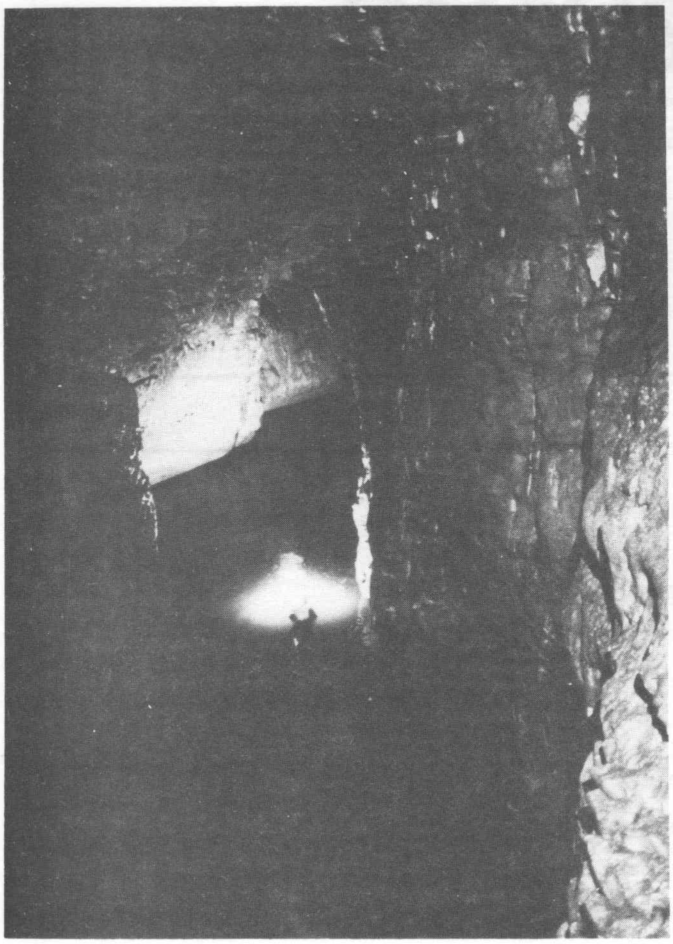

FURTHER STUDIES AT THE BLUE WATERHOLES, COOLEMAN PLAIN, N.S.W., 1969-77

PART II WATER CHEMISTRY AND DISCUSSION

J.N. Jennings

Abstract

The 1969-77 data confirm that groundwater temperature is significantly higher than air temperature at mean catchment altitude but provide only partial support for an explanation in terms of soil temperature and insulation of drainage from cold air ponding over the Plain. Higher pH of output than input streams is attributed mainly to percolation water chemistry.

Water chemistry of two contrasted input streams suggests non-karst rock weathering has an important effect on allogenic input streams.

An inverse relationship between carbonate hardness and output discharge is found again and attributed mainly to faster transit through the limestone at high flows. Summer has a steeper regression than winter due to precipitation and high flows depressing carbon dioxide and carbonate concentrations more in that season than in winter.

Picknett graphs show how solutional capacity varies through the hydrologic system, with aggressive input streams, mainly saturated percolation water, and rarely saturated output springs because of the allogenic component in the last.

The total carbonate load of Cave Creek is directly related to discharge, with little seasonal difference so the annual regression is chosen for later calculation.

When the carbonate load duration curve and frequency classes for Cave Creek are compared with those for other karsts, it falls into an intermediate class in which neither very high nor low flows dominate the pattern. This is attributed to a combination of a large allogenic input with a complex routing pattern.

Consideration of most input stream solute concentrations on one occasion indicates such close dependence on catchment geology that doubt is cast on the smallness of the 1965-9 allocation of carbonate contribution from non-karst rock weathering to the allogenic input.

This is explained by new CSIRO rainfall chemistry figures from the Yass R. catchment which are smaller than those used before and by elimination of a previous error in calculation. This time subtraction of atmospheric salts is done on a daily basis with a decaying hyperbolic function.

Correction of Cave Creek output for allogenic stream input follows the method adopted in 1965-9 but on a firmer basis, with the assumption of approximately equal water yield per unit area from the non-karst and karst parts of the catchment being more factually supported than before. It remains a substantial correction.

The correction for subjacent karst input to Cave Creek is also improved by putting the calculation in part on a seasonal basis; it remains small.

The exposed karst solute load output shows the same seasonal pattern as was determined earlier, with a winter/spring maximum, and it again evinced much variation from year to year. So did annual rates. The mean annual loss of 29 B was slightly greater than for 1965-9. If this difference is real and not an experimental error, the reduced allowance for atmospheric salts and greater annual rainfall in the second period could explain the increase. This erosion rate of 29 B from an annual runoff of about 400 mm places this karst where it would be expected in the world pattern of similar determinations in terms both of runoff and its proximity to the soil covered/bare karst dichotomy of Atkinson and Smith (1976).

Combined with the other work at Cooleman Plain on erosion at specific kinds of site, an estimate of the spatial distribution of limestone solution is presented. It agrees well with the similar attempt for Mendip by Atkinson and Smith (1976), when allowance is made for certain differences in method and context. The main conclusions are the great role of solution in the superficial zone and the unimportance of the contribution from caves.

Conflict between this process study and the geomorphic history of Cooleman Plain remains and once again an explanation is sought in long persistence of a Tertiary ironstone cover inhibiting surface solution.

WATER TEMPERATURE

Stream temperature of Cave Creek at the gauging site was determined on 105 monthly visits to ± 0.25°C. Seasonal change is apparent despite variation in the time of day at which the measure was taken (Figure 12). The mean annual range of 4.9°C for 1969-77 was significantly different from the 1965-9 means for the Cliff Foot Rising (the biggest single spring at the Blue Waterholes) of 3.0° and for Cave Creek immediately below the other Blue Waterholes springs of 2.8°. These differences are not thought to be caused by the different periods of observation but by the effect of atmospheric temperature variation over the 300 m surface flow of the groundwater component to the new gauging site. The extreme ranges of temperature follow the pattern of the annual ranges.

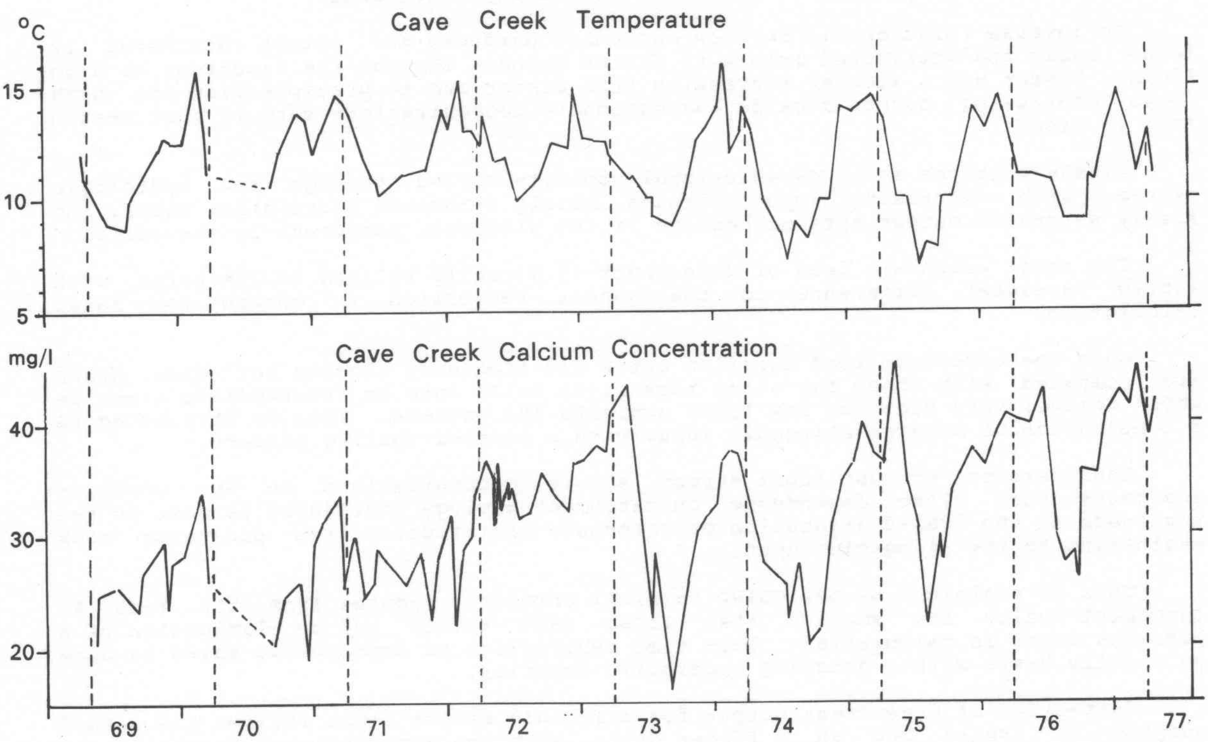

Figure 12 Temperature and calcium concentration graphs for Cave Creek for 1969-77

The differences in mean temperature, 11.8° for the new gauging site compared with 10.8° for Cliff Foot Rising and 10.9° for the upstream Cave Creek gauging site, may, however, be due to different climatic years being involved. The 1969-77 temperature mean confirms that there is a problem in spring temperatures being appreciably higher than the mean annual air temperature of 7.4°C (1973-7) at Coolamine Homestead which is at mean catchment height. Jennings (1979b) suggested two reasons why the spring waters were so much warmer. Soil temperatures were shown to be higher than air temperatures and it is these which will affect percolation water into the limestone. Secondly much of the drainage goes underground through the Plain, thus escaping the effect that cold air pondage over the Plain has on surface streams. The mean temperature of drip waters in Murray Cave close below the Plain of 10.8° (228 observations over 1972-3 (Jennings 1979a)) supports the first argument. In relation to the second argument, temperatures of peripheral streams were taken in daytime only and this makes comparison of their means with Cave Creek and Murray Cave, where diurnal variation is entirely or largely suppressed, misleading.

pH

Table VII sets out pH measurements by Lovibond Comparator precise only to ± 0.1 unit from Cave Creek, Doosey Gully and Devil Hole. Reducing the data set to the 70 days when all were measured has practically no effect on the statistics. The times of day at which pH was measured varied from place to place as well as from day to day. The results are presented because such a data set for input and output water from an Australian karst area has not been published before.

Table VII pH of Allogenic and Output Stream Water Cooleman Plain 1969-77

Site	Annual			Nov.-Apr.			May-Oct.			Dec.-May			June-Nov.		
	n	x	S.D.	n	x	S.D.	n	x	S.D.	n	x	S.D.	n	x	S.D.
Cave Creek	106	8.0	0.3	57	8.1	0.3	49	8.0	0.3	57	8.0	0.2	48	7.9	0.3
Doosey Gully	83	7.4	0.3	44	7.5	0.3	39	7.3	0.4	42	7.3	0.4	38	7.3	0.6
Devil Hole	80	7.3	0.5	41	7.4	0.4	39	7.3	0.6	44	7.3	0.3	39	7.3	0.4

Cave Creek's pH is significantly higher than those of the allogenic streams at P = 0.001 but the two input streams do not differ from one another at P = 0.05. The mean pH of drips in Murray Cave of 7.9 (Jennings 1979a) shows that autogenic percolation water causes most of the increase in pH between input streamsinks and output springs but solution of limestone by cave streams will make some small addition (Jennings 1977, 1981).

Whether these two factors explain all the difference between input and output appears doubtful when the seasonal pattern is considered. The seasonal breakdown shows a slightly higher summer/autumn pH than in winter/spring, with a slightly later changeover at the output end as might be expected. This is the opposite of the distribution found in Murray Cave drips (Jennings 1979a). Following Moore (1962), the latter distribution was attributed to the greater summer acidity of the drips through greater biogenic carbon dioxide production in the soil above in the warmer months. It is true that there is more allogenic water than autogenic water coming up at the limestone spring but one might have expected soil pH in the allogenic catchments to be controlled in the same way as above Murray Cave. Evaporative concentration of salts, which might raise pH, is reported from surface streams in Victoria (Anderson 1945). However the Devil Hole stream has steep gradient and rapid flow so this factor should be small in its case.

The pH of artificial catchments on bare limestone and soil-covered limestone (Jennings 1978) is relevant here. In both cases, the summer pH was higher than the winter one, thus agreeing with the stream data and departing from the drip data.

These crude seasonal figures conceal more complex variation such as the discussion, for example, by Miotke (1974) of soil carbon dioxide content would lead us to expect. Closer study over time is necessary to resolve the controls over pH variation.

SOLUTE CONCENTRATIONS

The purpose of this section is to characterise the nature of the chemical load put out of Cooleman Plain and to recognise its origins.

(a) Non-carbonate ions

(1) Sodium (by flame photometer, lithium internal standard; maximum expected error at c.10 ppm = ± 5%)(Table VIII).

Table VIII Na^{++} (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	16	1.44	0.41	0.92	2.32
Devil Hole	13	1.85	0.46	0.90	2.49
Doosey Gully	15	2.84	0.70	1.60	3.82

The mean concentration of sodium in Cave Creek (which agrees with the mean of a larger set in the earlier period) is significantly lower than in Devil Hole and Doosey Gully, suggesting there is a component from igneous rock weathering as well direct input from the rain. In this second period, no relationship between sodium concentration and discharge at Cave Creek was detectable, though a significant inverse relationship was determined in a larger sample set in the 1965-9 period.

(2) Potassium (by flame photometer, lithium internal standard; maximum expected error at c. 1 ppm = ± 5%)(Table IX).

