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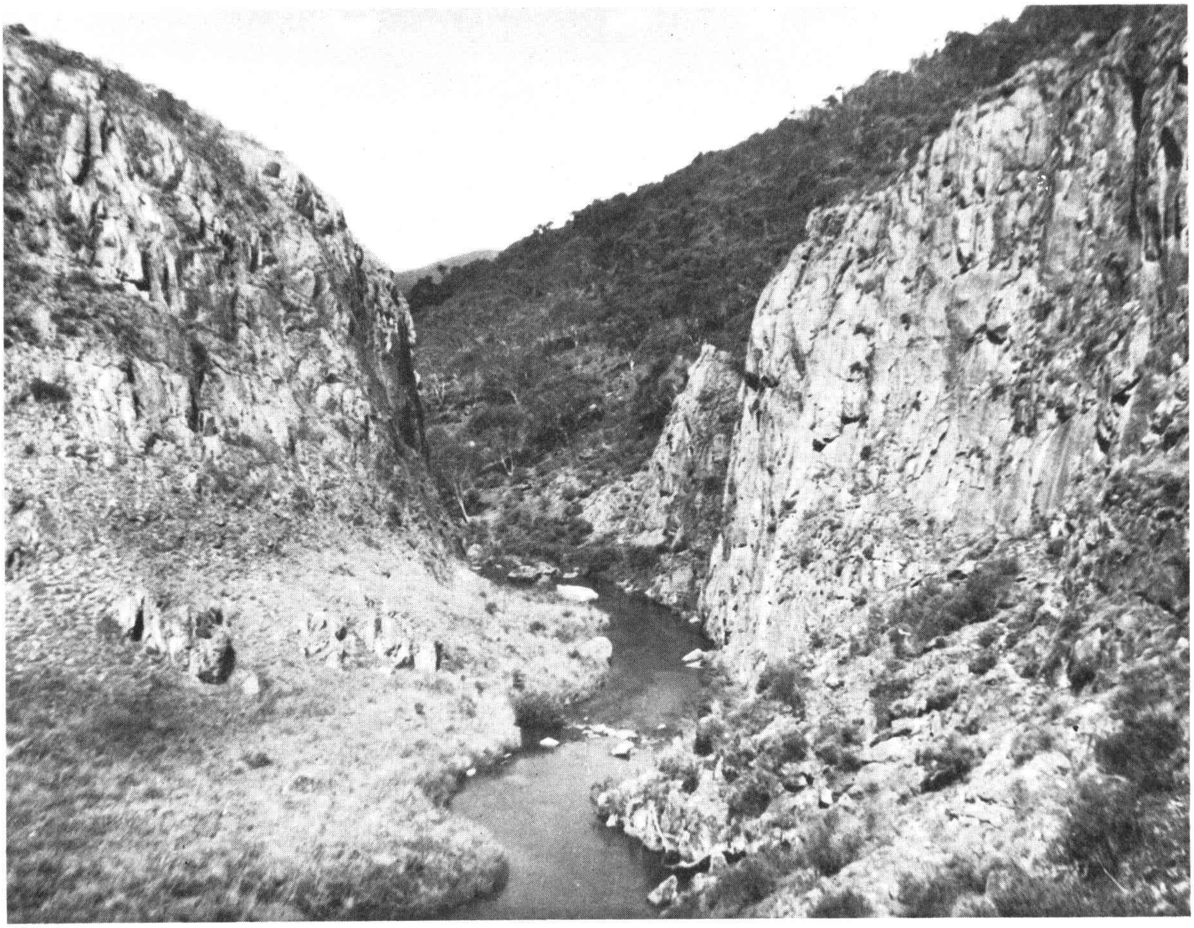

Study of limestone solution on Cooleman Plain, N.S.W., is helped by all drainage from the Plain passing from the karst, through Clarke Gorge (shown here), and onto igneous rocks.

"HELICTITE"

Journal of Australasian Cave Research

Editors

E.A. Lane, Aola M. Richards, J.N. Jennings, J.R. Dunkley

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J. N. Jennings

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"HELICTITE" EDITORIAL PANEL ENLARGED

For the past nine years "Helictite" has been edited by Dr. Aola Richards, Senior Lecturer in Zoology, University of New South Wales, and Mr. E.A. Lane, Deputy Director of Information Services, Australian Atomic Energy Commission. The success of "Helictite" as a scientific and technical journal has placed great pressure on the present editors and Dr. J.N. Jennings and Mr. J.R. Dunkley have agreed to join the journal's editorial panel. Each member of the panel will have equal status in deciding the content and policy of "Helictite". Dr. Jennings is Professorial Fellow in Geomorphology, Department of Biogeography and Geomorphology, Australian National University. He is also General Editor of the ANU Press series "An Introduction to Systematic Geomorphology", and author of volume seven of the series, "Karst" (252pp, 1971). Dr. Jennings is a past president of the Australian Speleological Federation. Mr. Dunkley is closely associated with Australian speleological societies. He is a member of the Speleological Research Council Ltd., is the present editor of the Australian Speleological Federation Newsletter, and has been the author or editor of a number of important publications on specific caves or cave areas.

OBSERVATIONS AT THE BLUE WATERHOLES, MARCH 1965 - APRIL 1969, AND LIMESTONE SOLUTION ON COOLEMAN PLAIN, N.S.W.

J. N. JENNINGS

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Abstract

After brief descriptions of the geomorphology of the Cooleman Plain karst and in particular of the Blue Waterholes, the methods adopted to analyse the functioning of these major risings are detailed. The discharge regime of Cave Creek below them is oceanic pluvial in type perturbed by drought and snow. There is much annual variation both in seasonal incidence and total amount, with catchment efficiency correspondingly variable. Suspended sediment concentration is even more erratic and monthly determinations are inadequate for calculating corrasional denudation rates. Mean concentrations of suspended solids are about 1/18th of solute load. Total dissolved salts have a strong inverse relationship with discharge, and mean values are high compared with those for other catchments in eastern Australia but none of these determinations are from limestone catchments. Sodium, potassium, and chlorine contents are low compared with the same catchments but silica is relatively high. The ratio of alkaline earths to alkalis indicate that Cave Creek carries carbonate waters and there is an inverse regression of the ratio on discharge.

There is inverse correlation of total hardness on discharge likewise due to concentration of surface waters by evaporation in dry periods, together with reduced underground solution rate at times of large, rapid flow. The spring waters remain aggressive. Close regressions of hardness on specific conductivity now permit the latter to be determined in the place of the former. Much evidence converges to indicate that all the springs at the Blue Waterholes are fed from the same conduit. The intermittent flow which comes down the North Branch on the surface to the Blue Waterholes differs significantly in many characters from the spring waters.

Rates of Ca + M carbonate equivalent removal vary directly with discharge since hardness varies much less than does water volume. These gross rates have to be adjusted for (a) atmospheric salts entering the karst directly, (b) peripheral solute inputs from the non-karst two-thirds of the catchment and (c) subjacent karst solution before they can be taken as a measure of exposed karst denudation. The methods for achieving this are set out. The total corrections amount to about one third of the total hardness, though the correction for subjacent karst on its own lies within the experimental error of the investigation. The residual rate of

limestone removal from the exposed karst also shows a winter/spring high rate and a summer/autumn low rate but the seasonal incidence and annual total varied very much from year to year.

In comparison with results from karsts in broadly similar climate, the seasonal rhythm conforms and so does the high proportion (78%) of the solution taking place at or close to the surface. This reduces the importance of the impounded condition of this small karst but supports the use of karst denudation rate as a measure of surface lowering. Cave passage solution may however be more important in impounded karst than its absolute contribution might suggest, by promoting rapid development of underground circulation. The mean value of limestone removal is low for the climatic type and this is probably due to high evapotranspirational loss as well as to the process of eliminating atmospheric, peripheral non-karst and subjacent karst contributions. The difficulties of applying modern solution removal rate to the historical geomorphology of this karst are made evident; at the same time even crude extrapolations are shown to isolate problems valuably.

INTRODUCTION

Modern quantitative interest in the spatial and temporal distribution of limestone solution is now over two decades old yet no results in this field of study have so far been published from Australia, where there are no official statistics such as Corbel (1959) tapped most effectively for his comparison of the subtropical Kissimee (Florida) and subpolar Tanana (Alaska) catchments in the U.S.A. This paper reports on the first four years of a continuing study to investigate some aspects of this theme as it is exemplified in Cooleman Plain, N.S.W. This area was chosen because it was thought to be as favourable for such investigation as any in the Eastern Highlands where limestone occurs only sporadically in small patches. Nevertheless many problems of method have arisen which have been discussed elsewhere, together with consequent modifications to the programme (Jennings, 1972). Here the results obtained so far will be discussed more fully and for their substantive import rather than for their bearing upon method.

THE COOLEMAN PLAIN KARST

Surrounded by higher ranges of Devonian intrusive and extrusive igneous rocks ranging from acid to intermediate in composition, Cooleman Plain (Fig. 1) is a small, impounded karst (Jennings, 1971b) of pure, compacted, partly crystalline Upper Silurian limestone (Stevens, 1958; Legg, 1968). Eight samples of the limestone from different stratigraphic levels had a mean increase in weight of 0.74% after seven days immersion in water; this is an indication of low intergranular porosity ("primary permeability"). The Cooleman Limestone formation is in general

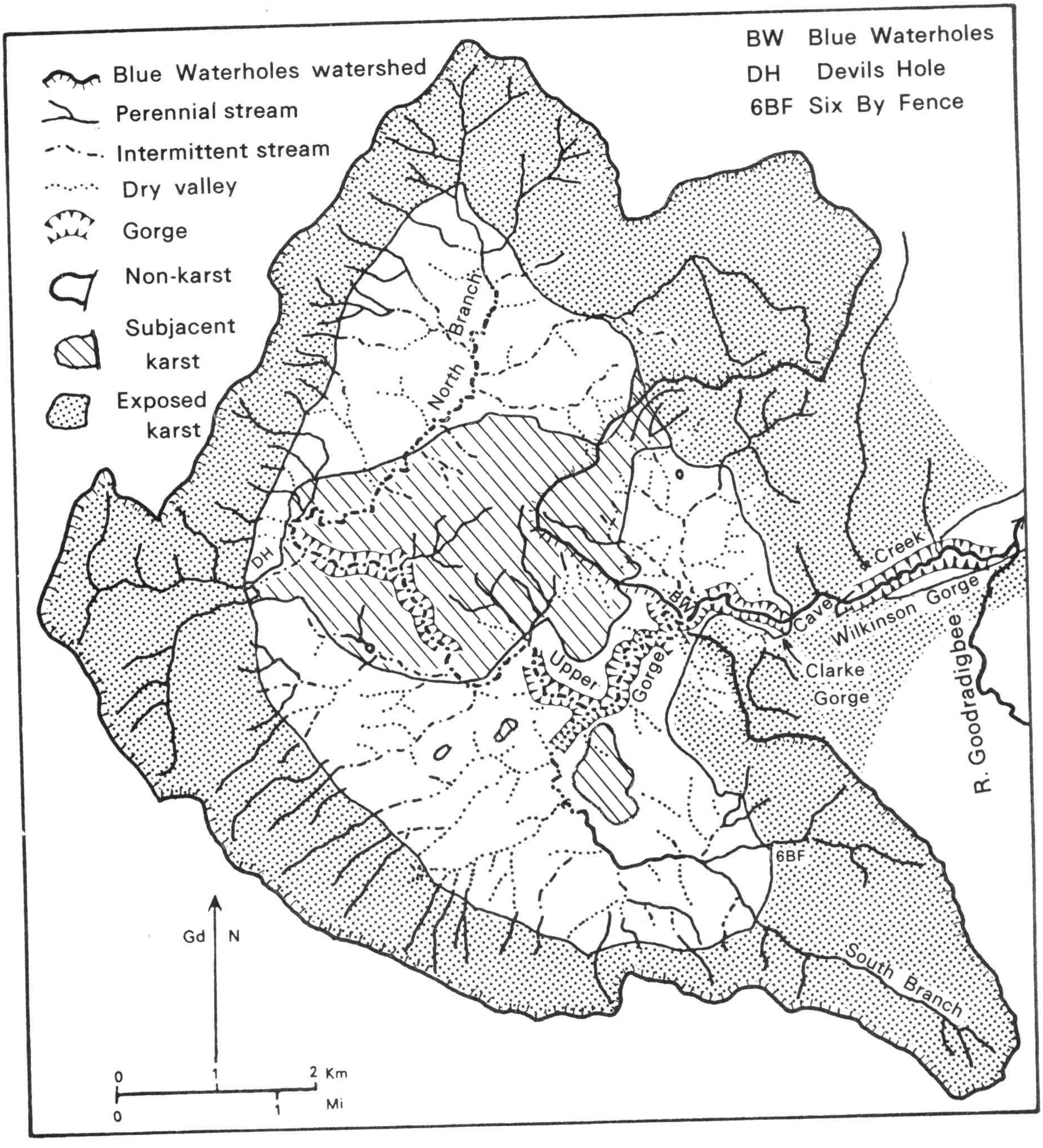

Fig.1 Morphology of Cooleman Plain and its outlet gorges.

thick-bedded to massive; on the other hand it is well jointed and in parts cleaved so that 'secondary permeability' is good.

The topographic basin has a well planed floor of probable Tertiary age (Jennings, 1967a), uplifted to its present elevation around 1250 m. This planation surface has been only partially encroached upon by a rejuvenated valley system.

The whole area is drained by Cave Creek so that there is no problem of definition of catchment but there is the disadvantage for solution studies that just over two-thirds (71%) of it is developed on non-carbonate rocks. Apart from the igneous surround and patches of Devonian lava on the plain, overlying siliceous and tuffaceous Silurian sediments survive in the middle of the structural basin into which the limestone is folded. They form low hills in the centre of the plain dividing it into northern and southern sections.

Rejuvenation has extended up Cave Creek from the Goodradigbee River to form the Wilkinson and Clarke Gorges in limestone (with a steep-sided, V-shaped valley on intervening felsite) between the granite of Black Mountain to the south and Jackson to the north. The Blue Waterholes are situated just above Clarke Gorge at a mid-point on the eastern flank of Cooleman Plain. From here gorges extend some way into the Plain up both the North and South Branches of Cave Creek. Most cave development has taken place in relation to this dissection. Towards its northern and southern ends the Plain has been scarcely affected by rejuvenation.

At the present time the drainage consists of many small, perennial or almost perennial streams flowing down the igneous rim onto the margins of the limestone plain where they become intermittent in their flow or else sink completely,their courses being continued by dry valleys cut shallowly into the planation surface. As a result, there are blind valleys such as that at Devils Hole on the western side and semi-blind valleys such as the one north of the Blue Waterholes at G.R. 705013 (Jennings, 1967b).

South Branch of Cave Creek fails to flow over the surface to the outlet of the Plain, certain parts of its gorge near the junction with that of North Branch never being occupied by a stream nowadays. On the other hand North Branch flows all the way to the Blue Waterholes for varying periods each year by a circuitous route around the west of the central hills on impervious rocks.

The Blue Waterholes mark the start of perennial flow down the outlet gorges through the igneous periphery to the Goodradigbee River. This group of karst springs is the resurgence of virtually all the streams sinking round the margin of the Plain or farther out in it, and it is also the exsurgence of rain falling onto the limestone plain itself and infiltrating into it without significant surface flow. Only a small area of the Plain immediately north of the Blue Waterholes escapes feeding these springs as is witnessed by the meagre discharge of three small springs which enter Cave Creek on its left bank between the Waterholes and Clarke Gorge.

Parts of the interfluves on the Plain bear thin covers of ferruginous sandstone of pedogenic origin and of fluvial gravels. There may have been a general cover of waste probably of Tertiary age prior to rejuvenation. There are also areas of blocky solifluction earth and small blockstreams on the flanks of valleys cut below plain level. The valley bottoms, including the larger dry valleys, have coarse alluvial fills unrelated to present discharge levels. Both the slope and floor deposits are considered to belong to a former periglacial climate, dated in the Snowy Mountains at 32,000 - 15,000 years ago (Costin, 1971). Despite the superficial deposits, there is a good deal of bare limestone outcrop, particularly in the more dissected parts.

Though in latitude 35°35-40'S, Cooleman Plain has a cool temperate climate because of its altitude. It is subject to temperature inversion and cold air drainage at night so it has a long frost incidence period. A temperature of -16.1 C at 1 m above ground surface has been recorded in incidental observations. Snow does not lie for long periods regularly; nevertheless it does do so occasionally for periods of several days to several weeks. Indeed the observations discussed in this paper were only obtained with the help of R.A.A.F. helicopters in the winters of 1965, 1966 and 1968, the access track being badly blocked by snow for even longer periods. Though the climate is humid with little seasonal concentration of precipitation, evapotranspiration rates are high in summer. Rainfall reliability in the area has been described as good by Griffith Taylor (1940), the average deviation from the annual mean precipitation being less than 20%.

Most of the Plain has subalpine grassland vegetation with sclerophyllous woodland on the slightly higher ground within it and on its margins; the surrounding ranges carry wetter sclerophyllous forest. The altitudinal vegetation succession is inverted as a result of the temperature inversions.

THE BLUE WATERHOLES

The Blue Waterholes lie at 1196 m above sea level and about 70 m below the level of Cooleman Plain, mostly around the end of a meander spur but with some small springs along the foot of the opposing meander cliff (Jennings, 1971a). The largest single spring emerges from a low cave at the foot of a small cliff somewhat recessed into the spur by springhead sapping (Fig. 2). The cave has been penetrated about 5 m where waterfilled constrictions have so far defeated further exploration. This Cliff Foot Rising feeds a stream flowing independently for 60 m before it joins Cave Creek. The peninsula between the two watercourses consists of very coarse alluvium, mainly andesitic.

Cliff Foot Rising has been shown by fluorescein tracing to be partly fed by the smaller stream which normally flows across the floor of a circular doline immediately to the west behind a narrow rock ridge. This stream emerges from bedrock cracks on the far side of the doline. There is a second swampy doline, liable to become a pool, to the south of this one. Both of these may be due to cave collapse.

To the southeast is a third circular depression occupied by a clear pool up to 1.6 m deep, walled by rock but floored by mud. The pool is fed from bedrock cracks on the southwest side but overflows to the river on the southeast. This depression may be due solely to solution by up-welling water. A considerable number of other springs also feed Cave Creek above the junction with the stream from Cliff Foot Rising. Some rise vertically under modest pressure through sand in the stream bed, sometimes cratering the sand; others flow out of the bouldery alluvium in either bank whilst there is yet another bedrock crack spring on the right bank. All these risings feeding Cave Creek directly are together referred to here as the Main Risings.

In certain wet conditions a number of other springs higher up the channel than any of those mapped on Fig. 2 may come into action. At times North Branch may lose all of considerable surface flow between the upper gorge in which Cooleman and Right Cooleman Caves are found and the Blue Waterholes. Some of this water passes through the bedrock spur to feed right bank springs below the meander cliff indicated on Fig. 2 but the bulk reappear in temporary springs higher up the channel, infiltrating through the small alluvial plain in the meander bend between the Blue Waterholes and the upper gorge in so doing.

When a flood brings a surface flow down to the Blue Waterholes, the water reaching there is at first extremely muddy through clearing the channel of accumulated debris. This muddy water is sometimes kept to the right bank half of the river by the pressure of water coming out of the left bank springs, which comprise the bulk of the Main Risings, though mixing takes place farther downstream. At a later stage in the flood, the reverse condition may occur with clear water now coming down the surface channel and muddy water issuing from the springs. It is not known whether this turbidity is due to muddy surface water arriving at the springs after a slower course underground than at the surface or is due to a flood pulse in the cave system churning up the bottoms of cave pools through greater than normal velocities and turbulence.

OBSERVATIONS

Between March 1965 and April 1969, approximately monthly observations were maintained at three points.

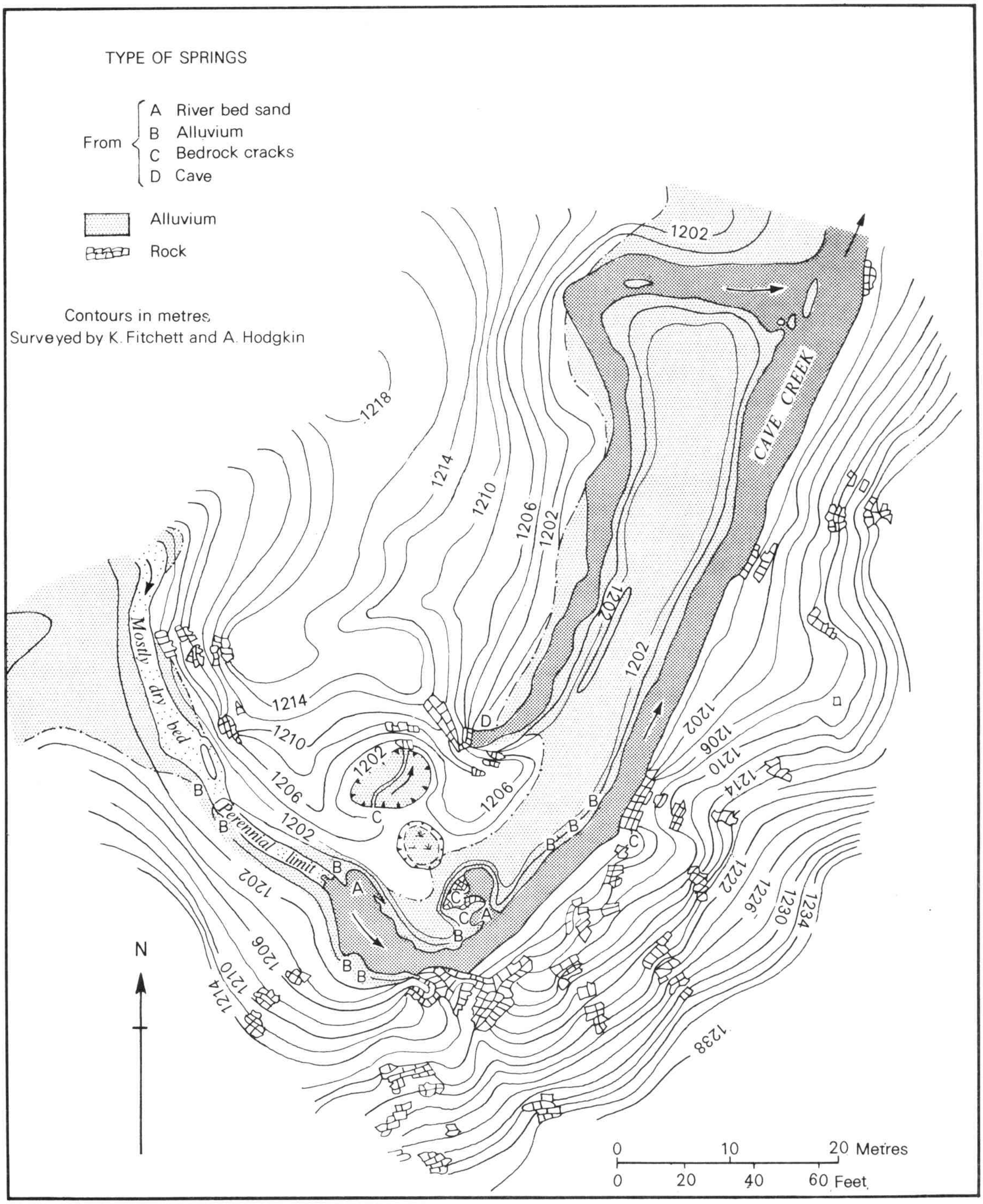

Fig. 2 Morphology of the Blue Waterholes.

(a) Cliff Foot Rising (CFR). Samples were taken and field observations other than discharge were made where the water emerges from the cave. After initial efforts to measure discharge at the same point had shown its unsuitability for this, it was subsequently measured at an artificially canalised, gravel-floored reach about 30 m downstream. There was modest escape of water from measurement in flood but at most stages this proved a much better gauging point.

(b) Cave Creek Below (CCB). Samples were taken and all field observations made in a short, straight,bedrock-floored channel of the main creek just below the most downstream springs marked on Fig. 2. This observation point summed the discharge of the Main Risings and the surface flow down North Branch when this was in action.

(c) Cave Creek Above (CCA). When there was surface flow into the Blue Waterholes, samples and field observations were also made about 30 m below the upper gorge, after some initial testing of gauging points. By subtracting Cave Creek Above discharge from that of Cave Creek Below, the outflow of Main Risings is obtained.

In the winter of 1968, snow and the grounding of helicopter squadrons enforced an 82 day interval in the sequence of observations.

The following observations were made in the field.

(1) Discharge. This was determined by flowmeter (Ott Type V 'Arkansas', Ott Type C31 and Pygmy Model P25/59 at different times). Measurements were made 2 ft apart at Cave Creek Below and at 1 ft intervals at Cave Creek Above and Cliff Foot Rising. For depths less than 1 ft one measurement was made at 0.6 of the depth from the surface; with depths greater than 1 ft observations were made at 0.2 and 0.8 of the depth.

(2) Temperature. This was normally measured to an accuracy of ± 0.25 C.

(3) pH. A Lovibond Comparator was read to 0.1 of a pH unit. For some periods, potentiometric pH readings were also taken with an Analytical Measurements Pocket pH meter. On a few occasions this was also used as a saturometer (Picknett, 1964).

(4) Specific Conductivity. This was measured with a Wissenschaftliche - Technische Werkstätten Conductivity Meter Type LF54.

Samples were collected in polythene bottles, initially of 500 ml, subsequently of 4500 ml, from the surface layers of the streams. The following determinations were made subsequently in the laboratory after mechanical shaking. Batches of samples were accumulated since experiments had shown negligible change in hardness with storage for various lengths of time.

(1) Calcium and total hardness by the EDTA method (Schwarzenbach, 1957). Magnesium hardness can then be obtained by subtraction. The common practice of presenting the results as carbonate equivalents was followed.