Table IX K^{++} (mg/l)

	n	x	S.D.	Min	Max
Cave Creek	20	0.59	0.21	0.26	0.95
Devil Hole	13	0.62	0.17	0.35	0.85
Doosey Gully	18	0.87	0.21	0.43	1.36

Again there is correspondence between the mean potassium concentration in the two periods of observation at Cave Creek. Devil Hole carries about the same as Cave Creek whereas Doosey Gully has significantly higher values than both. No relationship with Cave Creek discharge was recognised in both periods.

(3) Silica (colorimetrically with ammonium molybdenate; maximum expected error at c.10 ppm = ± 5%)(Table X).

Table X SiO_2 (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	8	12.11	4.51	5.6	20.0
Devil Hole	8	11.13	4.24	7.1	18.0
Doosey Gully	8	25.21	14.18	7.9	44.0

Few determinations were made in this second period of observation but the mean lies very close to that of the larger sample for 1965-9. Devil Hole did not differ significantly from Cave Creek whereas Doosey Gully gave substantially higher values. Again there was no significant relationship with the discharge of the river.

(4) Chloride (turbidometrically at 600 μm wavelength in spectrophotometer by precipitation of silver chloride; maximum expected error at c. 10 ppm = ± 5%)(Table XI).

Table XI Cl^- (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	16	2.6	1.2	1.0	4.6
Devil Hole	13	2.5	1.9	0.0	6.0
Doosey Gully	16	2.9	2.0	0.0	6.1

For the 1969-77 period Cave Creek yielded much lower concentrations than for the earlier period when they were already low compared with those from many catchments in eastern Australia. The agreement between results for the two periods for other ions suggests the possibility of experimental error for Cl^- in the earlier period, though of course other explanations offer. Again there was no significant relationship with discharge. The common value of input and output streams suggests that this ion is supplied by the rain.

(5) Sulphate (turbidometrically at 478 μm in spectrophotometer by precipitation as barium sulphate; maximum expected error at c.10 ppm = ± 5%)(Table XII).

Table XII SO_4^{--} (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	38	5.4	1.5	2.0	7.8
Devil Hole	34	4.0	1.1	1.5	6.6
Doosey Gully	35	4.3	1.1	2.0	6.2

The input stream means are not significantly different from that of Cave Creek. Pyrites occurs sporadically in the Cooleman Plain Limestone but evidently it has little effect on the solute load. There is no significant relationship with discharge.

The concentrations of these five ions are all lower in Devil Hole water than in that of Doosey Gully. Although the two catchments are much the same size, that of Devil Hole is steeper and quite a long reach of the Doosey Gully stream immediately above the sampling point is of low gradient and somewhat swampy. There is only slight lithological justification for this difference in solute concentration on the basis of the geological map (see section on allogenic input below). A variety of igneous rocks composes both catchments but there is less opportunity for take-up of weathering products in the Devil Hole basin and more opportunity for evaporative concentration of the Doosey Gully water along the flatter, lower part of its valley. Reason is given below for thinking that this cannot be the critical factor however.

(6) Alkaline earth/alkali ratio, (Table XIII).

The Cave Creek ratio shows again that its water is very much a bicarbonate water as it is to be expected since the proportion of limestone in the extended catchment for the second period of observations has not changed significantly.

Table XIII (Ca + Mg)/(Na + K)
(cations in equivalents per million)

	n	x	S.D.
Cave Creek	15	22.0	4.3
Devil Hole	12	3.3	1.6
Doosey Gully	14	7.0	6.5

The two input streams have much smaller ratios, with that of Devil Hole being statistically significantly lower than that of Doosey Gully. Both are high compared with igneous catchments reported by Douglas (1968).

(b) Carbonate Ions, (Table XIV).

The calcium and magnesium concentrations of Cave Creek are closely comparable with the 1965-9 figures; indeed total carbonate hardness with a mean of 88.2 is not statistically different from the earlier means from both Cliff Foot Rising and the creek immediately below the main Blue Waterholes. This low hardness for a karst river is largely due to the dilution of autogenic karst water by allogenic inputs from the igneous frame of the Plain. The low ratio(6-9%) of magnesium to calcium in the limestone springs means that its presence has nearly minimal effect on calcium solubility equilibrium (Picknett 1972).

The much lower calcium concentrations and higher calcium/magnesium ratios of the Devil Hole and Doosey Gully streams are to be expected from their igneous rocks. The sampling points for both catchments are right on the limestone/volcanic contact as mapped by Owen and Wyborn (1979). Nevertheless the means for calcium and bicarbonate of the Doosey Gully stream are surprisingly high, though, from a small sample set, Williams and Dowling (1979) do give a mean of 9 mg/l for Ca^{++} in runoff from volcanics in the Riwaka South Branch catchent.

The graph of calcium concentration against time in Figure 12 shows a seasonal pattern of a late winter minimum rising to a maximum in autumn, a pattern which parallels but sometimes lags behind that of temperature and biological activity.

In the second period of observation, strong inverse power relationships were found for Cave Creek between calcium and total hardness as dependent variables and discharge as the independent, comparable with those determined for Cliff Foot Rising and the creek immediately below the main Blue Waterholes for 1965-9 (Table XV). There is some loss of statistical explanation when the full sets of chemical determinations are employed since 'noise' will arise with the indirectly derived chart height discharges; nevertheless these regressions based on chart discharges will be employed in later calculation because of the wider range of ion concentrations incorporated in this way.

The inverse relationship is attributed primarily to the shorter transit time of high waters reducing the opportunity for solution of limestone then rather than to the achievement of saturation equilibrium at low stages. (See discussion of solutional capacity below). Also at high stage there is greater likelihood of water coming down the bed of North Branch on the surface. However a power relationship implies that floods are not so diluted that they become unimportant in the limestone solution regime.

Table XIV Karst Concentrations and Ratios

(1) Calcium (by EDTA to potentiometric endpoint; maximum eexpected error at c.10 ppm =&+2%, at c.100 ppm =&+1%).

Ca^{++} (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	104	31.6	6.3	16.1	45.2
Devil Hole	81	4.2	2.3	1.2	9.4
Doosey Gully	87	15.8	8.4	3.1	39.3

(2) Magnesium (by EDTA to potentiometric endpoint. Maximum expected error at c. 1 ppm=&+4%,at c.10 ppm =&+2%)

Mg^{++} (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	104	2.7	0.8	1.0	6.9
Devil Hole	81	1.5	0.7	0.3	3.7
Doosey Gully	87	2.6	1.0	1.2	6.5

(3) Bicarbonate (by titration with HCl to potentiometric endpoint: maximum expected error at c.30 ppm=+5%, at 300 ppm =+2%)

HCO_3^- (mg/l)

	n	x	S.D.	Min.	Max.
Cave Creek	96	110	17	63	146
Devil Hole	77	25	6	16	43
Doosey Gully	82	65	24	21	130

(4) Total Carbonate Hardness (calculated by equivalent of Ca and Mg)

Total Hardness ($CaCO_3$ + $MgCO_3$)

	n	x	S.D.	Min.	Max.
Cave Creek	104	88.2	16.9	47.5	123.3
Devil Hole	79	15.5	7.0	6.3	30.8
Doosey Gully	83	48.7	22.4	14.2	106.0
Cliff Cave Spring (1964-9)	7	109.5	5.7	104.0	118.0
Temporary western springs	20	137.5	14.5	115.0	173.5

(5) Calcium/Magnesium Ratio

Ca / Mg

	n	x	S.D.	Min.	Max.	C.V.%
Cave Creek	104	12.5	4.1	5.2	27.4	33
Devil Hole	79	3.5	2.8	0.7	16.0	81
Doosey Gully	87	6.8	3.7	1.6	17.3	55
Cliff Cave Spring	7	11.7	1.9	9.3	14.1	16
Temporary western springs	21	16.2	5.9	9.4	40.0	37

Table XV Regressions of Calcium and Total Hardness on Discharge
Cave Creek 1969-77

	n	r^2	
Ca = $164.6\ Q^{-0.28}$	28	0.83	Highly significant Q by flowmeter
Ca = $165.6\ Q^{-0.26}$	95	0.66	" " Q by chart height
Total hardness = $439.2\ Q^{-0.27}$	28	0.78	" " Q by flow meter
Total hardness = $415.0\ Q^{-0.25}$	95	0.65	" " Q by chart height
Total hardness (Dec to May) = $612.4\ Q^{-0.31}$	56	0.66	" " Q by chart height
Total hardness (June to Nov) = $283.6\ Q^{-0.19}$	48	0.52	" " Q by chart height

The total hardnesses were classified into rising and falling stage, "summer" i.e. December-May) and "winter" (i.e. June-November) subsets and these subsets regressed against discharge by log-log transform. There was not a significant difference between the rising and falling stage values; this could be simply due to the fact that there were only 6 values for rising limbs. Between "winter" and "summer', however, there was a significant and substantial difference. Therefore these regressions will be used later in load calculations.

For December to May

$$\log T = 2.787 - \log Q^{0\cdot308} \qquad r^2 = 0.67 \qquad (7)$$

and for June to November

$$\log T = 2.453 - \log Q^{0\cdot192} \qquad r^2 = 0.49 \qquad (8)$$

where T = total hardness in mg/l and Q = discharge in l/s.

The steeper summer regression can be attributed to the generally higher hardnesses of that season associated with higher soil carbon dioxide pressures; these suffer more extreme dilution by rainstorms and flood events.

SOLUTIONAL CAPACITY

A Picknett graph of pH against total hardness was used to assess degree of saturation towards limestone of Cooleman Plain waters in the 1965-9 period (Jennings 1972b). Since that time it has become the practice to employ better measures such as SATCAL (e.g. Ford 1971). However, for these measures, pH enters into the calculations as an exponent so precise measures of pH are necessary. At Cooleman Plain, pH continued to be measured with an error of ± 0.1 unit. Therefore the graph method (Picknett 1973) is retained here (Figure 13). With little sulphate and magnesium not far from the optimal 10% of calcium, some of the other risks in employing these graphs as a guide to aggressiveness or supersaturation are minimised. Argument from it must nevertheless remain broad. Observations from the 1965-9 period are included in constructing Figure 13 to strengthen the assessments being made. The saturation equilibrium band for 8-16°C covers nearly all the sample temperatures.

Devil Hole stream, an allogenic input from a steep catchment of igneous rocks, has low concentrations of calcium with a widely ranging pH. It is very aggressive water at all times.

Doosey Gully, another allogenic stream on igneous rocks but with a long reach at low gradient where evaporation may be significant, ranges more in hardness and less in pH. Though mainly aggressive water, it approaches saturation for calcite occasionally in summertime.

Autogenic diffuse infiltration is represented only by drips from Murray Cave, though sampling there has been done regularly through the seasons and from a number of points (Jennings 1972a, 1979a). The cave is horizontal and lies 5 to 50 m below the limestone surface; there is no correlation between hardness and depth. Hardness is high but remarkably variable. Since the samples were collected from stalactites or draperies, it is not surprising that about two-thirds of the samples were saturated or super-saturated.

Cliff Cave Spring is a small, permanent spring near the western margin of the Plain, thrown up by the overlying impervious Blue Waterholes Formation. Water tracing has so far failed to identify a streamsink linked to it. It now seems unlikely that Devil Hole is one such but the small stream near Harris Hut remains a probable contributor. However, the spring seems to be mainly fed by percolation water. Sampling has been infrequent but its hardness is generally higher than that of the Blue Waterholes. It has not yet been sampled at saturation or above.

In this western part of the Plain, several small, intermittent springs have been sampled a few times in winter and spring after periods of favourable water balance. These have the highest hardnesses of any springs sampled at Cooleman Plain but again never at saturation. They are probably supplied by what Gunn (1981) calls subcutaneous water.

Cliff Foot Rising, the largest single spring at the Blue Waterholes, is not thought ever to be supplied by water which has come down the surface channel. When this is happening, water is welling up from joints in the whole vicinity of the Blue Waterholes so Cliff Foot Rising is fed by groundwater even then. Nevertheless it has lower hardnesses than the springs just discussed because a large allogenic component passes through cave systems such as River Cave to this major output area (Jennings 1969). Only rarely did the water of Cliff Foot Rising reach saturation during observations between 1963 and 1969.

Samplings of Cave Creek just above the Blue Waterholes when North Branch is running down have lower hardnesses than Cliff Foot Rising yields but since pH ranges to higher values, a few samples reach equilibrium and beyond. The allogenic proportion is bound to be greater than with the underground circulation to the Blue Waterholes, though it is precisely when the stream reaches this far down that it receives accessions of groundwater from temporary springs (including Murray Cave, a flood overflow of the underground course of the South Branch) along its valley across the Plain. Higher pH may be due to CO_2 degassing from the autogenic component.