(2) Ca, Mg, Na and K cations by Perkin-Elmer Atomic Absorption Spectro-photometer Model 303.

(3) Silica colorimetrically using ammonium molybdenate, a thermostatically controlled waterbath and a Nessleriser Disc NN (Tintometer Ltd., n.d.).

(4) Chloride volumetrically by the silver nitrate (Mohr) method (Rainwater and Thatcher, 1960).

(5) Total dissolved salts by evaporation over a steam bath, oven drying of residue and weighing (Douglas, 1966).

(6) Suspended sediment concentration by filtering onto Whatman No. 542 paper in a Buchner funnel with a vacuum pump, oven drying, desiccating and weighing (Douglas, 1966).

DISCHARGE

The record of discharge will now be discussed in relation to Tantangara Dam precipitation (Fig. 3a). This station is 18 km away at the closely comparable height of 1250 m. The altitude and topography of Currango Plain in which the reservoir is situated are broadly similar to those of Cooleman Plain so that the course of precipitation and its amount are probably closely comparable. Measurements of discharge began late in March so the hydrologic year for the study became April to March; this fortuitously coincides with the sharpest break in the hydrograph in most years (Fig. 3b).

1965-6

Measurements began in March 1965 when flow was very low after two months of little or no rainfall previously. The lowest discharges recorded in the four year observation period were those of 12 June 1965; the whole discharge of 165 l/sec came from the springs with no water coming down the creek bed.

Heavy rains were recorded at Tantangara on 15-17 August, totalling 81.3 mm from the three days. By the end of August the Blue Waterholes were yielding 412 l/sec. Further rain in the first half of September brought the total discharge to 682 l/sec by late September with a slight flow in the creek bed above the springs. No rain till October led to a reduction in springs output with the bed dry again. Rain followed bringing a second peak in the record about the same height as the first with a slight surface flow once more. A good rain at the beginning of December may not have been fully registered by the highest discharge of the first year's observations of 841 l/sec on 14 December; this included 110 l/sec of surface flow. There followed a late summer-autumn decline in discharge despite occasional good rains, falling to a minimum of 275 l/sec on 5 March, all spring water.

1966-7

A very heavy rain in mid-March was reflected in increased flow in an early April measurement. Prolonged high flows from May to mid-December depended on winter and spring rains and these included substantial flows down the creek bed. A relatively low flow in early August resulted from a period of snow lie. The maximum measured during the hydrologic year of March 1966-April 1967 was 1610 l/sec on 7 September 1966, of which 236 l/sec was down the creek bed. Decline was continuous from January to March, the lowest discharge recorded being that of 317 l/sec on 8 March when the creek had ceased to run again.

1967-8

1967 and early 1968 was a drought period with the 1967 rainfall at Tantangara only 40% of that of 1966. No surface flow to the Blue Waterholes was recorded in the whole 1967-1968 hydrologic year. A slight peak in springs discharge of 329 l/sec in early September 1967 probably under-represents the effects of August rains.

1968-9

Recovery began in late May 1968. Inability to get to the Plain in July and August because of snow probably means that a July peak was missed. Spring and surface flows were big in September and on 14 November the biggest discharge of the 4 years series was measured at 2193 l/sec and this was the only occasion in the series when the surface flow was greater than the volume of the springs. Decline was drastic from December to March despite some good rains and the creek dried up above the springs. The March minimum for 1968-9 was 281 l/sec. A sharp reversal took place in April at the beginning of the succeeding hydrologic year.

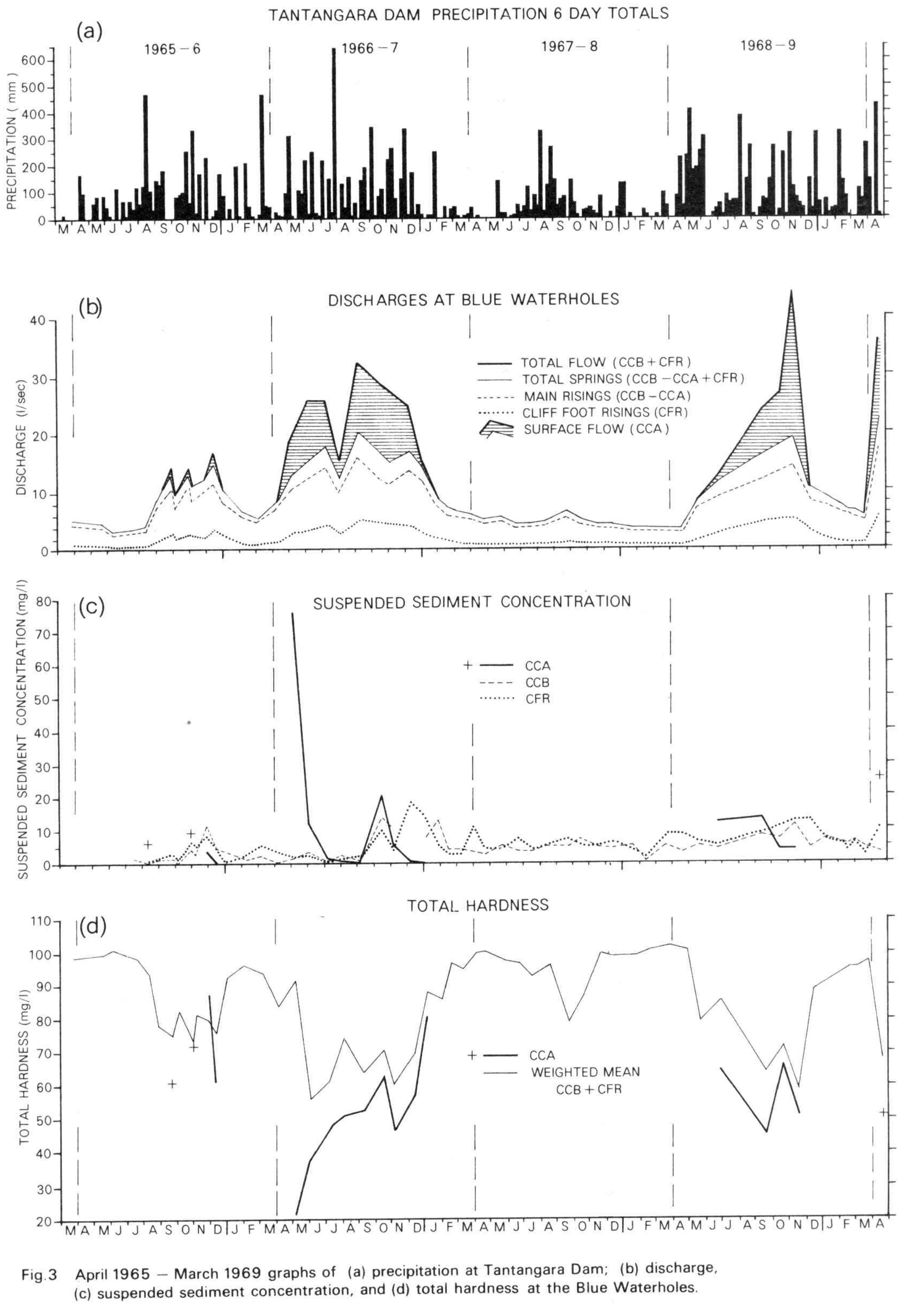

Fig.3 April 1965 – March 1969 graphs of (a) precipitation at Tantangara Dam; (b) discharge, (c) suspended sediment concentration, and (d) total hardness at the Blue Waterholes.

There was thus considerable variation from year to year, only 1966-7 and 1968-9 resembling one another at all closely. However an autumn low flow did occur each year and spring registered high flows with some discharge over the surface every year except for the drought year 1967. Surface stream flow duration varied from nil to 9 months. The total resurgence had to top about 550 l/sec before water came down the creek bed.

Despite the variation recorded in these four years, the Cave Creek regime below the Blue Waterholes may be regarded as a simple one of oceanic pluvial type (Pardé, 1933), the lack of seasonal concentration of rainfall and the high evapotranspiration of summer and early autumn resulting in two hydrologic phases. These consist of winter and spring high discharge compounded of groundwater and surface flow and late summer and autumn low discharge of groundwater provenance. Drought may reduce the discharge to low groundwater flow with little seasonal variation and long snow cover with subsequent melt may diversify the high flow period.

Cliff Foot Risings and Main Risings kept well together in their variations; regression of the former on the latter was very strong. Correlation between Cliff Foot Rising and the surface flow from the Plain was less close but still very significant.

Discharge ($\dot{Q}$) (l/sec)	r	Significant at
CFR Q = 0.365 Main Risings Q -39.73	0.963	0.1%
CFR Q = 0.164 CCB Q +15.05	0.945	0.1%
CFR Q = 0.236 CCA Q +67.35	0.913	0.1%

The annual runoffs from the Blue Waterholes catchment for the four hydrographic years yielded an annual variability (Gygax, 1948) of 5.7 which is extremely large for so short a period.

	Cave Creek runoff (April-March) mm	Tantangara rainfall (March-February) mm	Runoff/ rainfall as %
1965 - 6	233	874	27
1966 - 7	823	1159	72
1967 - 8	146	527	28
1968 - 9	579	1215	48
Mean	448	944	47

The preceding account of the course of discharge in relation to Tantangara rainfall showed that sustained rise in flow lagged about one month after heavy rainfall when there had previously been substantial depletion of groundwater in the late summer-autumn period or by prolonged drought. Therefore runoff is best compared with rainfall years from March to February.

However there is no network of stations close to Cooleman Plain for calculating its rainfall adequately. Tantangara Dam station lies low in the local relief and precipitation will be higher on the ranges around Cooleman Plain. There is also general decrease in precipitation northwards from Tantangara. Let it be assumed that these two factors balance one another an apply the Tantangara figures as a mean to the Blue Waterholes catchment. On this basis the catchment efficiency is as set out above. These runoff/rainfall ratios are very high and it seems therefore that the mean rainfall over the Plain may be greater than the Tantangara precipitation. The relative changes are probably reliable however. These are large and no doubt reflect significant differences in evaporation from year to year as well as in precipitation. Rainfall intensity could also be involved in this variation in efficiency from year to year but a crude analysis of the Tantangara daily rainfalls does not support this.

		1965-6	1966-7	1967-8	1968-9
Daily rainfalls	>0.5 in.	17	28	11	29
" "	>1.0 in.	8	9	2	6

However rainfall data from Cooleman Plain itself might tell a different story.

TEMPERATURE

Cliff Foot Rising waters were measured right at their resurgence and thus were unaffected by the atmosphere and so diurnal temperature changes. Their temperature varied between 8.5 and 13.5 C. The mean of 54 observations was 10.8 . Because of diurnal changes and weather conditions, the recorded temperature of Cave Creek Above ranged between 6.5 and 19. Nevertheless because of the usually greater volume of the Main Risings compared with that of surface flow, Cave Creek Below agreed very closely with Cliff Foot Rising, never departing more than 1.5 from it and varying between virtually the same limits (8.5 and 13.7). The mean annual air temperature of the Plain is probably therefore about 11 .

A seasonal temperature rhythm is evident in the Cliff Foot Rising and Cave Creek Below figures with the warmest months (12 - 13.5 C) in autumn (January-March) and the coldest (8.5 - 10.5 C) in spring (August-September).

SUSPENDED SEDIMENT CONCENTRATION

Because an integrating sampler was not used and near surface samples were collected, the determinations of suspended sediment load (SSC) are not regarded as absolutely very reliable though they should be satisfactory indicators of changes in load over time. The waters were generally clear and correspondingly the concentrations determined in Cliff Foot Rising and Cave Creek Below were low; the former ranged between 0.6 - 18.8 mg/l, with a mean of 5.68 mg/l and standard deviation of 3.91, the latter between 0.2 - 14 mg/l, with a mean of 4.69 and standard deviation of 3.29. Although the greater values occurred during periods of greater discharge, they did not persist throughout them (Fig. 3c). Consequently there was no close correlation between the sediment load and discharge. Generally CFR and CCB behave sympathetically in respect of suspended load but on five occasions Cliff Foot Rising had a margin over Cave Creek Below greater than sampling and determination errors. On two occasions the opposite occurred.

Cave Creek Above ranged between 0 and 70 mg/l with mean of 10.9 and standard deviation of 17.9 but the 70 mg/l was the sole high value recorded and related to a special circumstance. Surface flow in the creek above the Blue Waterholes began only one hour before the sample was taken and the first flow to come down was more turbid even than when it was sampled. The high sediment load was the result of a flushing of the river channel after it had been dry for about four months. On this occasion only did the clastic load exceed the solute load at any of the three sampling points over the four years. Storm water discharges not observed probably shifted significant bodies of sediment. The limited data indicated a tendency of Cave Creek Above to rise above the springs in suspended load concentrations about the flood peaks but to drop below as surface flow declined.

Because suspended load (and bedload) varies extremely greatly with discharge, the lack of a continuous record of discharge makes calculation of absolute load from a small number of determinations inaccurate to a degree which does not apply to the solute load to be discussed later. Therefore rates of solid particle removal have not been determined. Some crude indication of relative importance of the clastic and solute loads may be gained from the mean concentrations of suspended solids and total dissolved salts.

Weighted mean SSC for CFR + CCB = 5.15 mg/l σ = 3.62 V=70.2%
" " TDS " " " = 93.01 mg/l σ = 15.47 V=16.6%

The coefficients of variation (V) register the peakiness of solid load compared with the steadier solute load. The means are in the ratio of 1 to 18; even when surface layer sampling, bedload (10-20% of suspended load) and inadequate sampling of peak loads are allowed for, the solute load will still probably exceed solid load greatly. Cave Creek will thus conform to the generality of southern New South Wales catchments studied by Douglas (1966) in this respect.

TOTAL DISSOLVED SALTS

Total dissolved salts (TDS) had the following characterisitics.

	TDS (mg/1)			
	n	$\bar{x}$	σ	Range
CFR	50	95.1	14.4	74-125
CCB	50	92.7	17.1	50-118
CCA	18	61.2	14.6	45- 94

The solute concentration of the Creek above the Waterholes is nearly always lower than that of the Cliff Foot Rising. However, Cave Creek Below and Cliff Foot Rising are in close agreement.

At all three observation points the solute load varies inversely with discharge (Fig. 4a) though the correlation is weaker with the surface flow.

	TDS (mg/1)		Q (1/sec)	r	Significant at
CFR	TDS	=	-0.162 CFR Q + 111.55	0.826	0.1%
CCB	TDS	=	-0.03 CCB Q + 107.747	0.731	0.1%
CCA	TDS	=	-0.026 CCA Q + 74.44	0.61	1%

The inverse correlation of solute load and discharge is due to more than one factor. Low discharge in summer and autumn is partly a product of greater evapotranspiration and so of increased surface concentration. On the other hand during high discharges, rapid passage of water through the cave systems reduces the opportunities for limestone solution, keeping groundwater concentrations down. Also at these times CCA flow supplements groundwater in the CCB discharge and the former has had less opportunity for limestone solution than the latter because of higher CO_2 values underground (Douglas, 1968a). CCA flow does, however, include some groundwater from Cliff Cave Spring, spasmodically from Murray Cave and also from other springs which function in very wet conditions. The more variable nature of Cave Creek Above waters accounts for the less close correlation of TDS with discharge.

A useful basis for comparison with other rivers in eastern Australia is to be found in the data published in Douglas (1968b) for 39 gauging points from 31 catchments, of which 18 are from north-eastern Queensland and 13 from south-eastern New South Wales. Of these catchments, four only have total dissolved salts around the Cave Creek values; they are all from New South Wales, three mainly developed on sedimentary rocks and one on granite. On the other hand, twelve catchments have less than half the solute contents of Cave Creek and eleven of these are mainly on igneous rocks. Nevertheless although Cooleman Plain is more subject to chemical denudation than most catchments in eastern Australia, it will be seen later that it is less so than very many limestone basins in similar climates in other countries. It is unfortunate that as yet no data are available for comparison from other limestone rivers in eastern Australia.

(a) Sodium. Sodium concentrations are very low compared with the results obtained by Douglas (1968b) in the Eastern Highlands of Australia. The only correspondingly low value he records comes from the most comparable river in terms of climate, namely the Snowy River above Guthega, a granodiorite catchment.

Na (mg/1)

	n	$\bar{x}$	σ	Range
CFR	49	1.5	0.2	1.3-1.8
CCB	50	1.5	0.2	1.1-2.4
CCA	18	1.2	0.1	1.1-1.4

Cave Creek Above waters are not significantly different from the spring waters when the data sets are reduced to observations made simultaneously. It is necessary to do this because the times when the flow comes down the river bed are not random but related to specific conditions affecting the springs also.

The variation over time is not great but there is an inverse relationship with discharge on the part of the spring waters.

$$\text{CFR} \quad \text{Na(mg/1)} = -0.0015 \ \text{Q(1/sec)} + 1.619$$

$$r = -0.746 \text{ significant at } 0.1\%$$

This must be due to greater concentration of solutes by evapotranspiration at times of low flow. The Canberra rainfall mean for Na is 1.01 mg/1 and the sodium in the waters may therefore be derived entirely or almost entirely from the atmosphere.

(b) Potassium. Potassium concentrations are also very low though Douglas does record some ten catchments with values around those of Cave Creek. These catchments are varied in respect of lithology, relief and rainfall though a disproportionately high number of them are from the Southern Tablelands as compared with north-eastern Queensland.

K (mg/1)

	n	$\bar{x}$	σ	Range
CFR	48	0.5	0.2	0.2-1.1
CCB	48	0.6	0.2	0.3-1.2
CCA	16	0.5	0.2	0.2-1.1

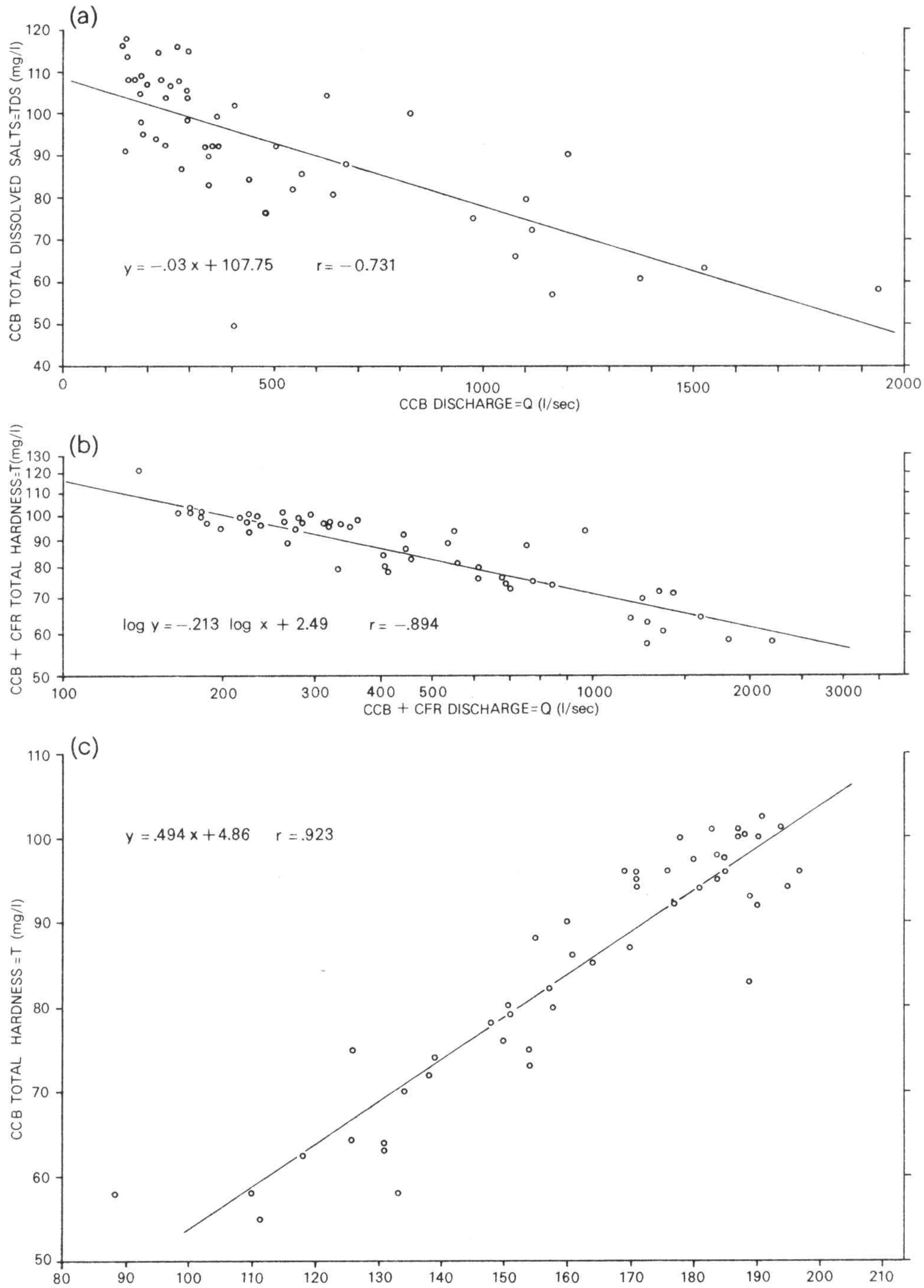

Fig. 4 Scatter plots and regressions of (a) total dissolved salts on discharge, Cave Creek Below; (b) total hardness on discharge, Cave Creek at Blue Waterholes; (c) total hardness on specific conductivity, Cave Creek Below.

The waters are not significantly different from one another in their potassium content. Nor is there any significant correlation between potassium and discharge at any of the three observation points. Whether this is real or a product of inadequately accurate measurement of the extremely small concentrations is not known, though Douglas (1966) found that potassium behaved anomalously in the Barron River, north Queensland, suggesting absorption onto clays in dry periods and resolution during turbulent flood flows.

The mean of K in Canberra rainfall is 0.86 mg/l and therefore the whole of the potassium in the water could be derived from the precipitation. Indeed the figures permit of accumulation of potassium within the catchment but present data do not allow it to be said that this is in fact happening.

(c) Chlorine. The chlorine content of Cooleman Plain water is also low compared with other streams in the Eastern Highlands though there are twelve catchments in Douglas' list with similar concentrations. These again vary widely in relief, lithology and climate. About half lie in southern New South Wales and half in northern Queensland but all the values lower than those of Cave Creek come from the Southern Tablelands.

Cl (mg/l)

	n	$\bar{x}$	σ	Range
CFR	50	6.1	1.4	3.2-11.0
CCB	50	6.4	1.7	3.2-12.0
CCA	18	5.6	1.7	3.6-5.9

There are no significant differences between the three waters in chlorine content nor any determinable relationship of chlorine concentration against discharge.

Canberra rainfall has a substantially lower chlorine mean of 2.8 mg/l and therefore despite increase in concentration implied in the runoff/rainfall ratio, it is likely there is a contribution from the catchment as well as from the atmosphere.

(d) Silica. The silica figures for Cave Creek are high in comparison with Douglas' catchments, only four of them yielding similar values and all of them from Queensland on igneous rocks. However Douglas (1968) states that high rates for silica also occur in wet cold climates with warm summers as in the Snowy Mountains; he cites the Cowlitz R. (14 mg/l).

SiO_2 (mg/l)

	n	$\bar{x}$	σ	Range
CFR	50	12.7	1.7	9.0-18.5
CCB	50	12.5	1.8	9.0-17.5
CCA	18	9.9	1.2	8.0-12.5

There are no significant differences between the data sets.

The spring waters show a weak inverse relationship with discharge in their silica content but surface flow down the creek bed to the springs has in contrast a direct relationship with discharge.

SiO_2 (mg/l) Q (l/sec)	r	Significant at
CRF SiO_2 = -0.009 CFR Q + 13.65	-0.399	1%
CCA SiO_2 = -0.002 CCA Q + 9.15	+0.548	5%

The former regression can be explained by concentration of surface waters by evaporation at times of low and slow flow but the latter is difficult to explain. No determination of silica in the precipitation is available to help in this matter but the values are so high as to suggest that much of the silica is derived from the igneous rocks in the basin rather than being blown in from outside.

Douglas (1966) found no systematic relationship between silica concentration and discharge in eastern Australian rivers, though he does quote Carbonnel (1965) who found an inverse relationship in the case of the rivers draining into the Great Lake in Cambodia.

(e) Ratio of calcium and magnesium to sodium and potassium. The prime purpose of analysing constituents of the waters other than those primarily derived from limestone was to see whether Cave Creek carries carbonate waters. The ratio of the alkaline earths to the alkalis has been chiefly used for this (Hack, 1960; Douglas, 1968b) and on this basis there is no doubt about the importance of limestone solution in the chemistry of the Blue Waterholes waters.

$\frac{Ca + Mg}{Na + K}$ (cations in equivalents per million = epm)

	n	$\bar{x}$	σ	Range
CFR	47	11.3	1.36	12.0-21.4
CCB	45	11.3	1.8	7.4-15.4
CCA	16	8.4	2.65	3.0-12.6

None of Douglas' basins have ratios approaching these; this is consonant with the fact that none of them is developed on carbonate rocks. It is also consistent with his generalisation that precipitation contributes more to the water chemistry in the catchments with the lowest rates of chemical denudation. His highest value of 2.95 comes from Flea Creek in A.C.T. Ranges, a rhyolite catchment chiefly.

There is no statistically significant difference between the surface flow and the springs waters, though the ratios from the surface flow vary more than do those from the groundwater.

The relationship of the springs ratios to discharge is inverse but not very strong.

	$\frac{Ca + Mg}{Na + K}$ (epm)	Q (l/sec)	r	Significant at
CFR	$\frac{Ca + Mg}{Na + K} =$	-0.011 CFR Q + 12.4	-0.59	0.1%
CCB	$\frac{Ca + Mg}{Na + K} =$	-0.003 CCB Q + 12.56	-0.535	0.1%
CCA	$\frac{Ca + Mg}{Na + K} =$	-0.004 CCA Q + 9.998	-0.468	5%

This inverse relationship is the result of a more sensitive inverse regression of total hardness on discharge (see below) combined with a less sensitive inverse regression of sodium and the lack of any simple relationship between potassium and discharge. Put in another way, the more dilute the solutions are the larger the relative contribution of atmospheric salts and the less that of limestone solution and vice versa; the greater the runoff/rainfall ratio the more dilute the solution.