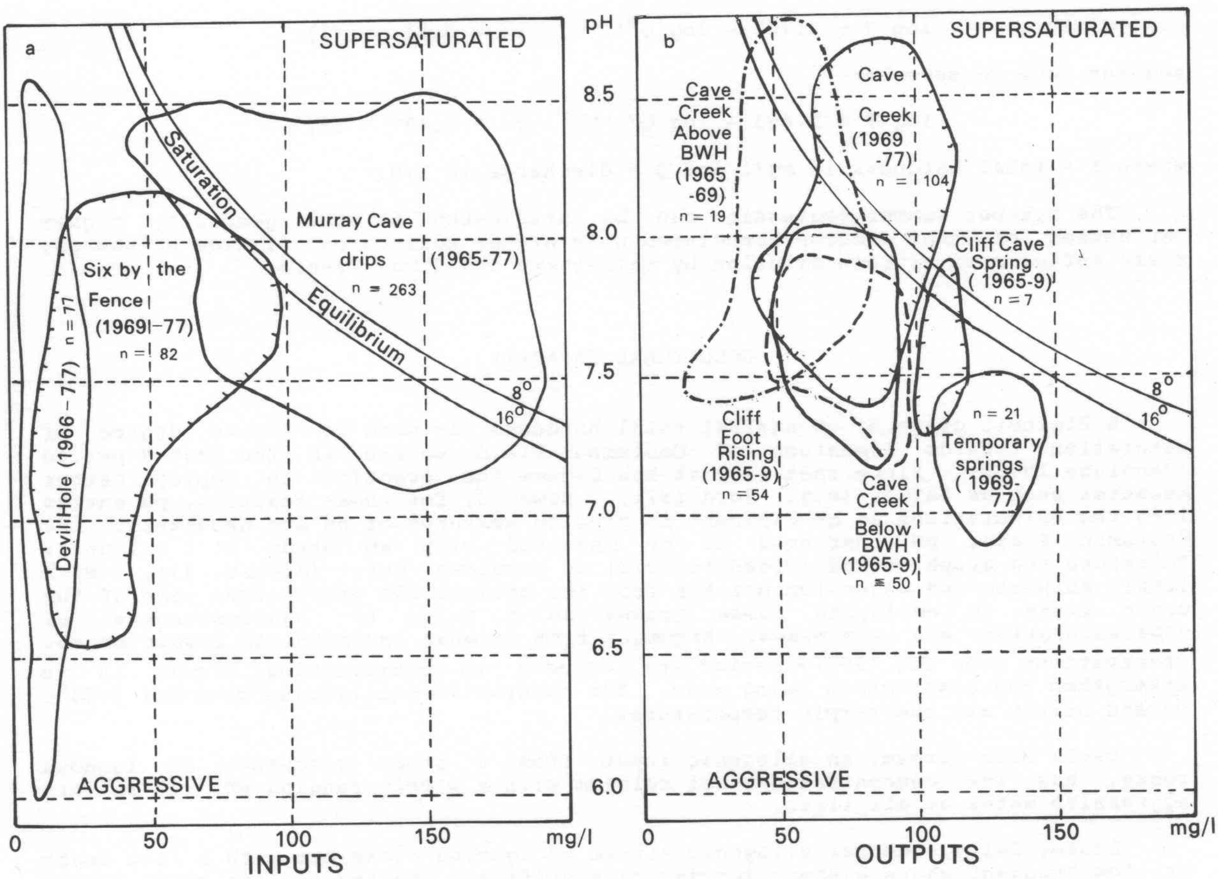

Figure 13 Picknett graphs to show solutional capacity of (a) input and (b) output streams, Cooleman Plain

The Cave Creek samples immediately below the main Blue Waterholes are so similar to those of the Cliff Foot Rising set that it has to be accepted that here the groundwater component is dominant at all times despite mixing with the smaller flows from North Branch when it reaches this point.

However, it appears that the characteristics of the waters of Cave Creek at the new gauging site are not due to a simple mixing of Cliff Foot Rising water with the flow down the main channel but to degassing of the groundwater during surface flow. At the new site more than one third of the samples are saturated or supersaturated and this explanation by degassing is called for. Nevertheless there is no sign of calcite precipitation along the course of Cave Creek at any point below the Blue Waterholes.

RATES OF CALCIUM AND MAGNESIUM CARBONATE REMOVAL

Figure 14 shows the carbonate loads of Cave Creek on the occasions of water sampling calculated from the calcium and magnesium ions and the discharge derived from chart height. The contrast with calcium concentration (Figure 12) is great. As in the 1965-9 period, there is pronounced reflection of the discharge because discharge varied more than thirteen fold whereas total hardness did so less than

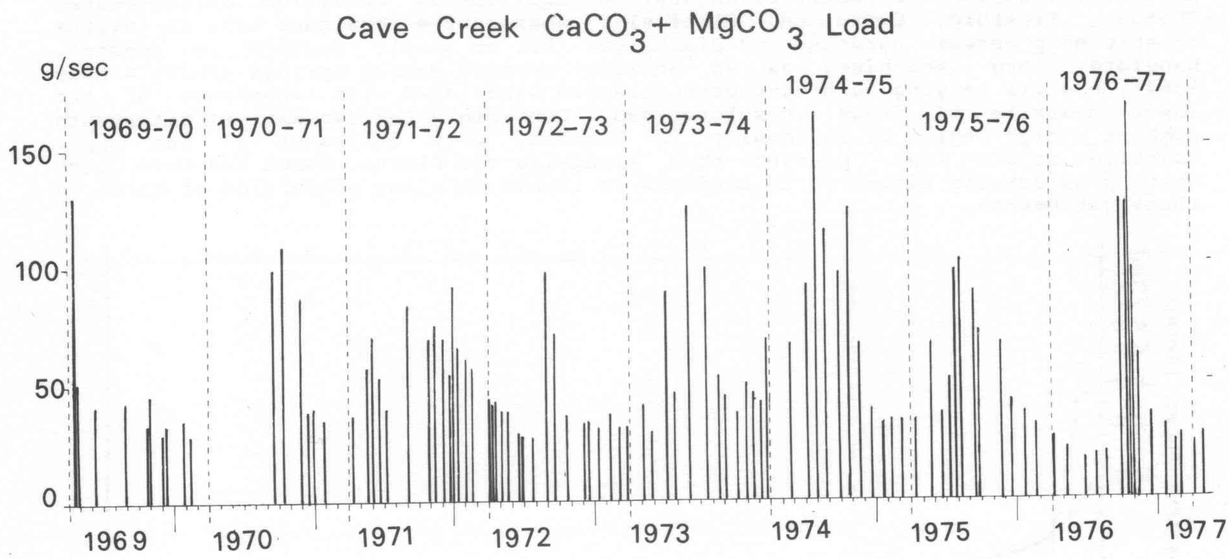

Figure 14 Instantaneous carbonate loads, Cave Creek, 1969-77

The regime is one of a winter-spring high level of load and a summer-autumn low removal rate. But, as before, there is little regularity about it; the peak may be sharp and occur within spring or winter only, or broad spreading over a longer period. In the earlier period, 1967-8 had low values throughout a drought year. The following year at the start of the later period was also anomalous in that April gave much the highest measured load when it is normally a month of low discharge and load. Nevertheless the total period of observation of 12 years can be taken to give a satisfactory indication of the present-day behaviour of this catchment in this respect.

Regression of load on discharge gave a power function

$$\log S = \log Q^{0.834} - 0.598 \qquad r^2 = 0.94 \qquad (9)$$

where S = carbonate load in g/sec and Q = discharge in l/s. Though winter-spring and summer-autumn figures give different functions, the difference in slope of the regressions is not great and the annual regression will be used in later calculations instead of seasonal ones.

MAGNITUDE-FREQUENCY DISTRIBUTION OF SOLUTE LOAD

A carbonate solute load duration curve was constructed with 20 duration classes (Figure 15). The mean discharge for each class was multiplied by its total hardness. Time is accumulated from high Q to low Q and load accumulated in the opposite sense in the manner of Williams and Dowling (1979). Similar curves for the Riwaka South Branch, N.Z. (Williams & Dowling 1979) and the R. Honne, Germany (Schmidt 1979) are added for comparison. In Table XVI the load contributions of different flow frequency classes for a wider range of karst areas are also presented (cf. Gunn 1982).

Cooleman Plain falls into a middle group with the biggest contribution coming from the upper quartile of the daily flows, which, however, does not exceed by much the interquartile half of the discharges. The top five percentile, the big floods, play a significant part but by no means as great as with the Riwaka catchment in the marble belt of the Southern Alps of New Zealand, which is distinguished from the remainder of the karst catchments of the table by the great dominance of upper quartile flows. The behaviour of the Riwaka may be taken to be characteristic of steep mountain catchments. It is true that 53% of the input of this catchment is allogenic but this is much less than the equivalent 71% from Cooleman Plain and the even greater non-karst proportion of the Honne R. basin.

At the other extreme are the three Mendip catchments where the importance of intermediate and low flows is much greater than with the middle group, especially in the case of the Cheddar springs, with nearly as much in the lower quartile as in the upper. These Mendip catchments possess modest relief and depend very little on allogenic inputs. The Waitomo catchments present an apparent anomaly amongst the middle group in that they are dominantly of limestone in bedrock geology and consist of doline karst. However, a cover of volcanic ash 3-6 m thick, reducing soil infiltration capacity, is probably a major cause of concentrating vadose water so that rapid access to underground rivers is prevalent here (Gunn 1981).

Another comparison that needs to be made is between these magnitude - frequency distributions and the variation in hardness of the outputs. Lack of variation as a result of saturation equilibrium condition characterises Cheddar, Rickford, Cymru and Glenfield, whereas the remainder have an inverse relationship between hardness and discharge. But no simple pattern is present. Langford, long recognised as an anomaly amongst Mendip springs (Smith & Mead 1962), has its varying carbonate concentration associated with importance of the lower quartile of flows in solute load. Conversely the two Waitomo catchments combine a high degree of uniformity in hardness with dominance of the upper quartile solute load, placing them alongside the Riwaka, Honne and Cave Creek where considerable variation in hardness is linked to a low proportion of karst in these catchments.

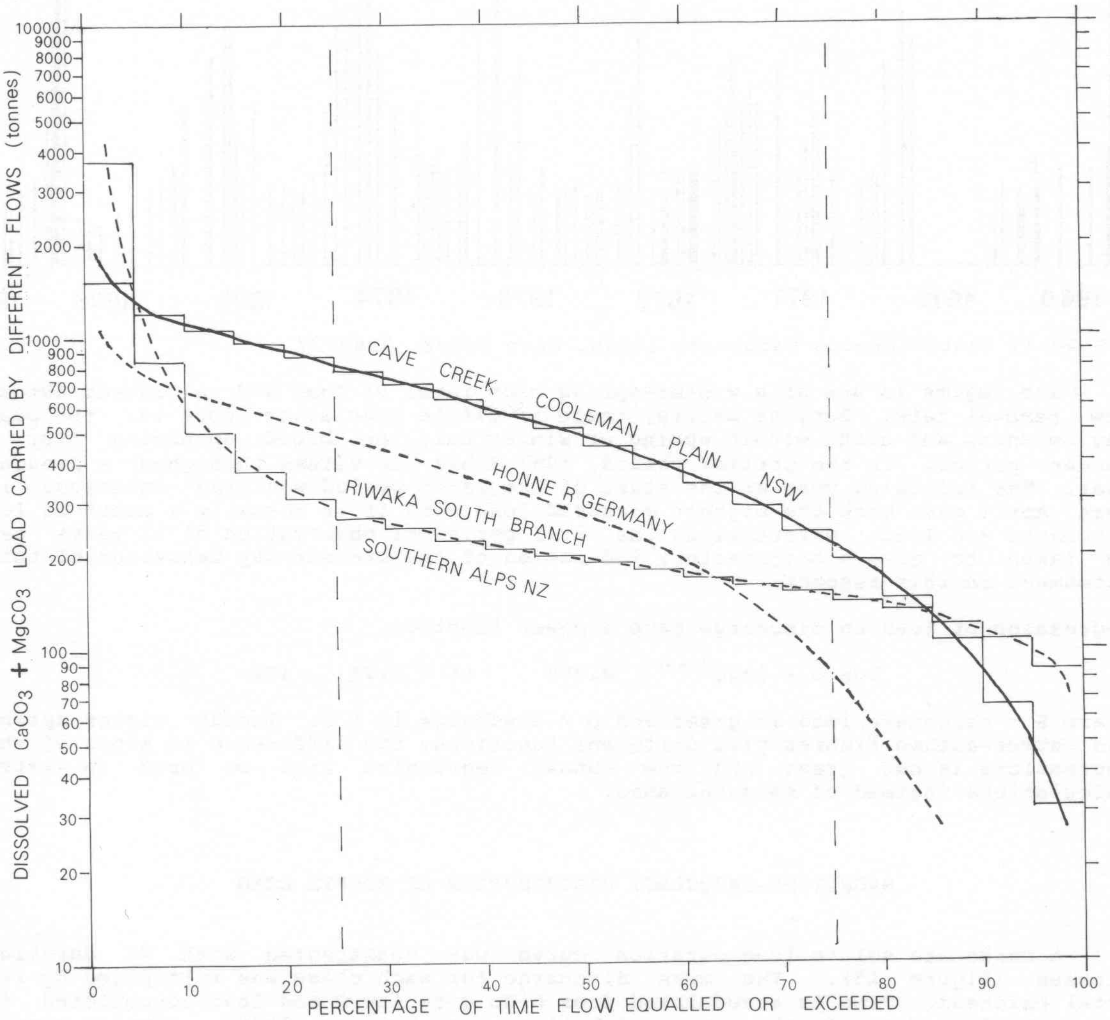

Figure 15 Solute load duration graph, Cave Creek, 1969-77, compared with those for Riwaka R., New Zealand, and Honne R., Germany. Time is accumulated from left to right and discharge from high to low values

Table XVI Contribution to Annual Solute Load of Selected Flow Frequency Classes

Area	Flow Frequency Classes			
	Top5%	Upper Quartile	Inter-quartile	Lower Quartile
Riwaka South Branch (Williams & Dowling1979) N.Z. ($45.1\ km^2$)	44	65	25	10
Cooleman Plain, N.S.W. (This study) ($55.8\ km^2$)	21	48	39	13
Honne R., Germany (Schmidt 1979)($123.8\ km^2$)	16	59	40	10
Cymru, Waitomo, N.Z. (Gunn 1981) ($0.1\ km^2$)	18	54	37	9
Glenfield, Waitomo, N.Z. ($0.4\ km^2$)	15	53	38	9
Langford ,Mendip, England ($<5\ km^2$) (Smith & Newson 1974)	10	38	42	20
Rickford, Mendip, England ($<10\ km^2$)	5	43	40	17
Cheddar, Mendip, England ($39.4\ km^2$)	1	33	39	28

ALLOGENIC INPUTS

In the 1965-9 study, 26% of the carbonate hardness of Cave Creek was attributed to inputs from the non-karst part of the catchment. If this is seriously in error, then limestone removal rates, at which this study is centrally directed, will also be uncertain. To put this matter onto a completely firm basis would have required so much discharge recording and water analyses as to be infeasible. However the previous approximation can be improved within limits.