TOTAL HARDNESS

There is no need for separate discussion of calcium hardness and magnesium hardness since calcium hardness makes up about 90% of total hardness and their variation in time coincides. The regressions and correlations with discharge are practically the same for both calcium and total hardness for all three points of collection. From the previous consideration of the chemical composition of the solutes, it also follows that total hardness will be closely comparable in behaviour to total dissolved salts.

The total hardness (T) of Cliff Foot Rising and Cave Creek Below are very similar but Cave Creek Above is not so hard and varies more.

T(mg/1)

	n	$\bar{x}$	σ	Range
CCF	54	86.4	12.8	58-102
CCB	50	85.6	13.9	55.103
CCA	19	56.6	14.8	22-87

These mean values are low compared with values for karst springs in broadly similar climatic conditions, e.g. 200 mg/1 for the common value for Mendip Springs, Somerset, for calcium carbonate hardness alone. The main cause of the low Blue Waterholes hardness is the high proportion of the water which falls on the non-karst two-thirds of the catchment and flows comparatively rapidly through the cave systems in the limestone. Pitty (1968, 1971) has demonstrated a direct relationship between water hardness and the proportion of limestone in each catchment in the Peak District, Derbyshire. Throughput times by fluorescein tracing between the South Branch watersink and the Blue Waterholes have been recorded of somewhat less than 65 hours 20 minutes for the straightline distance of 2.25 km at a time of low flow and between Devils Hole and the same risings of somewhat less than 50 hours 50 minutes for a distance of 4.3 km at a time of high discharge.

Inverse correlations of total hardness in Cliff Foot Rising and Cave Creek Below with their respective discharges are even closer than those of their total dissolved salts content (Figs 3; 4b) but with Cave Creek Above the correlation is less close, only becoming significant (and at the lower 95% confidence level only) as a log-log relationship. The logarithmic relationship is given below for all three though in fact there is a slight loss of correlation in the case of the Cliff Foot Rising.

T (mg/1)		Q (1/sec)	r	Significant at
log CFR T	=	-0.18 log CFR Q + 2.269	-0.853	0.1%
log CCB T	=	-0.217 log CCB Q + 2.486	-0.897	0.1%
log CCA T	=	-0.118 log CCA Q + 2.006	-0.572	5.0%

The lowest value for total hardness of Cave Creek Above of 22 mg/1 occurred on 5 May 1966 shortly after heavy rains sent North Branch down its surface bed to the Blue Waterholes. Though it swept down a great deal of detritus, it had not yet taken up very much limestone in solution.

The explanation already given for the inverse correlation of total dissolved salts with discharge applies also to the similar relationship between total hardness and discharge. It is the commonest relationship in karst hydrogeology, e.g. R. Ljubljanica, Slovenia (Gams, 1966), though it does not apply in all karst situations. Thus in Ireland, the

R. Shannon, with a large catchment and many tributaries, varies only 3.7% in total hardness (William, 1970). In Mendip most springs behave like the Shannon though there is one, Langford Rising, which is similar to the Blue Waterholes (Ingle Smith, 1965). Douglas (1968a) draws attention to the R. Hull, Yorkshire where there is no systematic relationship between hardness and discharge and the R. Thames at Oxford where there is a direct relationship between the two which is not properly understood. The presence of substantial areas of non-carbonate rocks in these catchments complicates their responses.

SPECIFIC CONDUCTIVITY

Specific conductivity (SC) correlates extremely closely with total hardness and calcium hardness at all three observation points (Fig. 4c).

	T (mg/l) SC (micromhos)	r	Significant at
CFR	T = 0.502 CFR SC + 4.03	0.94	0.1%
CCB	T = 0.494 CCB SC + 4.86	0.93	0.1%
CCA	T = 0.523 CCA SC + 0.31	0.98	0.1%

Therefore, for certain purposes at least, the simple field measurement of specific conductivity could be substituted for laboratory determination of hardness. However the differences between these regressions, especially between CCA and the other two, demonstrate the need for calibration of S.C. against the solute content of the waters at each observation point for the accurate use of such regressions.

Conductivity correlates inversely with discharge but the level of correlation at Cave Creek above the springs is only just significant at the 95% confidence level.

	SC (micromhos) Q (l/sec)	r	Significant at
CFR	SC = -0.288 CFR Q + 191.78	-0.85	0.1%
CCB	SC = -0.057 CCB Q + 192.71	-0.86	0.1%
CCA	SC = -0.047 CCA Q + 127.84	-0.46	5.0%

SOLUTIONAL CAPACITY

For many years the Trombe (1952) graph of saturation equilibrium for calcite against temperature and pH, both of which can be readily measured in the field, has been used as a means of determining whether natural waters are undersaturated and aggressive to limestone or are supersaturated and liable to precipitate calcite. Picknett (1964, 1972) has recently established a more accurate formula for these relationships by empirical determination of calcite saturation in controlled conditions. Graphs can be drawn with the formula for the appropriate temperatures for the field samples being considered. In addition Picknett (1972) has determined the effect of magnesium ions on the calcite equilibria. With about 10% of magnesium to calcium, this interference is at a minimum and can be neglected for gemorphological arguments from the results. Cooleman Plain waters have ratios close to this and therefore total hardness has been plotted on a Picknett graph (Fig. 5).

Cliff Foot Rising waters were aggressive on 53 out of 54 occasions. On one low discharge mid-winter occasion they were slightly supersaturated and on two other occasions they approached close to saturation. On 15 occasions a potentiometric pH meter was used as a saturometer (Picknett, 1964). On ten of them the pH change indicated aggressiveness in agreement with the Picknett curve; of the other five when they were also aggressive according to the graph, one indicated saturation and four supersaturation.

Cave Creek Above was much more variable in its condition. Of 17 determinations, four showed supersaturation, two saturation whilst two of the 11 aggressive samples lay near to saturation. Supersaturation and saturation corresponded with very small flows down North Branch bed in all but one case. Saturometer tests were made only twice, one being aggressive and one supersaturated, both agreeing with the results from the graph.

Cave Creek Below followed Cliff Foot Rising very closely in its behaviour in this respect despite the frequent admixture of surface water so these results are omitted from Fig. 5.

As drips from Murray Cave roof are employed at a later stage in this paper in the allocation of limestone solution to different domains, it is relevant to note their characteristics here. Of 35 drip measurements, all with greater hardnesses than any recorded at the Blue Waterholes, 28 were supersaturated and a majority of the seven aggressive samples came from one drip point just inside the cave entrance with only five m of rock above.

The persistent aggressiveness of the spring waters at the Blue Waterholes is readily interpreted in terms of great dilution of the exsurgent karst waters represented by the Murray Cave drips by resurgent input from the much larger igneous rim. The occasional achievement of supersaturation by North Branch waters reaching the Waterholes on the surface may be due to greater evaporation when flows are small, fail to fill the bed, pass through many quite pools and generally take much longer to reach there than when flows are big.

COMPARISON BETWEEN THE SPRINGS AT THE BLUE WATERHOLES

Extremely close correlation between the discharges of Cliff Foot Rising and Main Risings has been indicated with lesser correlation between Cliff Foot Rising and Cave Creek Above. Hardness figures for Cliff Foot Rising and Cave Creek Below are so nearly identical that it would be superfluous to calculate the correlation. There is more departure in hardness between Cliff Foot Rising and Cave Creek Above and this difference is also true for temperature and pH observations. Regressions and correlations calculated for total dissolved salts, total hardness and specific conductivity on discharge are very similar for Cliff Foot Rising and Cave Creek Below, with more departure for those for Cave Creek Above.

The only other Cooleman Plain spring for which a number of observations has been collected is Cliff Cave Spring near its western margin. Seven total hardness determinations gave a higher mean of 109 mg/l with a small standard deviation. Using determinations of total hardness at Cliff Foot Rising on the same seven occasions, the difference of means of the paired observations is significant at the 0.1% confidence level. This indicated that uniformity of spring waters throughout the Plain cannot be expected and therefore agreement between the data from Cliff Foot Rising and Cave Creek Below should not be regarded as explicable by separate underground waters of similar nature.

TABLE 1

	24/10/69			2/11/69				24/11/69	
Spring	T°C	Ca Hardness (mg/l)	Ca+Mg Hardness (mg/l)	T°C	SC (micromhos)	Ca Hardness (mg/l)	Ca+Mg Hardness (mg/l)	T°C	SC (micromhos)
1	10.8	75	84	10.6	98	61	70	9.8	106
2	10.8	76	88	10.6	100	63	71	10.0	110
3	10.8	75	87	10.6	104	64	73	10.1	107.5
4	10.9	75	85	10.6	99	62	71	10.2	110
5	11.8	74	83	10.6	99	60	70	10.2	106
6	10.8	75	84	10.6	100	62	70	9.9	110
7	10.8	74	83	10.6	100	61	70	9.8	107
8	10.6	74	84	10.6	99	61	70	9.8	109
9	10.8	76	84	10.6	99	62	70	9.8	112
10	10.6	76	86	10.5	105	64	73	10.0	100
11	10.8	75	84	10.6	104	71	70	9.8	100
12	10.6	73	84	10.6	100	62	71	10.0	99
13	10.6	74	84	10.6	99	62	70	10.0	105
14	10.6	77	88	10.6	104	66	74	10.0	110
15	25.0	79	86	14.4	85	45	54	Not flowing	

1 = Cliff Foot Rising   5 = Pool outflow affected by atmosphere   15 = Cave Creek Above

Thermometer used for these observations accurate to ± 0.1°C

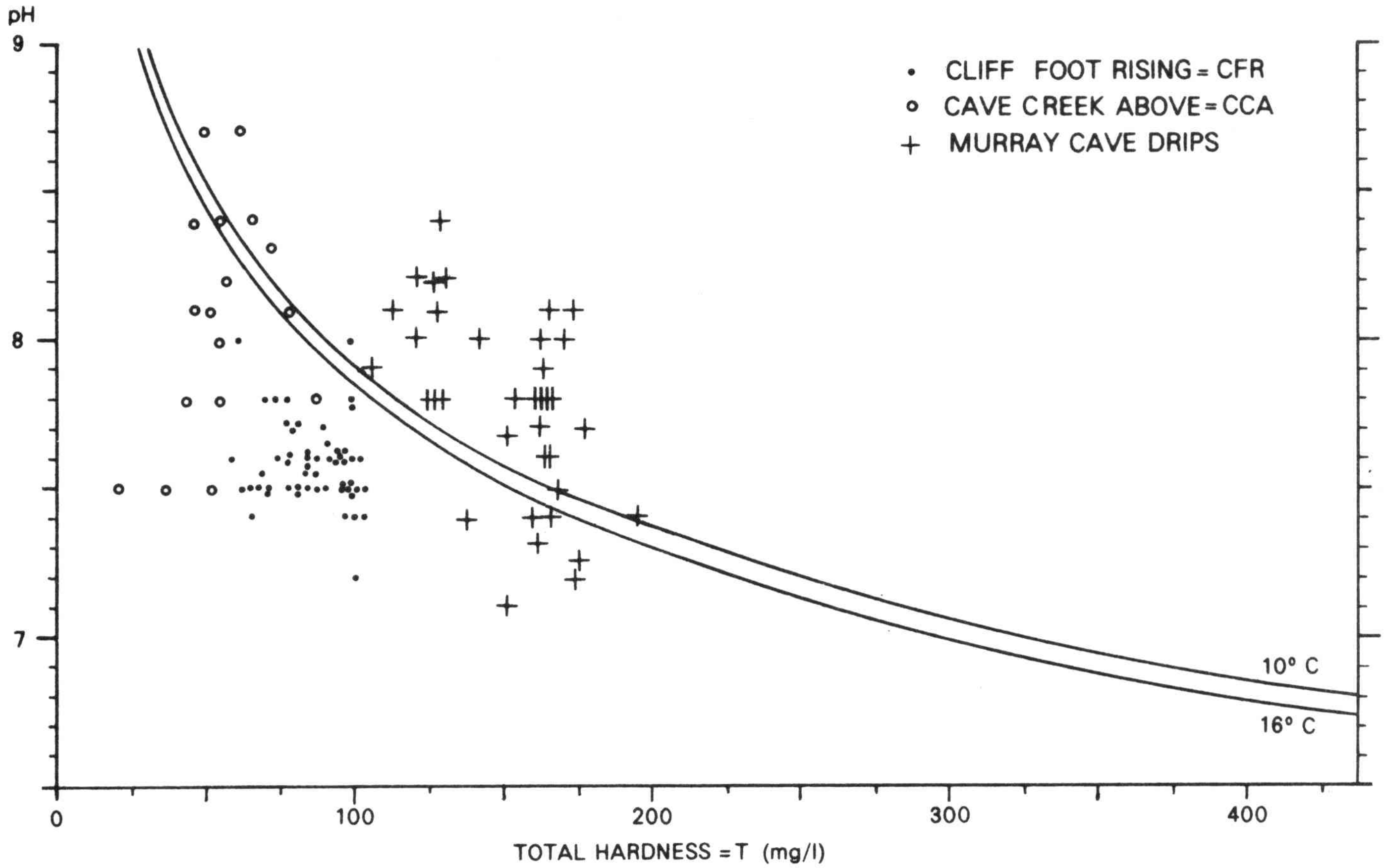

Fig. 5 Picknett graph of water samples from Cliff Foot Rising, Cave Creek Above and Murray Cave drips.