Over 9-11 December 1982 in dry weather after a long drought, 29 inputs were gauged and analysed for 9 ions (Ca, Mg, Na, K, HCO_3, SO_4, Cl, SiO_2, PO_4). In their chemical concentrations, the waters exhibited stronger relationship to the lithology of the catchments than was recognised in the previous study with less complete collections and against a less detailed geological mapping (Table XVII).

The purest waters come from acid intrusive rocks, granite and microgranite, with low carbonate hardness, low Ca/Mg ratio, low (Ca + Mg)/(Na + K) ratio and low total of determined ions(1). Acid volcanics (rhyolite, rhyodacite) followed with slightly greater carbonate hardness (2). The next higher carbonate hardnesses come from mixed acid volcanics and granodiorite, catchments (3) and from dominantly granodiorite catchments (4). Greater hardnesses and total solutes still come from a couple of dominantly granogabbro catchments (5); the calcium and magnesium probably derive from weathered pyroxene minerals, 25-30% of the rock (Owen and Wyborn 1979). Another two catchments, in which granogabbro is accompanied by Blue Waterhole Formation, jump significantly higher in all measures (6). Those catchments dominantly on Blue Waterholes Formation show further increase in all measures and their total hardness is very high for non-karst terrain (7). These beds are mainly mudstone and siltstone. There are megaclasts and some interbeds of limestone in this formation but the figures suggest that a calcareous fraction may be present in its main lithologies.

Finally there are two catchments, the outputs of which differ little from the full output of the Plain at Cave Creek. Seventeen Flat Creek includes some granogabbro as well as microgranite but the major source of calcium and magnesium must be the area of Pocket Formation, which includes interbeds of limestone within its mudstones, sandstones and tuffs. The solute load of Doosey Gully is, however, harder to explain since the mapping suggests that granogabbro and granite are the only bedrock lithologies involved. Less than half the hardness measured might be expected on these geological grounds. That the high value is not adventitious is shown by Table XIV where this catchment has an average total hardness of 48.7 ppm compared with 88.2 for Cave Creek from large data sets. This behaviour was previously explained in terms of evaporative increase in solute concentration over a long, flat valley floor above the collection point.

However, this factor should not cause an increase in the Ca/Mg and (Ca + Mg) /(Na + K) ratios also as is the case. Therefore this explanation may be mistaken and further enquiry is needed to find a convincing cause.

This close connection between geology and solute concentration suggests that the previous ascription (Jennings 1972a) of nearly 3/4 of the solute load of the allogenic inputs to rainfall chemistry is in error.

REDUCTION OF TOTAL CARBONATE HARDNESS OF CAVE CREEK TO EXPOSED KARST HARDNESS

(a) Correction for Atmospheric Salts

The chemical analyses of 12 rainfall events between 8 March 1980 and 28 July 1981 in the Yass R. catchment near Canberra in the Southern Tablelands were made available to me by Mr H. Crockford (CSIRO Division of Water and Land Research). The events ranged between 9 and 36.2 mm of precipitation and there was no relationship between event magnitude and chemistry. Nor could any seasonal variation be discerned. Therefore the approximation of applying the mean concentrations from this data set to all precipitations was adopted. The Na/Ca and Na/K ratios again supported the idea of Douglas (1968) that the rainfall chemistry depends more on terrestrial dusts than on oceanic salts. It was suggested in Jennings (1972a) that the calcium especially derives from the pedocalcic soils of the Mallee region of western New South Wales. Therefore applying these Yass catchment figures to Cooleman Plain may underestimate the atmospheric contribution, since rain on the ACT Ranges and their northward continuation to the Black Range may have cleaned the air in part before it reaches the Yass catchment to the east.

Table XVII Water Chemistry of Cooleman Plain Allogenic Catchments 9-11/12/82

Lithology of Catchments	Means				
	n	Total carbonate hardness (ppm)	Ca/Mg	(Ca + Mg)/ (Na + K) by epm	Total of 9 ions (ppm)
1. Dominantly Jackson Granite or Currangorambla Granophyre (microgranite)	4	4.4	3.4	0.8	41.6
2. Kellys Plain Volcanics (rhyolite, rhyodacite)	4	9.6	3.1	1.3	39.1
3. Kellys Plain Volcanics + Skains Hill Granodiorite	3	13.5	3.4	1.	45.9
4. Cooleman Mountains Granodiorite	8	14.5	4.1	1.9	54.0
5. Seventeen Flat Granogabbro	2	24.9	3.7	2.6	73.0
6. Mcleods Trail Granogabbro + Blue Waterholes Formation	2	32.4	4.3	3.6	80.7
7. Blue Waterholes Formation (siltstone, mudstone, sandstone, chert, megaclasts + interbeds of limestone)	4	55.7	13.4	7.7	109.8
8. Doosey Gully (granogabbro + granite)	1	64.4	11.5	7.6	136.4
9. Seventeen Flat (micro-granite + granogabbro + Pocket Formation (mudstone, tuff, limestone))	1	72.6	15.7	10.9	139.4
Total Output					
10. Cave Creek (all above + Mountain Creek Volcanics (rhyolite) + Rolling Grounds Grounds Latite (trachyandesite) + Cooleman Limestone)	1	86.6	16.0	13.8	153.2

The mean epm for Ca was 0.0178 and for Mg was 0.0063, which are considerably less than the equivalent figures from Douglas (1968) from a lesser but unspecified number of events. Douglas' water samples were collected in and around Canberra at a time when much ground was bare from rapid extension of suburbs. The Yass figures give a mean total hardness of 0.911 mg/l. (An error in calculation in Jennings 1972a makes the reduction in atmospheric salt contribution between the earlier and the present study even greater than the difference in actual rainfall hardness determinations).

In the previous study (Jennings 1972a), the monthly basis of the data made it inappropriate to consider a lag in applying the correction for rainfall hardness to the output from the karst. With daily discharges now available, such a lag becomes desirable. Study of drip hardness in relation to antecedent temperature and precipitation (Jennings 1979a) gave little clue about the time taken for water to percolate through the limestone into the caves. Percolation water contributes through some routes to the quickflow component of the recession hydrograph (Gunn 1981) whereas other routes feed it into the delayed flow (e.g. from the epikarstic zone of Mangin (1974-5) and Bakalowicz (1979)). In this complex circumstance it may be assumed as a first approximation that the contribution of rainfall to the output hardness will decay with the discharge. Comparison of rainfall events and flood events at the Blue Waterholes suggests that a lag of about a day for a rainfall input to arrive at the springs. By 20 days after a rainfall event, its carbonate contribution will have declined to negligible proportions. Therefore the hyperbolic function of the quickflow part of the generalised recession hydrograph was used to distribute nearly all of the mean rainfall hardness concentration of 0.911 mg/l between the 2nd and 19th days after the rain fell. Each daily portion was converted into a quantity of carbonate and allocated to the appropriate day's output; it was reconverted to a concentration with that day's discharge of Cave Creek. This concentration was then to be subtracted from the total hardness for that day.

The calculation is as follows.

Correction for rainfall hardness = ((RFL2 x 0.162) + (RFL3 x 0.089) + (RFL4 x 0.075) + (RFL5 x 0.065) + (RFL6 x 0.058) + (RFL7 x 0.052) + (RFL8 x 0.048) + (RFL9 x 0.044) + (RFL10 x 0.041) + (RFL11 x 0.038) + (RFL12 x 0.036) + (RFL13 x 0.034) + (RFL14 x 0.032) + (RFL15 x 0.030) + (RFL16 x 0.029) + (RFL17 x 0.028) + (RFL18 x 0.026) + (RFL19 x 0.025)) x 185.76 / discharge on day_n (10)

where RFL2 to RFL19 are the daily rainfall (mm) of the second to the nineteenth days previous to day , with the latter's discharge in litres per second.

(b) Correction for Allogenic Input

The method adopted in the 1965-9 study to correct output for the carbonate hardness contributed by streams from the rocks surrounding and overlying the limestone can only be improved to a modest degree. Some evidence has been given above for retaining the previous assumption that water yields per unit area are approximately the same for limestone on the one hand and the other rocks on the other. Given that assumption a correction for the allogenic input for the present study was obtained in the following way.

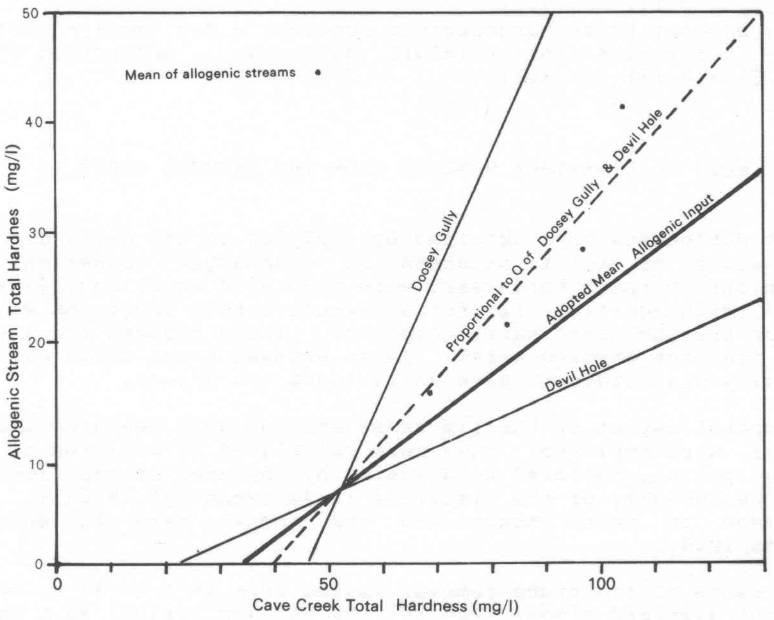

Figure 16 Allogenic input correction graph for Cave Creek output

Simple linear regressions between Doosey Gully and Devil Hole hardnesses and Cave Creek hardness were calculated and drawn on Figure 16. Then a line between the two was inserted on the basis of the ratio of the mean discharges of the two allogenic streams from the 9 occasions when they were both gauged; this line was, of course, placed nearer the bigger stream's regression line. Finally a further line was drawn for 71% of the hardness of the inputs ratio line to allow for the proportion of non-karst discharge to karst discharge on the basis of uniform yield. A simple linear function was then calculated, which was used to correct the total hardness on each day for this contribution from the other rocks; this of course includes their rainfall hardness as well as hardness from weathering.

A check on the validity of this procedure was provided by the mean hardnesses of the allogenic inputs on the four occasions when a large proportion of the inputs were analysed. It was necessary to adjust the means of the 3 occasions from the 1965-9 study by small amounts to accommodate the increase in catchment in the 1969-77 period. These four means were plotted on Figure 16 by reference to the corresponding hardness of Doosey Gully, the more sensitive of the two allogenic streams. They straddle the line based on the ratios of the discharges of Doosey Gully and Devil Hole and so suggest that the basis of the correction is reasonably satisfactory.

The regression for the correction is:

Correction for allogenic hardness (mg/l) = 0.37 total hardness Cave Creek - 12.58 (11)

(c) Correction for Subjacent Karst Hardness

The increased area of subjacent karst in the later study did not add to the part of it considered to play an active role in the karst hydrology. There is no known or suspected underground connection between the northern plain and the Blue Waterholes, and Zed Cave output is appropriate for the size of the New Years Cave-Frustration Cave catchment behind it. So the part of its subjacent karst area along its southern margin assumed to be active remains at 3.3 km^2, 17% of the total of 19.5 km^2 of active karst, exposed and subjacent.

However subjacent karst only takes part in some of the limestone solution; most importantly it does not take part in the superficial zone of solution. The latter can be approximated from the hardnesses of Murray Cave drips over 1972 and 1973 (Jennings 1979a). These hardnesses did not show any relationship to the discharge of Cave Creek but did present a seasonal contrast, the mean of 131.6 mg/l for June-November being significantly different from that of 146.5 mg/l for December-May. These two means were therefore used to subtract the superficial zone hardness from the total hardness attributable to limestone. They will of course be diluted by allogenic water so the means actually subtracted will be 29% of the gross figures (38.2 mg/l for 'winter' and 42.5 mg/l for "summer").

The calculations are therefore as follows:

Correction for subjacent karst hardness for June-November (mg/l) = (total hardness Cave Creek - correction for rainfall hardness - correction for allogenic hardness - 38.2) x 0.171 (12)

Correction for subjacent karst hardness for December - May (mg/l)= (total hardness Cave Creek - correction for rainfall hardness - correction for allogenic hardness - 42.5) x 0.171 (13)

RATE OF LIMESTONE REMOVAL FROM THE EXPOSED KARST

Daily total hardnesses were obtained by applying to the daily discharges the seasonal regressions of total hardness on discharges (equations (7) and (8) above). Corrections to these hardnesses were made with equation (10) for rainfall on the limestone, with equation (11) for allogenic stream input and with equations (12) and (13) for the subjacent karst component. These reduced the gross figures to the hardness from the exposed karst. These exposed karst daily hardnesses were multiplied by daily discharges to give daily loads (in g/sec).