The possibility that different waters emerge from the individual springs feeding Cave Creek Below and mix to yield a common water matching that from Cliff Foot Rising is small and can be eliminated on the basis of sets of observations made simultaneously on most of the individual springs of the Blue Waterholes (Table No. 1). The small differences between springs 1-14 are unsystematic and are all considered to be observational error.

Visual observations of turbidity mentioned in the previous description of discharge have on all occasions but one agreed with the implications of the data so far presented. When Cave Creek Above has been turbid from surface runoff, all springs have been clear or all turbid. When springs have been turbid and Cave Creek Above clear, the springs have all behaved sympathetically with one another. However, on 18/12/70, K. Fitchett and W. Hocking observed a contrary indication. Turbidity of Cave Creek Above rendered the centre of the main pool moderately turbid whilst both sides remained clear from strong spring flows. However Cliff Foot Rising was very turbid and its discharge was in strong contrast with that of Cave Creek at the junction of the two. This is surprising in the light of all the other evidence, including the fact that Cliff Foot Rising lies central to the small dispersion in the values of the springs in Table No. 1. A possible explanation is that though the major artery feeding the Blue Waterholes was lacking suspended load at that moment, increased discharge and turbulence had churned up sediment in a short separate distributary channel just behind the Cliff Foot Rising.

It can be argued from this evidence that one underground conduit supplies all springs at the Blue Waterholes except those which only come into action when there is surface flow down the creek bed.

RATES OF Ca + Mg CARBONATE EQUIVALENT REMOVAL

Since the waters of Cliff Foot Rising and Cave Creek Below have practically the same chemistry at any given time, further analysis will be based on the total discharge of Cave Creek (CFR + CCB) and the hardness assigned to it will be derived from the separate hardnesses where there is departure between them by weighting in proportion to their respective volumes.

Total hardness figures have been commonly accepted as a reasonable basis for calculating rates of limestone removal from catchments with substantial limestone outcrop. This has to be qualified significantly in the present study area as will be seen below but it will be useful first of all to look at the results of division of the gross total hardness by the corresponding discharges, regarding them as rates of removal of Ca + Mg carbonate equivalent from the whole catchment.

The instantaneous rates of removal of carbonate equivalent from Cave Creek below the Blue Waterholes are set out in Fig. 6 where it can be seen how closely they match the discharge despite inverse relationship of total hardness concentration with discharge. Total hardness only varies about twofold whereas discharge varies about thirteenfold. There is a highly significant regression of rate of carbonate equivalent removal against discharge of Cave Creek.

$$\text{Rate of Ca + Mg carbonate equivalent removal (g/sec)} = 0.63(\text{CCB} + \text{CFR Q})\ (\text{l/sec}) + 5.6$$

$$r = 0.97 \text{ significant at } 0.1\%$$

The mean of all determinations of rate of carbonate equivalent removal from the catchment is 45.08 g/sec with a standard deviation of 27.88 and a range of 17.52 g/sec to 127.75 g/sec. The mean annual rates were 37.5, 67.5, 22.7 and 50.6 for the four years, giving a large annual variability (Gygax, 1948) of 2.99 for this short period of observation. There was a broad tendency to a winter-spring peak and summer-autumn trough nevertheless.

CORRECTIONS FOR OTHER INPUTS

The low hardnesses and low rates of carbonate equivalent removal from the catchment makes it necessary to correct these gross figures for inputs from other sources than the exposed limestone before relating them to the area of limestone to obtain rates of limestone removal per unit area.

(1) Atmospheric Salts

Douglas (1968b) and Goudie (1970) have pointed to the need to allow for the chemical composition of rainfall when determining solute loads and rates of erosion. Williams (1968) decided to neglect it in his study of the Fergus Basin, Ireland, but the Fergus hardnesses are considerably larger than those from Cooleman Plain. Moreover the less efficient the catchment the higher the contribution of a given concentration of atmospheric salts in the rainfall will be to the runoff concentration; loss by evapotranspiration is considerably greater over Cooleman Plain than over the Fergus Basin.

No rainfall chemistry analyses were made at Cooleman Plain. Douglas (1968b) applied his Canberra determinations generally to his catchments in the Southern Tablelands of New South Wales. His averages of 2.16 mg/l and 0.39 mg/l for the ionic concentrations of Ca and Mg respectively give a total carbonate equivalent of 6.74 mg/l. In coastal Australia, the atmospheric salts in the rain have been regarded as of marine origin for a number of reasons including gradients of declining amounts of 'cyclic salts' from the coast. However, in arid inland areas surface deflation of dust involves a local origin for some of the atmospheric salts. Deflation has not been observed anywhere on Cooleman Plain and is certainly not a significant process there today. Nevertheless it is very likely that the calcium falling at Cooleman Plain is of terrestrial origin carried by westerly winds from the calcareous Mallee soils of western New South Wales (Walker and Costin, 1971). It is possible that the rain over Cooleman Plain may carry more calcium than that over Canberra so the use of the latter could be a source of underestimation. The correction was determined in the following way.

The Tantangara rainfalls were summed over the periods of time to which each hardness determination at the Blue Waterholes related. Applying this rainfall to the Cooleman Plain limestone area and using also the Canberra Ca and Mg concentrations, the total Ca and Mg carbonate input for each period was obtained. This was then converted to an average concentration for the period by dividing by the related Blue Waterholes discharge. This concentration was then deducted from the Blue Waterholes hardnesses.

(2) Solute Load from Surrounding Terrain

Wherever there is runoff from other rock terrains into karst areas, there are inputs of calcium and magnesium derived from weathering and erosion there, but not necessarily from carbonates, together with atmospheric inputs such as have already been discussed. Usually they are quantitatively negligible in karst study.

Williams (1968) was, however, faced with a major problem of this nature since some of the tributaries of the Fergus had high total hardnesses derived from calcareous till. He allowed for this by adding the area of this calcareous drift to that of the limestone outcrop in determining the rate of erosion. However, he recognised this did not solve the problem completely as the amount of carbonate in solution from the glacial deposits beyond the limestone outcrop is less than that from within the outcrop.

The inputs of hard water into Cooleman Plain from the surrounding rocks do not, on the average, reach such high levels of concentration as complicated the R. Fergus study. Nevertheless they must seriously affect the determination of karst denudation rates. The mean total hardness of 96 determinations of waters of streams from the surrounding igneous rim and overlying impervious beds is 26.46 mg/l (σ 25.59). This mean conceals marked spatial and temporal variation in these inputs.

Fig. 7a illustrates the spatial distribution of total hardness in a number of the streams peripheral to the limestone on one of three occasions.* On 13/4/63 after a long dry spell, the measured hardnesses from sixteen streams ranged from 5 to 78 mg/l with a mean of 26. After

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* Collected and analysed by Prof. I. Douglas, then a member of the Department of Geography, Research School of Pacific Studies, A.N.U.

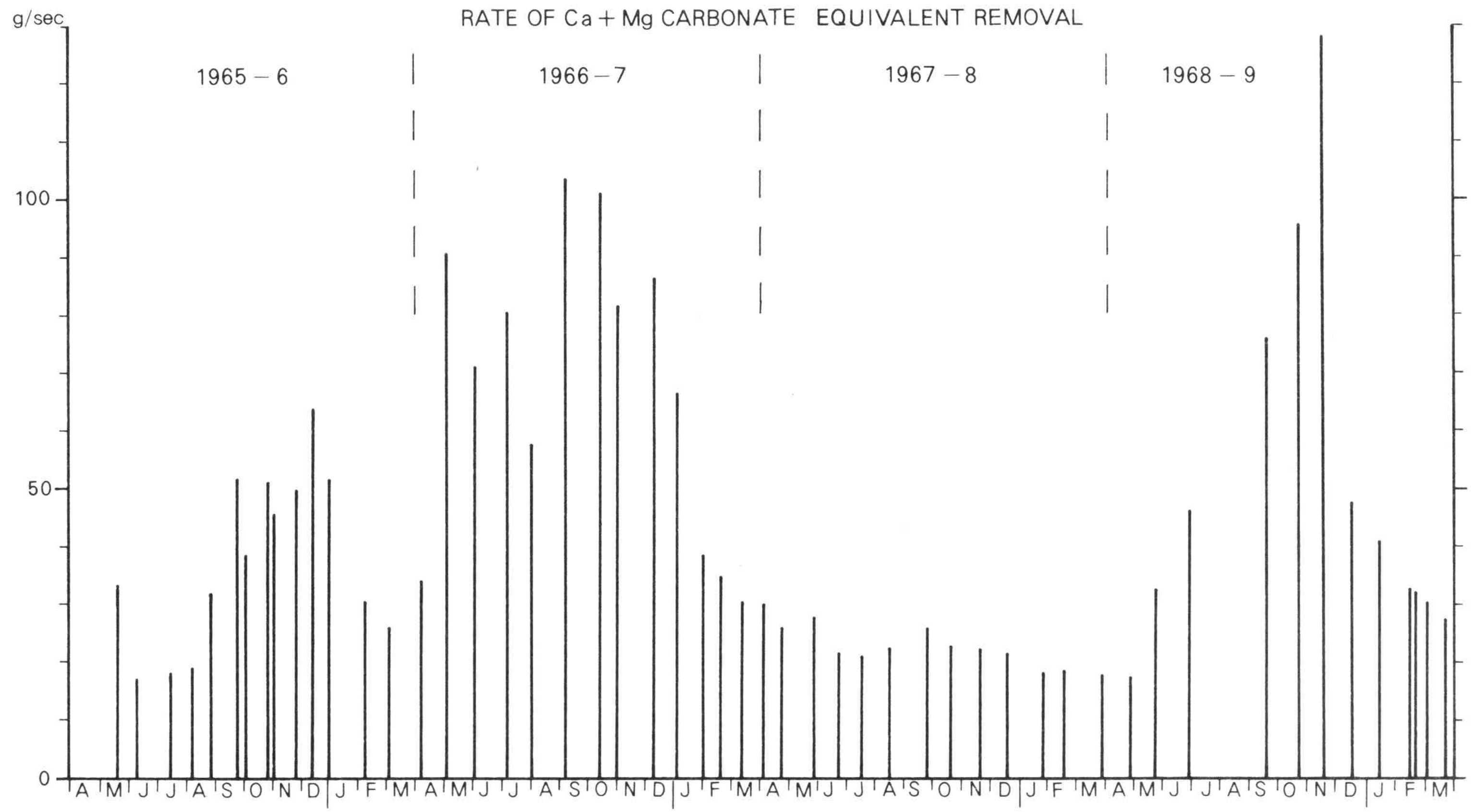


Fig. 6 Instantaneous rates of Ca + Mg carbonate equivalent removal by Cave Creek at the Blue Waterholes, April 1965 – March 1969.

heavy rain, the mean from eighteen streams on 25/8/63 was 14 mg/l with a range of 4 to 55. On 20/10/63 after 3 dry weeks, the mean from seventeen streams had risen to 17 mg/l with a range of 1 to 74. The high concentrations come from catchments with flatter floors where slower flow allows evaporation to concentrate the solute contents of the peripheral streams more.

To get a better idea of temporal distribution, two catchments of similar size, one with fairly low concentrations and one with fairly high concentrations as indicated by these three sets, were sampled from time to time. Ten determinations of the Devils Hole catchment on the western side of the Plain ranged from 6 to 26 mg/l, with a mean of 10, whereas eighteen values from the Six by Fence catchment on its eastern side lay between 20 and 91 mg/l, averaging 60 mg/l (Fig. 7b). The regression between the hardness of Devils Hole and of the Blue Waterholes output had small trend and was not statistically significant but between Six by Fence and the Blue Waterholes there was a strong and sensitive positive correlation (significant at 0.1%).

From the data available for peripheral inputs it is not possible to derive by proper statistical techniques a correction to apply to the Blue Waterholes hardnesses. A crude correction has been devised by the following method.