For the temporal aspect of the limestone erosion both measured and estimated daily discharges were employed. They were calculated by addition of daily loads over the relevant period, followed by division by the area of the limestone (16.05 km^2) and by the density of the limestone (2.71 (Jennings 1972a)). The monthly rate was expressed in mm/km^2/month and the annual rate in Bubnoff units, i.e.$m^3/km^2/y$ = mm/1000y.

The annual rates of limestone removal ranged from 16 B to 41 B, much the same as for 1965-9, but averaged higher than for the earlier period, 29 B compared with 24 B. That difference could certainly be largely due to measurement error but there are certain differences between the two periods that would be substantively causative. There is a net reduction in the non-karst proportion of the total hardness because of greater reduction in the estimate for rainfall carbonate hardness than increase in the non-karst weathering input. This gives an apparent increase in karst removal rate. The average annual rainfall was greater in 1969-77 than in 1965-9 and would have caused a real increase in limestone erosion.

The monthly rates (Figure 17) show the basic tendency to a high winter/spring removal rate and a low summer/autumn one. This is to be expected from the runoff regime, and the seasonal relationship between carbonate load and discharge. Nevertheless, just as in 1965-9, there is a great difference from year to year in the seasonal pattern; the seasonal rhythm may be either of a drastic nature or almost suppressed.

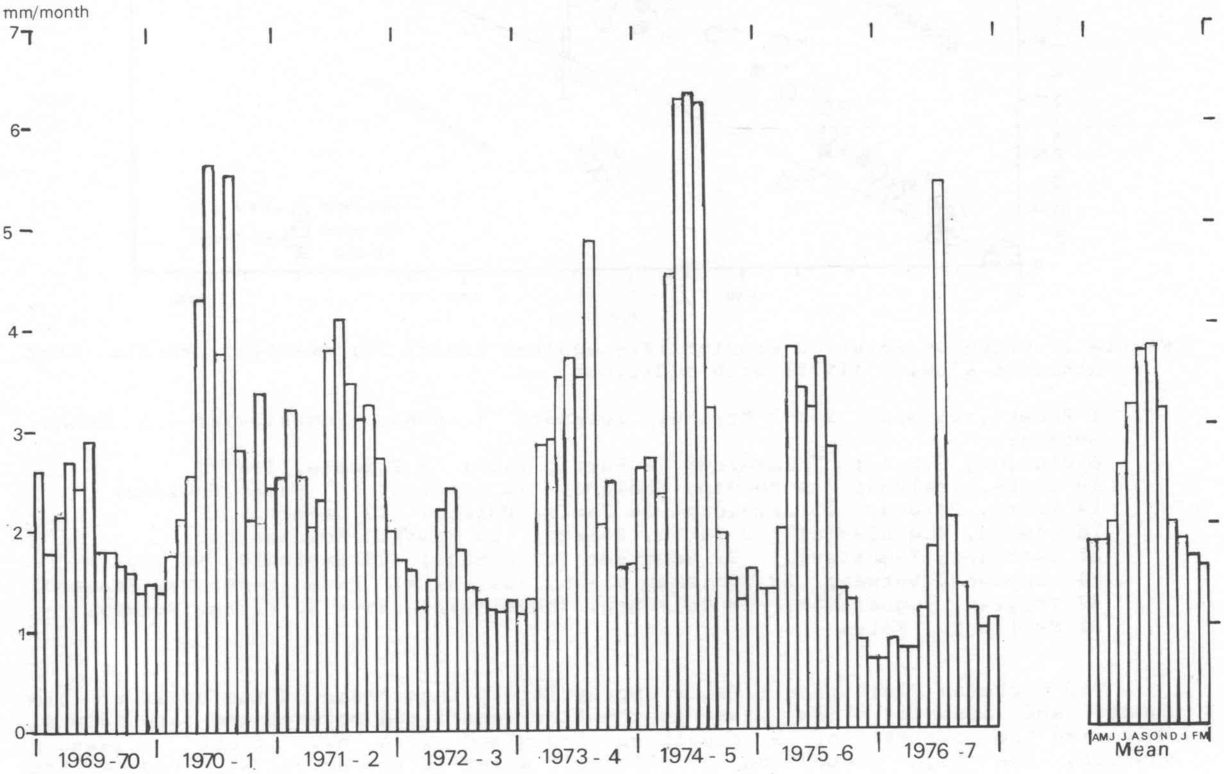

Figure 17 Monthly carbonate load from exposed karst, Cooleman Plain, 1969-77

DISCUSSION

In some recent studies (Williams & Dowling 1979: Gunn 1978), maximum error terms have been put on limestone erosion rates. These have been derived by addition of error terms arising in many ways - catchment area accuracy, discharge determinations, chemical analysis reproducibility, regression standard errors, etc. Worthy though the intention is, this practice will not be followed here, though where it has been possible to estimate particular errors, these have been given above. Most of the errors are not additive but random in relation to one another. Nor are all sources of error considered by these authors, e.g. the accuracy of the geological mapping, the need for more than one year's observations. Thus the Green River at Munfordville, Kentucky, for which good chemical analysis records are available, yields different regressions of carbonate hardness and solute load on discharge from year to year. Here it is simply recognised that substantial errors may be involved and therefore argument will not be allowed to rest on small differences in erosion rate.

The mean annual rate of limestone removal from the exposed karst of 29 B is plotted on Figure 18 against a range of results from other karsts. Figure 18 is based on a figure of Atkinson and Smith (1976), which depends in part on rates based on estimates of runoff from precipitation minus evapotranspiration. More reliable results based on measured discharges have been added here; they confirm that runoff is the main control of limestone removal, which depends essentially on how much water gets contact with this rock.

Atkinson and Smith inserted a line separating soil covered karsts of middle and tropical latitudes from dominantly bare karsts of Arctic and Alpine environments. Only one of their points fell on the wrong side of this line, namely the Mellte R. figure from Wales (Groom & Williams 1965). There seems to be some uncertainty about the extent of limestone involved in contributing to the

Mellte output, which might explain the anomaly. The Waitomo karst rate inserted by me from Gunn (1978) also falls on the wrong side; however, the error term placed on it by Gunn could take it to the appropriate side of the line. An additional factor may be the tephra cover over this karst, which speeds up entry of water to the cave passages. This reduces the contribution of percolation water to the hardness and may help explain a lesser rate of limestone removal for the runoff.

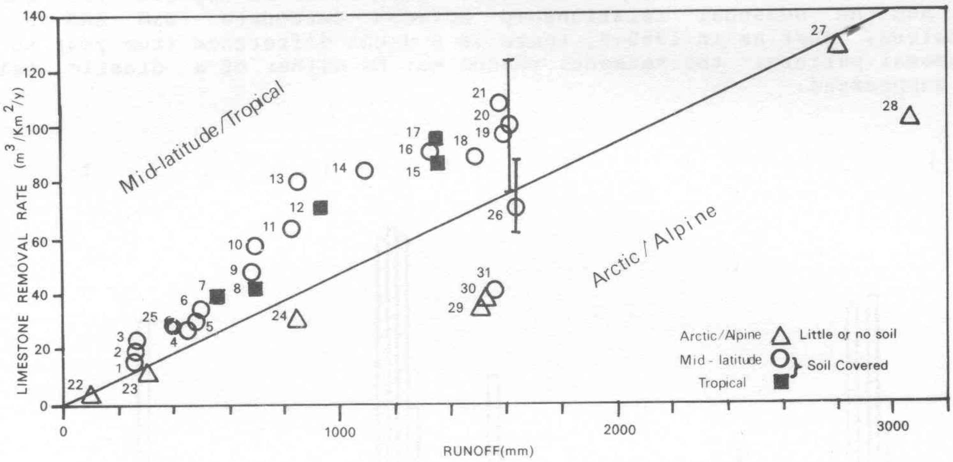

Figure 18 Graph of solution erosion rate against runoff for selected karsts from Atkinson & Smith (1976) with additions.

1 Podera, Poland; 2 & 3 Krakow, Poland; 4 Senj, Yugoslavia; 5 Honne, Germany;
6 Florida, U.S.A.; 7 Jamaica; 8 Puerto Rico; 9 Trieste, Italy;
10 Clare, Ireland; 11 Mendip, England; 12 Jamaica; 13 Peak, England;
14 Tatra, Poland; 15 Jamaica; 16 Tatra, Poland; 17 Jamaica;
18 Bosnia, Yugoslavia; 19 Tatra, Poland; 20 Riwaka, New Zealand;
21 Postojna, Yugoslavia; 22 Somerset I., Canada; 23 Svalbard, Norway;
24 Lappland, Norway; 25 Cooleman Plain, Australia; 26 Waitomo, New Zealand;
27 Triglav, Yugoslavia; 28 Tolminka, Yugoslavia; 29 & 30 Tatra, Poland;
31 Mellte R., Wales

The Cooleman Plain result falls appropriately into place on the basis of its runoff and also it lies close to the line separating covered and bare karsts. This fits the context of a subalpine grassland with high frost incidence. However, the high proportion of allogenic water in the output also reduces the erosion rate having regard to runoff.

Figure 19 indicates the spatial distribution of limestone erosion at Cooleman Plain. It is based only on daily loads calculated from measured Cave Creek discharges but inclusion of the estimated values for the gaps in the record scarcely changes the figures. Nevertheless giving results to 1% presents an appearance of greater reliability than they possess as description of their derivation will reveal.

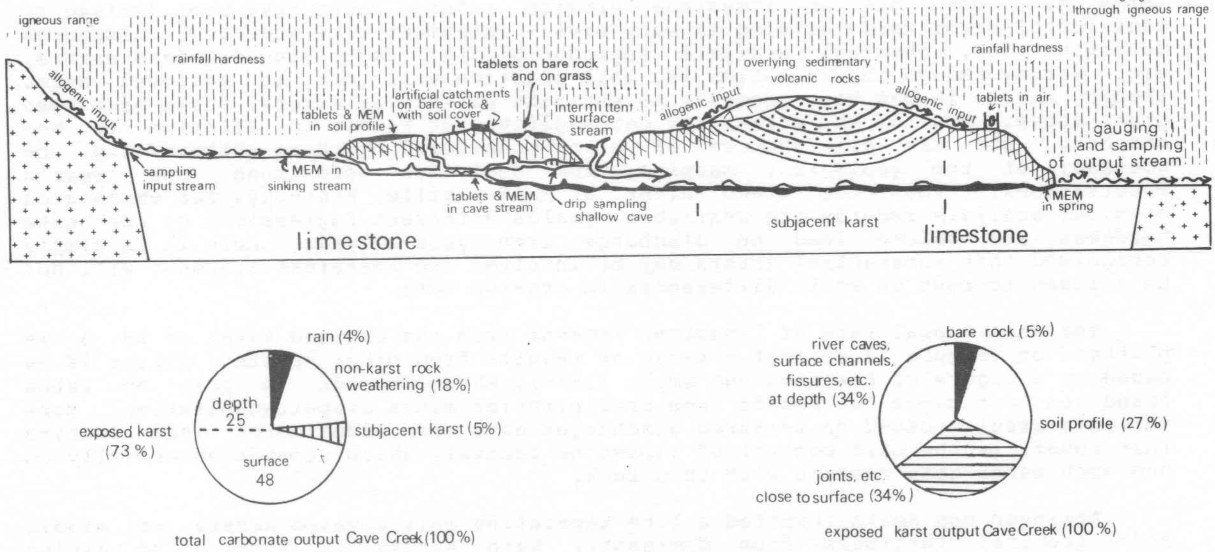

Figure 19 Schematic diagram of measuring system at Cooleman Plain with circular graphs of spatial contributions of carbonate load, 1969-77

The way the rainfall hardness for the exposed karst, the allogenic stream hardness and the subjacent karst hardness were calculated has already been described. Subtracting these quantities from the daily total carbonate concentrations gave the exposed karst hardness.

The contribution from the superficial zone of exposed karst was determined from the concentrations of Murray Cave drips over 2 years. The ratio of their mean concentration to the mean exposed karst hardness allowed an estimate of the contribution of that zone to the output load. The remainder of the exposed karst carbonate load after this was subtracted was attributable to stream caves, to surface stream channels on the limestone and also to fissures and small tubes at depth in the bedrock. The last are probably most numerous and effective in terms of process near to the cave passages because of interchange during flood events (see above).

The contribution to the load from rock weathering outside the limestone was obtained by subtracting the rainfall load from the allogenic stream input; the rainfall load was calculated in the same manner as for the rainfall load on the limestone, allowing for the greater area and so greater rainfall amount.

Attempting to break down the load from the superficial zone of the limestone depends on the separate experiments conducted to determine limestone erosion at various kinds of site.

For the bare karst, results are available from:

(a) micro-erosion metering (Spate et al. 1983, unpublished results)
(b) tablet weight loss from Slovenian limestone exposed here (Jennings and Spate in Gams 1981 and in prep.)
(c) one artificial small catchment (Jennings 1978).

Three MEM sites on bare rock with 27 - 29 measured points on each yielded a mean lowering of 9 B over 1978-83. Over nearly the same period the Slovenian limestone tablets gave a rate of 4 B from 3 sites, each with 3 tablets. The artificial catchment also gave 4 B over 2 years (1975-7). The mean on a site basis is 7 B.

For the soil covered karst, there are results from the three sources mentioned above, together with local limestone tablet loss (Jennings 1981). The MEM was used at only one grassland subsoil site (21 B) but another site poorly covered in forest litter may be included here (7 B). Slovenian limestone tablets yielded 9 B from two subsoil sites, one grassland, the other forest. The artificial catchment, recognised to be an extreme case on the unfavourable side, yielded only 5 B. The value of 8 B was given by 3 local limestone subsoil sites over 6 years (1973-9). Averaging these on a site basis (and disregarding different exposure periods) the mean is 9 B.

The area of soil covered karst at Cooleman Plain is estimated at 4 times that of bare karst; putting the two together gives a mean of 9 B. Subtraction of this from the estimate of 19 B for the whole superficial karst zone leaves 10 B for the solution in joints and other planes of weakness, etc. in the upper part of the limestone.

There is less basis for subdividing the other part of the exposed karst load, that from stream caves, surface channels and small voids at depth. MEM results from two cave stream sites yielded 21 (for 1978-83) and 10 (for 1978-81) respectively. Local limestone tablets in a cave stream gave 8 B over 1976-83 by solution (and about the same amount by abrasion, Jennings 1981). MEM also gave 16 B from a surface stream well within the limestone outcrop. Averaging, again on a site basis, furnishes 14 B. It is difficult to say much about the area streams represent but it is several magnitudes smaller than the soil and bare karst area. It follows that solution along them represents less than 1% of both total carbonate output and exposed karst output from the system. This leaves most of the 25% of total output (34% of karst output) to solution in small voids in the lower parts of the limestone.

Thus caves are unimportant as a direct component in the limestone erosion of this karst, though their functioning is vital to solution elsewhere, especially to that in fissure storage near to caves at depth in the limestone. The evidence presented shows that abrasion only adds about as much again to the erosion along the caves here, leaving the total cave action small.

Before making comparisons with other areas, it is advisable to compare these 1969-77 results with those for 1965-9 (the latter were on concentrations only, not loads, but this makes for little difference in proportions). There are big differences but they arise from one main cause - overestimation of the rainfall contribution in the earlier calculations for 1965-9.

There are not many similar attempts at apportionment of limestone erosion in this way for other karsts. However, there is broad agreement with the conclusions of Williams (1968) for Clare, Ireland (though he could not break down the results to the same degree) and also a good correspondence with that of Atkinson and Smith (1976) for the Mendip, when the factor of a much smaller allogenic influence in the latter is weighed. The striking difference between the two areas is in the relative roles of the soil profile and the uppermost rock zone, where for Mendip a ratio of 1 to 6 is given and for Cooleman Plain a ratio of 1 to 1.2 in round terms. However, this difference is more apparent than real. The soil profile figure for the Mendip is based on soil water collections within the soil, which is not calcareous, whereas the soil profile figures for Cooleman Plain are in effect measures of the soil-rock interface solution, which is probably the locus of greatest action of all. When the two zones - soil and upper rock - are added together for both Mendip and Cooleman Plain, the result is in both cases about two-thirds of the karst solution.

It is advisable to be cautious about applying elsewhere the conclusion from Mendip and Cooleman that rate of removal is small from the caves themselves. The hydraulic gradients are small in both of these karsts and a quite different role may be found for caves in high mountain karsts in temperate and tropical high mountain karsts, at least as regards the relative importance of mechanical erosion and solution in them.

Discussion of the 1965-9 results ended with an attempt to relate the modern rate of surface lowering to the landforms of the Plain and what little is known of their history. On the one hand the denudation rate supported general argument against a Devonian age which had been proposed for the erosion surface that survives on the interfluves. On the other hand, small as the rate is, it seemed incompatible with survival of this surface from a much younger and more acceptable date in the Upper Tertiary. The 1969-77 figure for a longer observation period is so little different from the earlier figure that this problem is posed even more forcibly now. Later work on the geomorphology hereabouts also makes the conflict even greater; Rieder et al. (1977) argue for the possibility that the Cooleman erosion surface is older rather than younger than Lower Miocene basalts in the region. Assuming a minimum of 20 m.y. for subsequent denudation, the modern solution rate if it had ruled over that period would have brought about a lowering of 400 m, which is unacceptable. In 1972 when the problem was discussed before, the notion of Pleistocene climate prevailing was less clear than now; today it is thought with some confidence that the Pleistocene was overall one of reduced water availability and so of reduced solution. However, this reduction would not have been great enough nor its duration long enough to account for the discrepancy. So it still seems necessary to fall back on the idea that an ironstone cuirass, remnants of which survive, acted as a seal protecting the limestone surface from solution for a long time.

It is laborious to arrive at denudation estimates from modern process study and it would be fallacious to claim great reliability for them. Nevertheless this process approach sets valuable constraints on our thinking about landform evolution and we can afford neither to neglect the method nor the apparent conflicts of interpretation to which it may give rise.

ACKNOWLEDGEMENTS

The frustrating task of trying to keep instruments going at Cooleman Plain fell even more upon the head of Keith Fitchett than on mine; his devotion was exceptional. In the laboratory Jim Caldwell maintained the highest reliability in the chemical analyses. So many friends helped with the field work from time to time that it is impossible to mention them by name; I can only trust that to visit the Plain was its own reward. I must single out Andy Spate whose practical knowhow in matters hydrological is outstanding. Dr. John Chappell was my normal recourse in matters mathematical but also Dr. Tony Jakeman and Mark Greenaway most generously undertook to fill in gaps in the discharge record with CAPTAIN. Mr. H. Crockford of CSIRO provided Yass R. catchment rainfall chemistry data and the SMHA supplied Tantangara Dam weather data. Mr. D.I. Smith and Dr. J. Chappell made useful comments on the paper. The New South Wales Parks and Wildlife Service gave permission for access and for the installations. Without all this help this study could not have been accomplished and I am grateful to all concerned.

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PREDICTION OF CLIMATIC TEMPERATURE DATA FOR KARST AREAS IN THE CENTRAL AND SOUTHERN TABLELANDS OF NEW SOUTH WALES.

Erik J.M. Halbert

Abstract

The use of multiple regression analysis is shown to overcome current limitations in availability of climatic temperature data for caving sites in the Central and Southern Tablelands of New South Wales. The developed equations are used to calculate climatic data for Jenolan, Wellington, and Oberon which agree well with the recorded data at these sites. The equations are also used to calculate data for six major caving areas in New South Wales, including the tourist areas Wombeyan and Yarrangobilly and frequently visited areas such as Bungonia and Wee Jasper.

INTRODUCTION

Cave climate studies usually involve consideration of the surface site climate as well. This is particularly the case where major features of the cave's climate such as cave ventilation or temperature distribution are concerned. This type of work is currently being carried out at Bungonia, Jenolan, Wombeyan, and Yarrangobilly in New South Wales. At all of these sites there are problems in establishing local climatic data and recourse is often made to the closest official weather station. This station is usually many kilometres distant, many tens of metres different in altitude and may well be atypical due to location.

The problem of topography is most serious in hilly or low mountain areas (Yoshino, 1975) since the climate in such places depends on small scale effects such as available relief, slope aspect and angle, vegetation, and prevailing winds, rather than on any single large scale effect such as altitude. The Tablelands area of eastern Australia is such an area and has the further complication of rapid variation in climate type from east to west due to the tilted-block build of the eastern highlands (Gentilli, 1972) and the proximity of large oceanic expanses.

Due to the limitations inherent in using data from a small number of stations to estimate climatic conditions for a locality where there is no information, it is preferable to utilise data from as many stations as possible. Through multiple linear regression analysis, estimates of climatic conditions for the locality can then be obtained. Australia as a while is covered by a broad network of weather stations and the eastern states in particular have quite an extensive network. These stations have long data runs and in toto represent one of the most reliable and independent data banks for studies within the Australian region. Multiple regression analysis allows the individual data to be integrated into small networks which can be tailored to any chosen area and equations can then be developed to generate specific data by interpolation for any location within the network.

The aim of this work was to apply the technique to the Central and Southern Tablelands area of New South Wales, within which lie some 60 per cent of the cave systems of the state, and to generate site data for several of these areas where cave climate work is being carried out.

The methodology used here to establish average air temperatures was similar to that applied by Johnson, Kalma and Caprio (1976) in a study of mean air temperature variations at 22 stations in the south coast area of New South Wales, by Edwards and Johnston (1978) in the Upper Murrumbidgee River Valley, and by Booth (1981) in a study of the mean values of 9 am dew-point temperatures at 494 stations in mainland eastern Australia. Work has also been carried out in the United States of America (Hopkins, 1960) and in Canada (Hopkins, 1968) but very little speleological work employing this technique has been reported. Ford, Harmon, Schwarcz, Wigley, and Thompson (1976) established climatic data for Mount Castleguard and the Columbia Icefield in a study of Castleguard Cave in Canada, while in Australia, Goede, Green and Harmon (1982) used the technique to establish climatic data for three caves in Tasmania from three local weather stations. There do not appear to have been any regional studies similar to the present one carried out in Australia by speleologists.

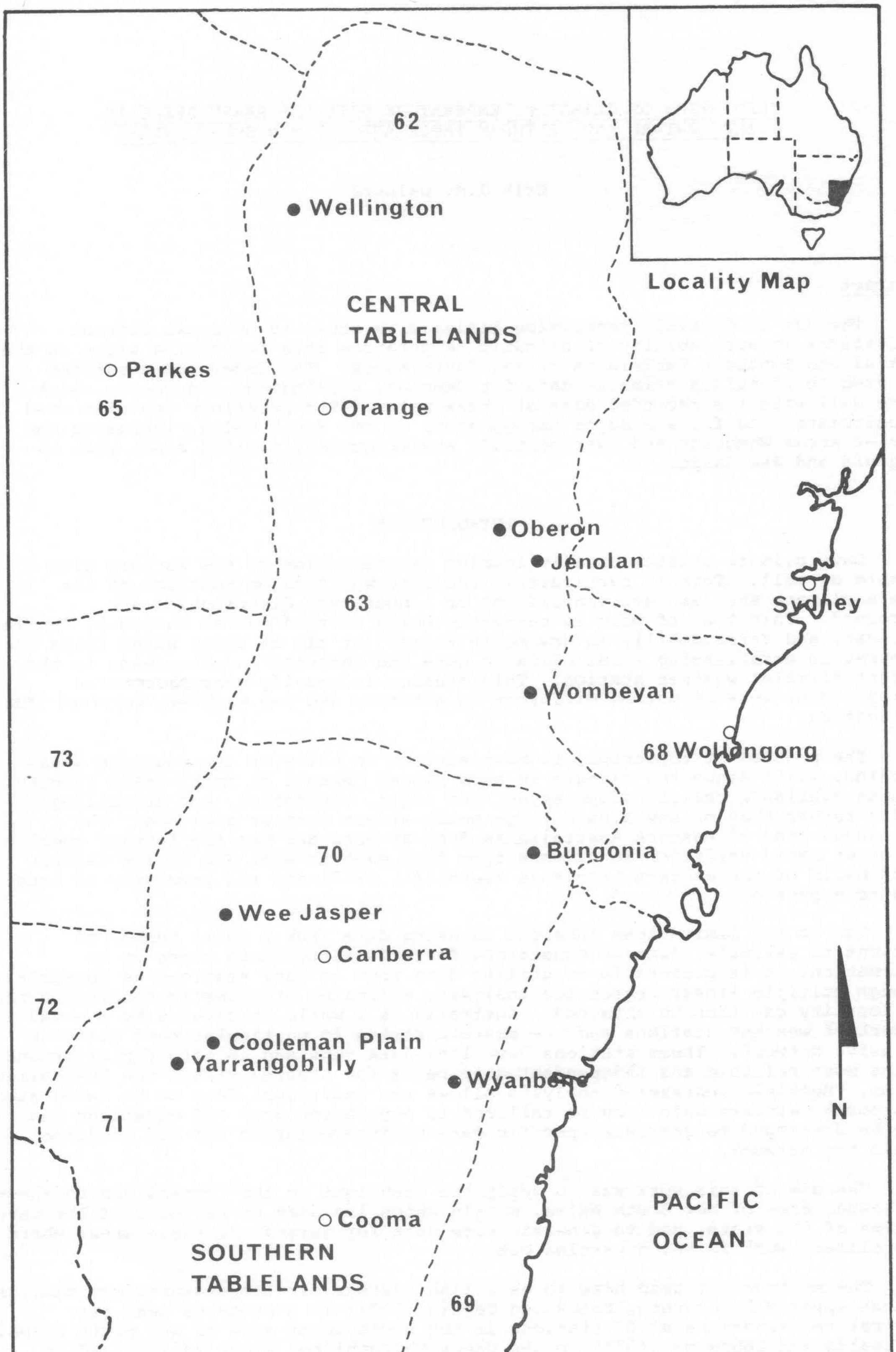

Figure 1 Location map of Central and Southern Tablelands of New South Wales and adjacent meteorological districts.

METHODS AND RESULTS

Data

Average daily maximum and minimum temperatures for each month and for the year were obtained from the Bureau of Meteorology (1975). Average daily mean temperatures (using the nomenclature of the Bureau of Meteorology, 1956, 1975) were calculated for each month and for the year, using the arithmetic mean of the corresponding average daily maximum and minimum temperatures. The mean temperatures were calculated for all stations.