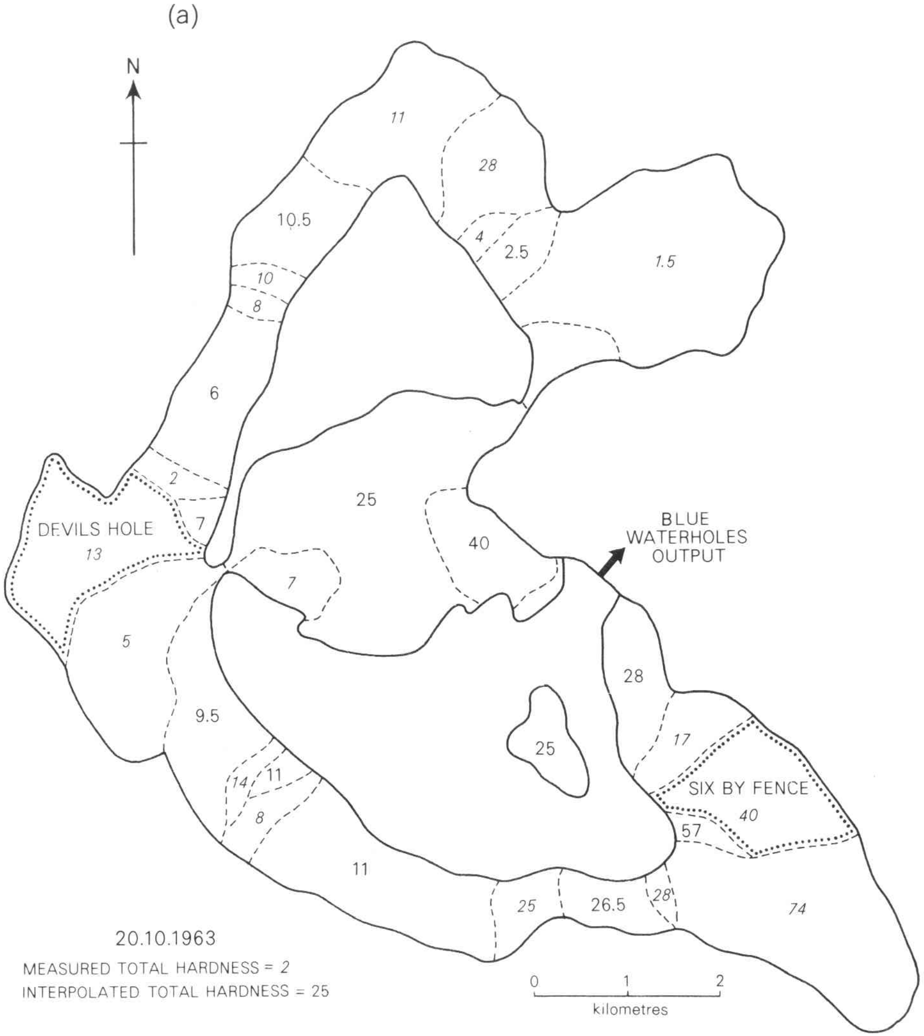
(a) For the three spatial sets of peripheral inputs, concentrations have been interpolated for the catchments not measured.

(b) Assuming that discharges varied with catchment area, mean input concentration (T) was obtained for each of these three occasions by weighting the individual input catchment concentrations (T_1, T_2 .....) in accordance with their particular areas (C_1, C_2 .....) as proportions of the total peripheral catchment.

$$\overline{T} = \frac{(T_1 x C_1) + (T_2 x C_2) + (T_3 x C_3) \; ..... + (T_n x C_n)}{C_1 + C_2 + C_3 \; ..... + C_n}$$

(c) A regression of total hardness of Six by Fence on total hardness of Cliff Foot Rising was calculated and drawn.

(d) The weighted mean peripheral hardnesses for the three occasions when a number of peripheral streams were sampled were plotted on this graph by reference to the hardness of Six by Fence on these occasions. A straight line was drawn in by eye through these three points which lay nearly in a straight line.



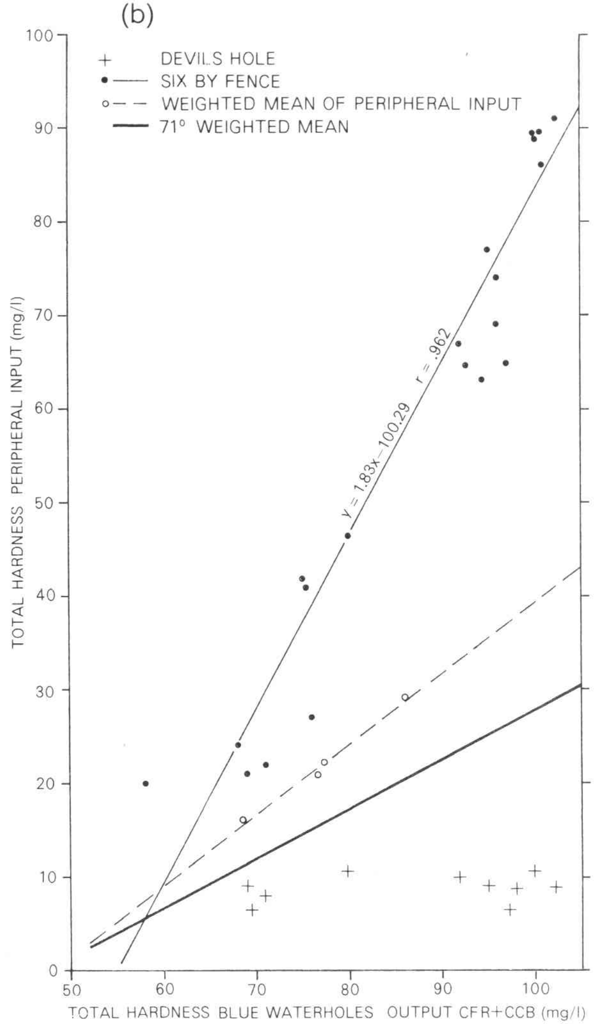


Fig. 7 (a) Spatial variation in total hardness of peripheral catchments on 20 October 1963.
(b) Relationship of peripheral input hardnesses to the Blue Waterholes output hardness.

(e) The peripheral input hardnesses are diluted by the groundwater and surface runoff of the limestone part of the catchment. Rainfall may be somewhat higher on the other rocks which form the surrounding rim and central hills. On the other hand evapotranspiration of the forest on these hills is probably greater than from the grassland of the limestone plain. Moreover limestone forms a more efficient catchment than other rock (Pardé, 1965) because of more rapid infiltration. Therefore it is probably not introducing great error to assume equal effectiveness on the limestone and non-limestone parts of the catchment area for area. Accordingly another line was drawn in at 71% of the one already obtained, i.e. at the proportion the non-carbonate rock area bears to the total catchment. This was used to correct the Blue Waterhole hardnesses for peripheral input, including its atmospheric salt component.

(3) Subjacent Karst

The net total hardness after correction for atmospheric salt accession and peripheral inputs is attributable to limestone solution. However, before these net figures are converted into rates of limestone removal per unit area, a further complication needs to be assessed.

It is evident that some underground flow takes place through limestone where it is overlain by other rocks. Thus the waters of Cliff Cave Spring flow over the surface of Blue Waterhole Beds for a short distance before meeting a ridge of limestone projecting into these beds where they normally sink. Thereafter, for more than 3 km, these waters almost certainly pass through limestone underneath the Blue Waterhole Beds. At high stage there is also surface flow over them. The water sinking at Devils Hole has never been detected at the surface before the Blue Waterholes and it is most likely that it travels to these springs beneath the intervening lavas, cherts, siltstones and other rocks. The same thing must happen to those waters of the North Branch of Cave Creek which sink whilst passing across the northern limestone plain. When its waters pass further down the surface course, large bodies are lost underground at G.R. 689997 and it is very likely that part of their onward course to the Blue Waterholes lies under lava-covered limestone between the two points.

It is unlikely however that all the limestone overlain by other rocks (which amounts to 12.7% of the whole catchment) constitutes active subjacent karst. In a section across the Cooleman Plain basin structure, Stevens (1968) shows a thickness of Blue Waterhole Beds of 300 m and it is likely that this thickness is exceeded in the most central area of these beds. Underground drainage probably detours round the deeper parts of this inlier of overlying beds.

If no allowance were made for subjacent karst activity, the karst denudation rate would be exaggerated. If, on the other hand, the whole area of buried limestone were included in the karst equation, that rate would be underestimated. On the basis of our present small knowledge of the active subjacent karst, half of the total area of subjacent limestone is assumed to be active karst (6.4% of catchment).

However this cannot be simply added to the exposed limestone area in the karst equation because it does not participate in all kinds of limestone solution. Thus there is no surface channel corrosion on it, nor subaerial solution of outcrops nor at the soil-rock contact. Moreover there may be little seepage solution in joints in the subjacent limestone for there is little or no development of dolines in the covering rocks. Probably the only significant kind of subjacent karst solution is that along cave passages.

Cave drips have been used by various karst investigators as a measure of the aggregate of outcrop, subsoil and joint seepage solution. Thirty-five samples of drips from the roof of Murray Cave where it lies 5-45 m beneath the ground surface were collected on five occasions (three in summer, two in winter). The mean total hardness is 152 mg/l with a standard deviation of 21 mg/l. Allowing for dilution of the limestone waters by the runoff from the other rocks on the same basis as has already been set out, there remains a substantial contribution to the total hardness of the Blue Waterholes of 44 mg/l (29% of 152) in which the subjacent karst participates little or not at all.

The surface channel component cannot be readily estimated. Even after correction for atmospheric accessions and peripheral inputs, the surface runoff intermittently reaching the Blue Waterholes contains not only the products of streambed solution but also some from seepage and cave stream solution such as comes into the river from Murray Cave and Cliff Cave at high stages. It is possible that subjacent karst flanking Cave Creek upstream of the Blue Waterholes also contributes. Conversely channel solution occurs along some streams above their sinking points as for example in the case of the South Branch of Cave Creek. This contributes to the total hardness of the groundwater emerging at the Blue Waterholes.

Surface channel and cave passage solution therefore cannot be separately determined. It will be assumed that the complicating effects cancel out more or less and that the active subjacent karst contributes in proportion to its area to the sum of these kinds of solution. Therefore it is calculated as follows.

$$\text{Mean Total Hardness from Subjacent Karst} = \left(\text{Mean Total Hardness from all Limestone} - \text{Mean Total Headness from Surface and Near Surface Solution} \right) \times \left(\frac{\text{Active Subjacent Karst Area}}{\text{Exposed Karst Area + Active Subjacent Karst Area}} \right)$$

This amounts to 3.3% of the total hardness from the limestone and this percentage was deducted from each hardness determination of the Blue waterholes output. However it is clear that this % lies within the error of discharge determination and it could have been neglected without significant effect on the argument.

RATE OF LIMESTONE REMOVAL FROM EXPOSED KARST

These corrected hardnesses were then employed in Corbel's karst denudation equation as modified by Douglas and Williams (Williams, 1968).

$$S = \frac{Q.\overline{T}}{A.D.10^9}$$ where

S = limestone removed in solution in m^3/km^2/year of mm/1000 years for specified period

Q = total discharge in m^3 for period

$\overline{T}$ = mean total hardness in mg/l for period

A = area of exposed karst in km^2

D = density of limestone

The bulk density of ten samples of limestone in a transect west to east across the structural basin was determined for use in the equation. The mean was 2.71 in a range of 2.455 - 3.189.

The rates of limestone removal from the exposed karst on a monthly basis through the period of observation expectedly follow the same pattern as the instantaneous rates of total carbonate removal, reflecting the discharge record (Fig. 8). There is the basic tendency to a winter/spring high rate of removal and a summer/autumn low rate. The high removal rate season was suppressed entirely in the drought year and nearly so in another, whereas in a third the high rate persisted through ten months of the year. The regression of monthly removal of limestone on monthly mean discharge is highly significant.

Limestone removal (mm/month) = .0000032 Q (1/sec) + .00015

r = .991 significant at 0.1%

The annual rates of removal were 16,41,11 and 28 mm/1000 y respectively with a mean of 24. The various corrections involved a scaling down of about one-third from the results which the gross Ca+Mg carbonate equivalent rates would have yielded (Jennings, 1972).