The records cover about 15 to 17 years since processing of data in computer compatible form was begun in 1957. For this study it was important to use data from areas experiencing broadly similar weather patterns and the core areas chosen were those of the Central and Southern Tablelands (Meteorological Districts 62, 63, 70 and 71). To those areas were added the weather stations situated higher than 300 m altitude in neighbouring districts (Meteorological Districts 65, 68, 69, 72, and 73) to give a data file comprising 70 stations. Several stations where site information was incomplete were omitted from the data file and the three stations with altitudes greater than 1700 m were also omitted.

The area covered in this study (Figure 1) lies between latitudes 32.0 and 36.5 S, longitudes 148.0 and 150.5 E, and altitudes 300 to 1400 m. Distances to the sea were estimated from the World Aeronautical Chart (Sheet Numbers 3456 and 3470) on a scale of 1:1 000 000.

Multiple Regression Equations

Multiple regression equations were calculated for the average daily maximum, mean and minimum temperatures for each month and for the average annual maximum, mean and minimum temperatures from the 70 stations described above against their geographical coordinates and altitudes. Each equation had the form

$$Y = a+b(X1)+c(X2)+d(X3)$$

where Y = average temperature (^{o}C), X1 = latitude-34.44 (decimal degrees), X2 = longitude-149.07 (decimal degrees) and X3 = altitude-735.4 (metres). The numerical values in the expressions for latitude, longitude and altitude were the corresponding mean values and a, b, c, and d were the appropriate regression coefficients for the month and year.

Initially, a stepwise multiple regression analysis was carried out with a variety of other possible independent variables in addition to X1, X2 and X3. Distance from the coast and log distance were used as variables, following the procedure of Johnson et al. (1976) and Booth (1981). However, it was shown that distance was not an independent variable but was strongly related to both latitude and longitude, as would be expected with the substantially straight coastline of New South Wales. The six second order terms of X1, X2 and X3 were also examined in the stepwise multiple regression analysis but these gave very low t-values (usually $t<1.5$) and were discarded. None of the second-order terms led to significant improvement in the coefficients of determination (R2) and so the simple regression model shown above was adopted. The simplicity of this model compares very favourably with other models in which as many as 22 terms (Hopkins, 1968) have been used. It has the further practical advantage that all data required for the equation may be obtained from the medium scale maps (1:25 000 to 1:100 000) used by speleologists.

Regression Results

The results of the analyses are shown in Tables I and II, in which the truncated regression coefficients a, b, c, and d for each month and the year are displayed as well as the corresponding coefficients of determination (R2). The R2 values are high, in all cases being greater than 0.87 indicating that the model is accounting for a large proportion of the variance.

The R2 values for the regression coefficients obtained using the minimum temperature data ranged from 0.49 to 0.78. These were regarded as unsatisfactory, and this method was not used to predict minimum temperatures. Instead, the minimum values were obtained from the average and maximum values using the formula

$$T_{minimum} = 2 \times T_{mean} - T_{maximum}$$

where Tmean and Tmaximum were obtained from Tables I and II. It was also found that in each case the coefficients of determination were higher for the average annual temperatures than for the individual average daily temperatures for each month. This may be due to the tendency for unconsidered small scale effects to compensate for one another in the production of average temperatures (Hopkins, 1960).

TABLE I Regression coefficients for average mean temperature versus latitude, longitude and altitude for 70 stations in the Central and Southern Tablelands of New South Wales.

MONTH	a	b	c	d x 10^2	R^2
January	19.622	-0.781	-0.784	-0.7129	0.917
February	19.431	-0.779	-0.816	-0.6708	0.920
March	17.061	-0.761	-0.476	-0.6371	0.922
April	13.049	-0.738	-0.056	-0.5848	0.878
May	8.807	-0.591	0.130	-0.5155	0.880
June	6.504	-0.707	0.136	-0.4895	0.869
July	5.365	-0.518	0.215	-0.5289	0.880
August	6.802	-0.479	0.212	-0.5746	0.932
September	9.175	-0.416	0.329	-0.5774	0.877
October	12.718	-0.717	-0.117	-0.5609	0.912
November	14.784	-0.757	-0.036	-0.6378	0.887
December	17.833	-0.836	-0.499	-0.6594	0.932
Year	12.599	-0.672	-0.150	-0.5957	0.933

TABLE II Regression coefficients for average maximum temperature versus latitude, longitude and altitude for 70 stations in the Central and Southern Tablelands of New South Wales

MONTH	a	b	c	d x 10^2	R^2
January	26.696	-0.711	-1.307	-0.2475	0.906
February	26.088	-0.642	-1.400	-0.7999	0.863
March	23.835	-0.674	-1.021	-0.7989	0.927
April	19.767	-0.694	-0.167	-0.7810	0.932
May	14.508	-0.508	0.202	-0.6918	0.915
June	11.810	-0.560	0.139	-0.6771	0.913
July	10.616	-0.444	0.580	-0.7624	0.915
August	11.986	-0.388	0.545	-0.7875	0.939
September	15.265	-0.351	0.564	-0.7833	0.883
October	19.163	-0.632	-0.121	-0.7471	0.924
November	21.600	-0.841	-0.282	-0.7990	0.889
December	25.015	-0.747	-0.841	-0.8306	0.948
Year	18.866	-0.598	-0.260	-0.7758	0.952

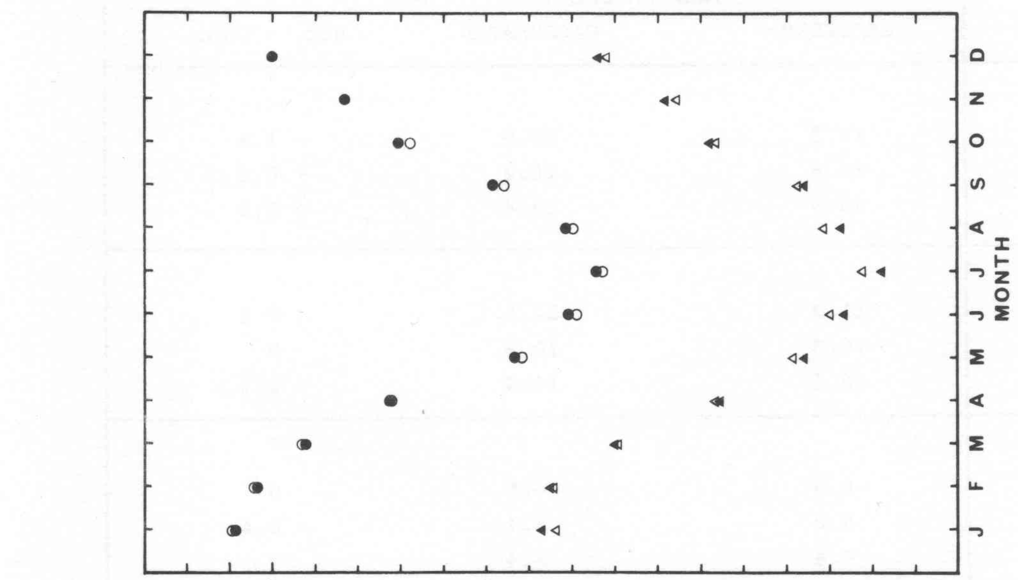

Figure 2 Wellington Post Office - recorded (solid symbols) and calculated (hollow symbols) average daily maximum and minimum temperatures.

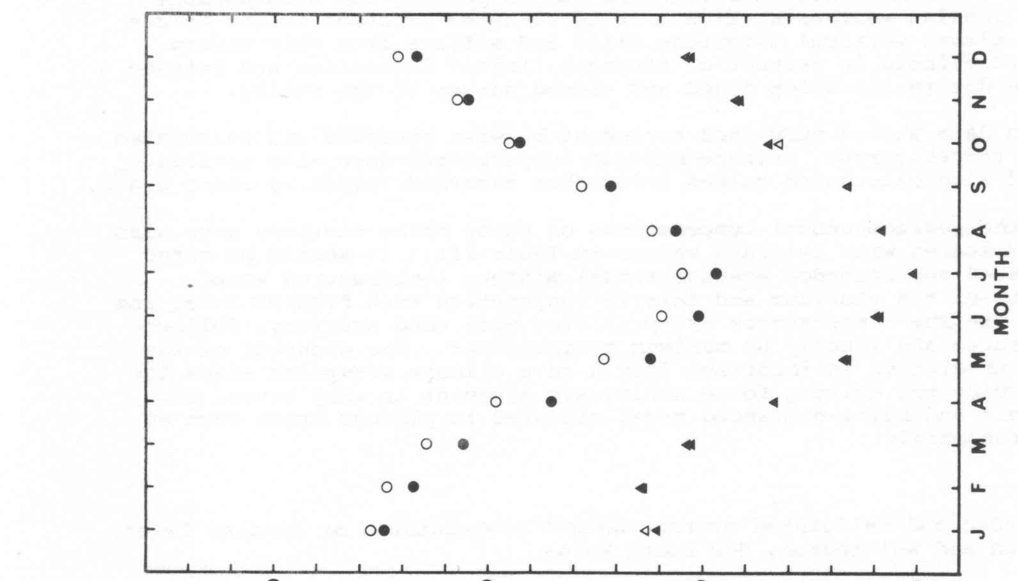

Figure 3 Jenolan Caves Post Office - recorded (solid symbols) and calculated (hollow symbols) average daily maximum and minimum temperatures.

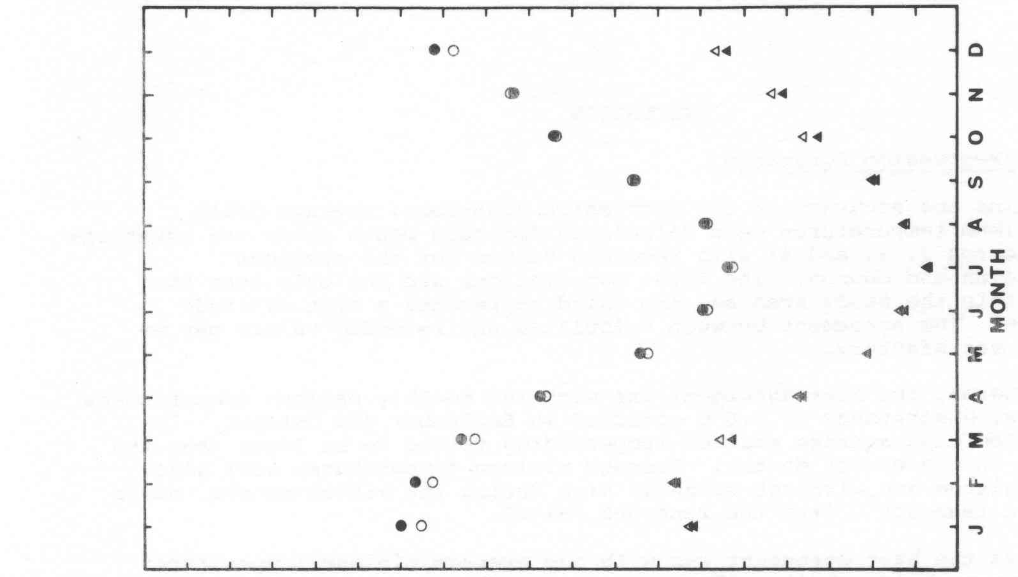

Figure 4 Oberon Post Office - recorded (solid symbols) and calculated (hollow symbols) average daily maximum and minimum temperatures.

DISCUSSION

Accuracy of the Regression Equations

To determine the accuracy of the regression equations, average daily maximum and minimum temperatures were calculated for each month using the equations and plotted (Figures 2, 3, and 4) with recorded values for the stations Wellington, Jenolan and Oberon. The first two stations are the only ones at caving areas within the study area and the third represents a high altitude (1105 m) station. The agreement between calculated and recorded values may be seen to be very satisfactory.

For Wellington, the best agreement was with the monthly maximum temperatures with the greatest discrepancy of 0.6°C occuring in September and October. In general, the calculated average maximum temperatures tended to be lower than the recorded values in the winter months. Average minimum temperatures were also accurately calculated and although slightly high during the winter months, never differed by more than 0.6°C from the recorded values.

For Jenolan the best agreement was with the average minimum temperatures with the discrepancy being about 0.2°C. The worst agreement was with the average maximum temperatures, where calculated values were consistantly higher than recorded values, and this trend was also seen in the average mean values. It is considered that these discrepancies are due in part to the unfavourable location of the Jenolan weather station. It is situated adjacent to the Guides Hut, next to an almost vertical limestone cliff and suffers from very severe local topographic effects in respect of strongly limited insolation and intense cold air ponding due to the steep sided and closed nature of the valley.

The Oberon data showed very good agreement between recorded and calculated average minimum temperatures. Average maximum temperatures were also satisfactorily predicted with calculated values lower than recorded values by about 0.4°C.

Data for the average annual temperatures of these three stations were also calculated and compared with recorded values in Table III. It should be noted that the calculated and recorded average annual minimum temperatures were identical for two of the stations and this in conjunction with Figures 2, 3, and 4 suggests that minimum temperatures are predicted with good accuracy, followed by mean temperatures and finally by maximum temperatures. The accuracy of the low temperature prediction is important from a cave climate viewpoint since low temperatures provide the driving force behind air movement in many caves, in particular, single and multi-entranced caves situated in plateau areas such as Bungonia or Yarrangobilly.

TABLE III Recorded and calculated average annual temperatures at Jenolan Caves, Oberon and Wellington, New South Wales.

SITE	TEMPERATURE (°C)		
	RECORDED	CALCULATED	REC. - CAL.
Maximum			
Jenolan Caves	17.2	18.5	- 1.3
Oberon	16.6	16.2	+ 0.4
Wellington	23.6	23.4	+ 0.2
Mean			
Jenolan Caves	11.9	12.5	- 0.6
Oberon	10.8	10.8	0
Wellington	16.5	16.4	+ 0.1
Minimum			
Jenolan Caves	6.5	6.5	0
Oberon	5.0	5.4	- 0.4
Wellington	9.4	9.4	0

A further check on accuracy was carried out by calculating the average annual maximum temperatures for each of the 70 stations and comparing it with the recorded value at that station. Only five of the stations had temperature differences greater than 1°C and of these, only two had differences greater than Jenolan Caves, substantiating the suggestion that this station is somewhat anomalous. The standard error of the estimate for values of the annual maximum temperature was 0.6°C and a similar value was obtained for the average annual mean temperatures. With these figures the 95% prediction interval on estimated maximum and mean temperatures will be about 1.2°C for the annual values. The 95% prediction interval for average daily maximum and mean temperatures for individual months is similar to the annual values. Even in the case of the mean temperature in June with the poorest coefficient of determination of 0.87, the interval is still less than 1.5°C. These results are similar to the ones obtained by Ford et al. (1976) and Booth (1981) and are quite satisfactory for the majority of cave climate requirements.

Application of the Results

The regression equations were used to derive climatic data for six representative cave sites within the study area, these sites being ones in which climate studies are being or might be carried out. However, the same data may be generated for any site.

The values for latitude, longitude and altitude for each site were obtained from the appropriate 1:25 000 topographic map with the exception of Bungonia where the 1:31 680 map was used. Latitude and longitude were estimated to one minute and altitude was estimated to five metres (Table IV). The latter figure is not critical however and altitude accuracy of 10 m would have little effect on the derived temperatures. The results of this application are shown in Table V, and were readily obtained using a hand calculator.

There are few published data with which these figures may be directly compared. A notable exception is Cooleman Plain, where a study by Jennings (1979) has been published on the thermal regime of the area. The Cooleman work, carried out over the period 1973-1977 is of relevance to the present study; however, there are some aspects which make it necessary to discuss the results in more detail than is appropriate in this paper. These aspects include the frost hollow effect, the relative shortness of the record obtained within the area, and the altitude of the study sites. For example, the altitude of Jennings Mountains site is outside the altitude range of the present work. A detailed evaluation of the Cooleman data forms part of a current study (Halbert, in preparation).

TABLE IV Topographic data for selected karst sites in Central and Southern New South Wales

SITE (TOPOGRAPHIC MAP)	LATITUDE (DEC. DEG.)S	LONGITUDE (DEC. DEG.)E	ALTITUDE (M)
Bungonia (8928 - III - N Caoura)	34.82	150.02	530
Cooleman Plain - Blue Waterholes (8626 - IV - S Rules Point)	35.63	148.68	1175
Wee Jasper Caves (8627 - IV - S Couragago)	35.13	148.67	450
Wombeyan Campsite (8829 - II - N Richlands)	34.32	149.97	600
Wyanbene Main Cave (8826 - III - N Krawaree)	35.80	149.68	930
Yarrangobilly Caves (8526 - I - S Yarrangobilly)			
Coppermine Cave - Yans Crossing	35.68	148.47	930
Eagles Nest Cave	35.70	148.48	1090

TABLE V Calculated average monthly and annual climate data for selected karst sites in Central and Southern New South Wales

SITE	MONTH, AVERAGE TEMPERATURE (°C)												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Bungonia													
maximum	26.9	26.2	24.2	20.9	15.9	13.1	12.6	14.0	17.3	20.3	22.7	25.6	20.0
mean	20.0	19.7	17.6	13.9	9.8	7.4	6.5	8.0	10.5	13.5	15.8	18.4	13.4
minimum	13.1	13.2	11.0	6.9	3.7	1.7	0.4	2.0	3.7	6.7	8.9	11.2	6.8
Cooleman													
maximum	22.6	22.4	19.9	15.6	10.8	8.1	6.5	7.8	11.2	15.2	17.2	20.8	14.8
mean	15.9	15.9	13.5	9.6	5.8	3.5	2.3	3.6	6.0	9.4	11.1	14.1	9.2
minimum	9.2	9.4	7.1	3.6	0.8	-1.1	-1.9	-0.6	0.8	3.6	5.0	7.4	3.6
Wee Jasper													
maximum	29.1	28.5	26.1	21.6	16.1	13.3	12.3	13.7	17.0	20.9	23.4	27.2	20.8
mean	21.4	21.1	18.5	14.2	9.8	7.4	6.4	8.0	10.4	13.9	16.1	19.3	13.9
minimum	13.7	13.7	10.9	6.8	3.5	1.5	0.5	2.3	3.8	6.9	8.8	11.4	7.0
Wombeyan													
maximum	26.8	26.0	24.1	20.8	15.7	12.9	12.2	13.6	16.9	20.1	22.5	25.5	19.8
mean	20.0	19.7	17.6	13.9	9.7	7.4	6.3	7.8	10.3	13.5	15.7	18.4	13.4
minimum	13.2	13.4	11.1	7.0	3.7	1.9	0.4	2.0	3.7	6.9	8.9	11.3	7.0
Wyanbene													
maximum	23.3	22.8	20.7	17.2	12.6	9.8	8.9	10.3	13.6	16.8	18.7	21.9	16.4
mean	16.7	16.6	14.5	10.9	7.1	4.7	3.8	5.2	7.7	10.6	12.5	15.1	10.4
minimum	10.1	10.4	8.3	4.6	1.6	-0.4	-1.3	0.1	1.8	4.4	6.3	8.3	4.4
Yarrangobilly Coppermine													
maximum	24.9	24.6	22.1	17.5	12.4	9.7	8.2	9.6	13.0	17.0	19.2	23.0	16.8
mean	17.7	17.6	15.2	11.0	7.0	4.6	3.6	5.0	7.3	10.8	12.6	15.8	10.7
minimum	10.5	10.6	8.3	4.5	1.6	-0.5	-1.0	0.4	1.6	4.6	6.0	8.6	4.6
Eagles Nest													
maximum	23.6	23.3	20.8	16.2	11.3	8.6	7.0	8.4	11.7	15.8	17.9	21.6	15.5
mean	16.6	16.6	14.1	10.1	6.2	3.8	2.7	4.0	6.4	9.9	11.6	14.7	9.7
minimum	9.6	9.9	7.4	4.0	1.1	-1.0	-1.6	-0.4	1.1	4.0	5.3	7.8	3.9

CONCLUSION

It has been shown that multiple regression analysis using published climatic data can be used to generate site information of relevance to cave climatologists and others interested in local climate. The main advantages are the simplicity of the regression equations and the objective nature of the procedure and results. Although independent evaluation of the accuracy of the equations was not carried out, a large number of stations was employed and a high proportion of variance was accounted for. Local topographic effect may account for part of the residual variance and this factor should always be taken into account in specific situations.

ACKNOWLEDGEMENTS

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REASSESSMENT OF CAVE AGES AT ISAACS CREEK

M.D. Connolly

In a previous paper Connolly and Francis (1979) described the Isaacs Creek Caves and their setting, and concluded that the caves began forming as early as the Cretaceous. I have now realised that the assumptions made in the basic mapping were incorrect, leading to false conclusions. This paper is to rectify these errors.

The basic mistake in the earlier paper was in the mapping of the basalt in figure 9 of that paper. The base of the basalt was mapped at the highest outcrops of underlying Palaeozoic mudstone. Subsequent fieldwork has shown that the true basalt margin does not occur here, but has been hidden by basalt creep that has created a thick mantle of basaltic debris on the upper slopes. Other rocks in the region show limited hillslope movement, but the basalt is very mobile.

The valley side slopes along which the Tertiary basalt contact was mapped are steep, usually 15°-30°. They are also unstable, with many obvious landslide scars, particularly on the north-facing slope between Isaacs Creek Road and Isaacs Creek. Terracettes are ubiquitous. The slope instability renders ineffective any attempt to map the basalt contact using surface evidence, as the real upslope limit of Palaeozoic mudstone is always covered by a substantial mantle of basalt colluvium.

The volcanic knolls and breaks of slope previously thought to be volcanic plugs have also been re-examined. They can be explained adequately as accumulations of corestones exposed by removal of finer material. Magnetic anomalies measured over these rocky outcrops simply correspond to areas where weathered material has been removed, and do not supply conclusive evidence that the outcrops are the surface expressions of volcanic plugs.

Connolly and Francis (1979) argued that there was only ever a patchy and localised Tertiary basalt cover in the Isaacs Creek area, with the basalt emanating from numerous small vents and only partly infilling the pre-basalt tributaries of Isaacs Creek. These basalts have been dated at 54-50 m.y. (McDougall and Wilkinson, 1967; Wellman and McDougall, 1974).

From these arguments it was concluded that the Isaacs Creek valley floor in the vicinity of the caves 'was cut down to within 35 m of its present depth in late Palaeocene to early Eocene times'. It was further suggested that just prior to the extrusion of basalt one of the tributary valleys of Isaacs Creek had a gradient of at least 35 m/km. This suggestion was based on the observed fall in the elevation of the basalt contact over a distance of several hundred metres.

Connolly and Francis (1979) argued that Main Cave at Isaacs Creek was formed between Jurassic and Palaeocene times, probably in the Cretaceous, and Helictite, Shaft, Belfry and Hill Caves were thought to have formed some time in the Palaeocene.

These arguments and the conclusions about the ages of the caves must now be revised following reassessment of field evidence. New fieldwork shows that features previously thought to be flow edges are slope terracettes, and that the basalts in the present landscape are remnants of a once substantial basalt cover in response to which the present drainage has evolved.

Caves Ridge, the limestone ridge on which most of the Isaacs Creek caves are situated, is 2.5 km west of the steep and unstable basalt-capped slopes, and Main Cave, near the summit of Caves Ridge, is at about the same elevation as the creek bed in the basalt area. Given the steep and unstable slopes in this area it is unlikely that there has been only minor erosion of Caves Ridge in the last 50 m.y. It seems more likely that when the basalts were extruded Caves Ridge was not a prominent feature in the landscape, but has been formed by erosion of the valleys in post-basalt time.

Main and Belfry caves could not have formed prior to the intrusion of the basalt dykes that they intersect. These dykes are too weathered for petrological study and isotopic dating which might indicate whether they were intruded in the Mesozoic or in the Tertiary.

The simplest possibility with least assumptions is for the flows and dykes to belong to the same period of volcanicity, and if this is so all the caves are younger than 50 m.y. As basalts are commonly permeable, phreatic development could have taken place prior to the removal of the basalt cover.

If the dykes pre-date the basalts the phreatic phase of Main Cave could have been pre-basalt, but in the absence of ancient cave deposits it is simpler and therefore preferable to conclude that this phase was post-basaltic. Vadose features in the other caves on Caves Ridge are related to the downcutting of the Isaacs Creek valley and imply that they must be younger than the basalt flows.

Conclusion

From the reassessed evidence it is concluded that Main Cave post-dates the basalt extrusions, and is probably of Tertiary age. Helictite, Shaft, Hill, Belfry and other caves lower down Caves Ridge must be substantially younger than Main Cave, as their well-developed vadose forms indicate they developed when the Isaacs Creek valley had incised well below the level of Main Cave.

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COMMENT - REASSESSMENT OF CAVE AGES AT ISAACS CREEK

G. Francis and R.A.L. Osborne

Connolly (1983) has concluded that the Main Cave at Isaacs Creek post-dates extrusion of basalt in the area and is therefore Tertiary in age. Connolly and Francis (1979) considered that Main Cave had formed during the Cretaceous. Connolly's arguments are based on a revised mapping of basalt contacts, which he believes indicates that Caves Ridge formed after extrusion of Palaeogene basalts, and on the assumption that dykes in Main and Belfry caves are the same age as the basalt.

The assumption that the dykes are Palaeogene in age is made purely on the basis of economy. Wellman and McDougall (1974) made similar assumptions about the age of intrusives in the Hunter Valley and these later proved to be incorrect. Dulhunty (1976) and Galloway and Webb (1979) found that four out of five intrusives believed to be Cainozoic were in fact Triassic in age. In this context the appeal to economy is very dubious and in the absence of petrographic, geochemical and isotopic data the age of the dykes must remain open to question. Recent work (W. Jones, pers. comm. and J. Field, pers. comm.) suggests that in spite of their weathered state, petrographic analysis of the dykes could be possible. If so, this could resolve the question.

Connolly's main argument concerns the relationship between basalt flows and pre-basaltic topography in an area 2.5 km east of Caves Ridge. Connolly infers from his revised mapping that Caves Ridge was likely not to have been a prominent feature in pre-basaltic times but has formed by post-basaltic erosion. This is not a necessary conclusion from Connolly's data. His evidence for active slope processes on basalt does indicate relatively rapid valley widening and interfluve lowering on basalt under modern conditions. It does not, however, support the inference of rapid valley floor lowering on basalt nor, for that matter, rapid incision of valleys into Palaeozoic rocks downstream of the basalt.

The evidence for active slope processes on basalt does not refute a hypothesis of slow denudation of the limestones and mudstones of Caves Ridge, nor does any of Connolly's work explain the lack of relationship of Main Cave to the present relief. Both of these considerations tend to support an ancient origin for Main Cave, as argued originally by Connolly and Francis (1979).

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EDITORS' NOTE: G. Francis is currently resident in a remote part of Papua New Guinea, without access to library facilities, etc. This Comment was written as a letter to the Editors, and was edited, expanded and prepared for publication by R.A.L. Osborne.

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WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain caves. In: J.R. DUNKLEY and T.M.L. WIGLEY (eds), Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Australia: 32-34. Speleological Research Council, Sydney.

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