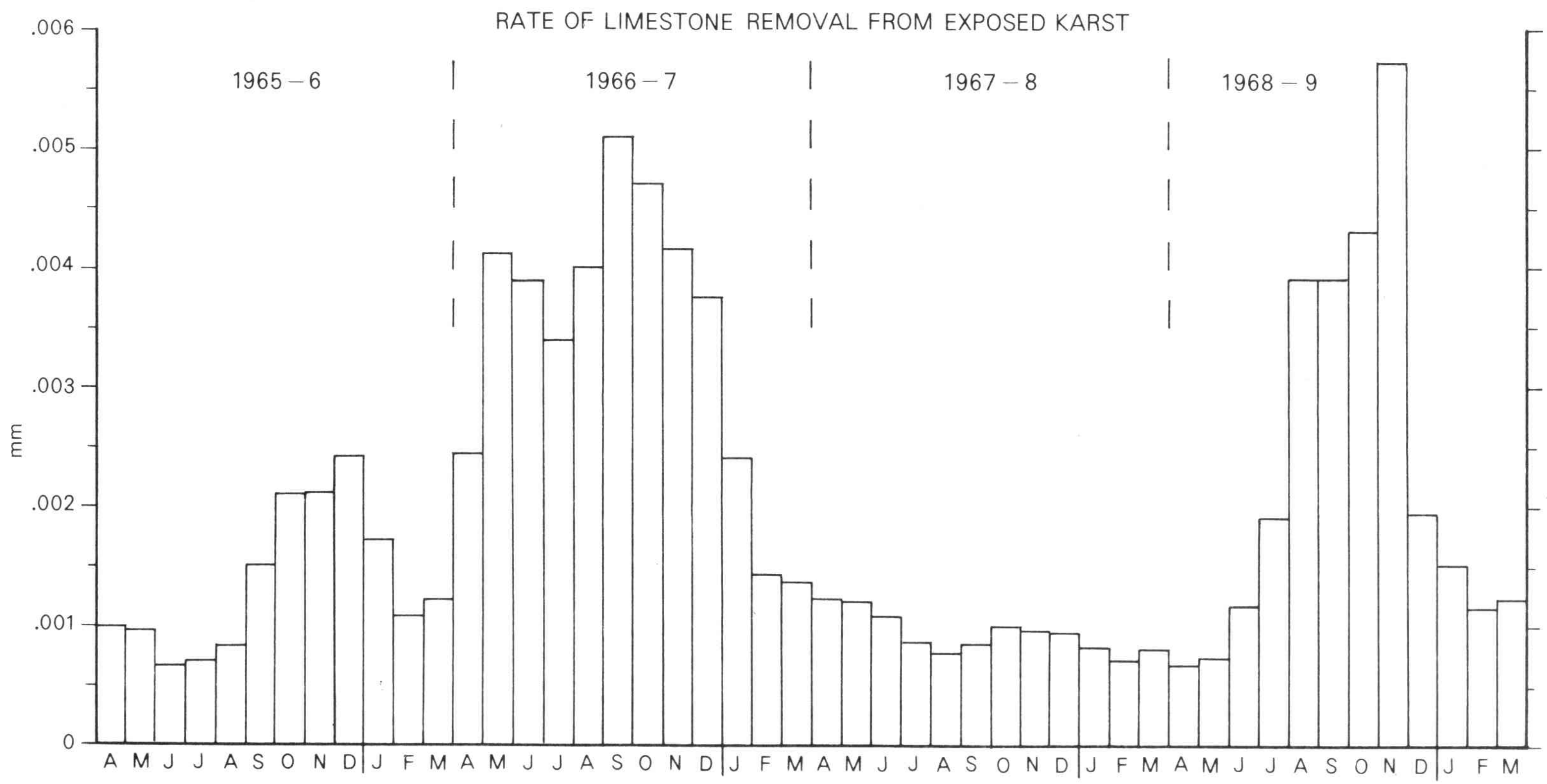


Fig. 8 Monthly rate of limestone removal from Cooleman Plain exposed karst, April 1965 – March 1969.

DISCUSSION

In some respects the Cooleman Plain results conform to those obtained previously from karst in the same climatic type (Köppen Cfb) - humid mesothermal without pronounced seasonal incidence of rainfall.

As with most, but not all, such karsts there is an inverse relationship between water hardness and discharge, though despite this a strong positive correlation exists between limestone removal and discharge. Larger volumes of water less rich in solution products in winter and spring are more important for karst denudation than smaller flows with greater concentrations in summer and autumn when evapotranspiration causes less favourable water balances.

However pronounced variation from year to year in the annual course of limestone removal but especially in its total amount makes a longer series of observations necessary for a really satisfactory basis for comparison between regions. Douglas (1966) and Goudie (1970) have stressed the need for this on general grounds; Cooleman Plain has yielded in these first four years a very clear instance.

Evidence provided by cave drips not far below the surface shows that the bulk of the limestone solution from the karst exposed in the basin takes place superficially or beneath the soil and in planes of weakness close to the surface. This high proportion is consistent with results of previous estimates of this kind. Williams (1968) has shown that more than 80% of the total solution may sometimes be accomplished in the top eight metres of limestone in the Burren in Ireland. He also reviewed results in the same sense from Slovenia, the Mendip, the Peak District and from the Chalk of East Anglia near Cambridge. Pitty's observations from Poole's Cavern in the Peak District also indicate this same distribution (Pitty, 1966).

Correspondingly the contributions of solution along surface river channels and cave passages are small. In the study area the data available do not permit the separation of these two components but it can be estimated from the volumes involved and distances travelled that the opportunities are greater in the caves than along the watercourses open to the sky.

The small part played by these domains together in the total yield of carbonate diminishes the importance of the distinction between the impounded and the free karst condition (Jennings, 1971b). The large bodies of water pumped into the limestone have contributed little to the total of rock removal. Nevertheless it is possible that the role of cave passage solution may be more important that the magnitude alone of its contribution might suggest. By feeding concentrations of aggressive water into the karst at particular points, peripheral input has occasioned the development of major conduits which in turn promote vertical movement through the limestone in their vicinity. Vadose seepage alone would have taken much longer to establish effective underground circulation.

It was realised that some of the limestone removed from the catchment came from karst buried beneath overlying sediments and lavas in the middle of the plain. Virtually all this must take the form of cave passage solution. However the amount of rock consumed in this way cannot be isolated with any accuracy from the surface channel and cave passage corrosion in the exposed karst. The crude estimate for this subjacent karst component of 3% of the total solution from limestone was based on certain arbitrary assumptions and it was fortunate that it proved so small; quite large error in the assumptions would not seriously have affected the overall picture of the spatial distribution of solution in this karst.

The problem of the contribution of mechanical erosion of the total denudation of the area was not investigated as much as recent work elsewhere in this direction (Newson, 1971) indicated may be necessary. Not only are there quartz sands and igneous pebbles and boulders common along the surface channels through the limestone, they are equally important along the active cave passages, e.g. in River Cave (Jennings, 1969). Measures taken of suspended load were less satisfactory than those of solute load and probably underestimated it, particularly though lack of storm flow observations. Nevertheless the results were so much smaller than those of solutes that it is not likely that an accurate measure would alter the balance greatly. Most of the solid load comes from the periphery, not the karst itself, in any case. Nevertheless the availability of these foreign tools to the surface and underground streams would enhance solution by breaking off fragments from the bedrock limestone and comminuting these fragments, thereby increasing the surface area of limestone available for solution. How important this factor is, has not yet been estimated here or elsewhere but clearly it is an aspect of differentiation between impounded and free karsts.

Accepting the mean value for limestone removal by solution from the four years as a basis for comparison, Cooleman Plain has a low rate for its climatic type. Quite a number of reasonably well based values are now available, from the British Isles and Slovenia in particular, and these range between 30- 80 mm/1000 y compared with 24 from Cooleman Plain. Gams (1966) cites two smaller values of 18 and 10 but these are from catchments of dolomitic and Flysch bedrocks respectively so are not validly compared with Cooleman. Groom and Williams (1965) also give a low value for the Mellte River where it crosses the North Crop of the Carboniferous Limestone in South Wales. But this was based on a fairly large stream passing through a narrow belt of limestone and the authors explain the low value by rapid transmission of the water through the limestone. Perhaps more critical was the small contribution of seepage water to the Mellte in its underground course compared with the volume of allogenic water in transit.

The comparatively low value of corrosional denudation on Cooleman Plain is probably to be explained in two ways. To some degree it may not be truly anomalous in that allowance for atmospheric and peripheral inputs was made here and this may have been necessary in some other cases where this was not done. Table 2 shows the importance of this procedure and it is relevant to note that Groom and Williams (1965) did allow for peripheral input in obtaining the low value quoted above. Binggeli (1961) has shown that in the Ticino valley, Switzerland, crystalline rock yielded 15-25% as much Ca and Mg as the carbonate rocks in the catchment whilst Jaekli (1957) gave 30-35% for the Rhine valley in its Swiss section.

But there can be little doubt that it is in part a real difference and due to high water losses through evapotranspiration in this low latitude, low humidity climate. At the moment this factor cannot be quantified in a satisfactory way and the statement rests on broad climatic comparisons. Even the Slovenian karsts probably have more favourable water balances since winter is the main season of precipitation there and there is less water about on the surface to be lost when temperatures promote evapotranspiration most.

Finally there is the possibility to consider of employing the determination of limestone removal to help in understanding the historical evolution of the karst. Since the bulk of the solution takes place at or near the surface, it is a reasonable approximation to employ limestone removal rate as a measure of surface lowering. In this case the round figure of 20 mm/1000 y amounts to about 80% of the gross figure, the proportion estimated for that part of the solution which closely relates to surface lowering. Applying it to the length of the Pleistocene and to the time since the beginning of the Pliocene, lowerings of 40 and 140 m result respectively. However we know that climate has not been the same throughout this period. It is sure that one and probably more periods of tundra climate have been experienced on Cooleman Plain in the Pleistocene when the mean annual temperature may have dropped by 6 C, the actual precipitation halved but the effective precipitation made greater than at present. Perhaps the most comparable area to these former conditions for which a karst denudation rate has been determined is the R. Tanana basin in central Alaska and the value Corbel (1959) derived was 40 mm/1000 y. If this is transferable to Cooleman Plain, then there periods in the Pleistocene when the rate doubled its present one. So the Pleistocene lowering of 40 m may be an underestimate but perhaps by no more than 4 m.

TABLE 2.

APPROXIMATE COMPOSITION OF CAVE CREEK OUTPUT HARDNESS

Non-karst hardness	34%	Atmospheric salts hardness	27%	In rain on exposed karst	8%	
				In rain on non-karst rocks	19%	Peripheral karst hardness 26%
		Hardness from weathering and corrosion of non-karst rocks	7%			
Karst hardness	66%	Exposed karst hardness	63%	Outcrop, subsoil and vadose seepage hardness	49%	
				Exposed karst river channel hardness	14%	
				Exposed karst cave passage hardness		
		Subjacent karst hardness (in cave passages	3%			

N.B. These figures differ slightly from those published in Jennings (1972) The differences are due to the use here of approximate monthly values for the non-karst hardness instead of the mean annual figure employed in the previous calculation.

It is generally thought that warmer and wetter conditions were more widespread in Australia in the Pliocene and it may be that uplift had not yet carried the Plain to its present height so that yet other rates of denudation applied to the area then. If a guess is hazarded, comparison may be made with Florida when Corbel determined a rate of 6 mm/1000 y for the Kissimee R. catchment. Such a rate would reduce the previous figure of 140 m to 74 m. However many authorities would dispute these single comparisons as an adequate basis for selecting rates to apply to the past geological periods in the history of other areas, maintaining for example that the greater availability of biogenic CO_2 in wet subtropical climates should generally result in greater solution than Corbel's figure allows. So the chief value of this exercise is to demonstrate the need for both more data from many parts of the world on rates of karst erosion in different climates and from Cooleman Plain itself about its climatic history on an absolute chronological basis before modern rates of limestone removal can be used for historical extrapolation with any accuracy over the lengths of time such as have been thought to be involved in the development of the present landscape.

However the exercise of confronting these possible extrapolations with what has been inferred about the evolution of the area is worthwhile. The older view (Stevens, 1958) that the Plain represents an exhumed sub-Devonian surface is regarded as untenable. Instead it is accepted that the interfluves are remnants of a planation surface of much younger but undetermined age, probably Tertiary (Jennings, 1967). This is difficult to reconcile with either 70 or 150 m of surface lowering on the assumption of an early Pliocene age for the surface following David (1950).

Such conflict between modern process study and classical denudation chronology led Aubert (1969) to deny the reality of Tertiary planation surfaces previously claimed in the Jura Mountains. Instead he asserts that these surfaces were due simply to flattening and uniform lowering of the limestone in anticlinal areas rendered weak by joint frequency and openness compared with limestone in other structural situations such as synclinal cores. However the reality of a dissected erosion surface on Cooleman Plain cannot be denied on similar grounds. It is only one of many upland valley plains in the high ranges of southern New South Wales Thus west of Cooleman Plain at much the same altitude there is the Long or Sixteen Mile Plain and to the south is Currango Plain. They truncate a variety of rocks but not limestones, and on Peppercorn Hill overlooking Long Plain there is a residual of Tertiary basalt lava of undetermined age. Moreover the planation surface on Cooleman Plain extends from the limestone onto other rocks without any sharp break of slope or change of altitude, this most clearly along the South Branch towards the col leading south to Pocket Saddle on Currango Plain.

Instead other means to resolve the difficulty must be sought. A younger age for the surface would reduce it since a more modest lowering, say of about 40 metres corresponding with the possible Pleistocene denudation, is perhaps compatible with the present configuration, particularly in the relationship of the limestone surface to its extensions onto the peripheral igneous rocks. Alternatively it may be postulated that the Tertiary waste cover, particularly its ironstone cuirass, restrained surface lowering of the limestone for some time until it was broken up and scattered as it is in some parts and finally removed as elsewhere. It is relevant to note that the most continuous areas of ferruginous sandstone cover as mapped by Stevens (1958) lie at a slightly higher level than the practically bare limestone interfluves more centrally disposed in the Plain.

These ideas cannot be regarded as more than suggestions whereby two approaches to the geomorphology of the Plain may be reconciled. At the moment our understanding of karst denudation rates is not great enough for results from such studies to do more than pose problems which it is hoped will in the future yield to conjoint attack from morphometric, process and historical geomorphic approaches.

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