Proc. Univ. Bristol Spelaeol. Soc. 1973, **13**(2) **171-226**

A STUDY OF THE HYDROLOGY OF G.B. CAVE, CHARTERHOUSE-ON-MENDIP, SOMERSET

By

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ABSTRACT

In 1968 the surface stream, cave stream and certain drip inlets of G.B. Cave, Somerset were studied. Chemical and physical characteristics were measured weekly from February until the great flood of the 10th July 1968, and irregularly for the rest of the year. This paper presents statistical summaries of site characterstics and their inter-relationships, and a statistical examination of measurements of limestone solution between the surface swallet and the cave. Several smaller sections discuss the relevance of the results to a number of different branches of limestone studies, such as temperature variations in drip inlets, and the significance of infilled depressions in the drainage of limestone on the Mendip Hills. Some hydrological side-effects of the July flood are also examined.

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1. INTRODUCTION

G.B. Cave (N.G.R. ST 477 562) drains a part of Blackdown (Fig. 44). The relevant structural geology and soil-type distribution have been discussed in earlier publications (Findlay, 1965; Ford, 1964; Stenner 1970a and b).

In February 1968 a programme of work was started in G.B. Cave, with two purposes in mind. The first was to gather sufficient data to evaluate a procedure for the measurement of the aggressiveness of water towards calcium carbonate, and the second was to incorporate the

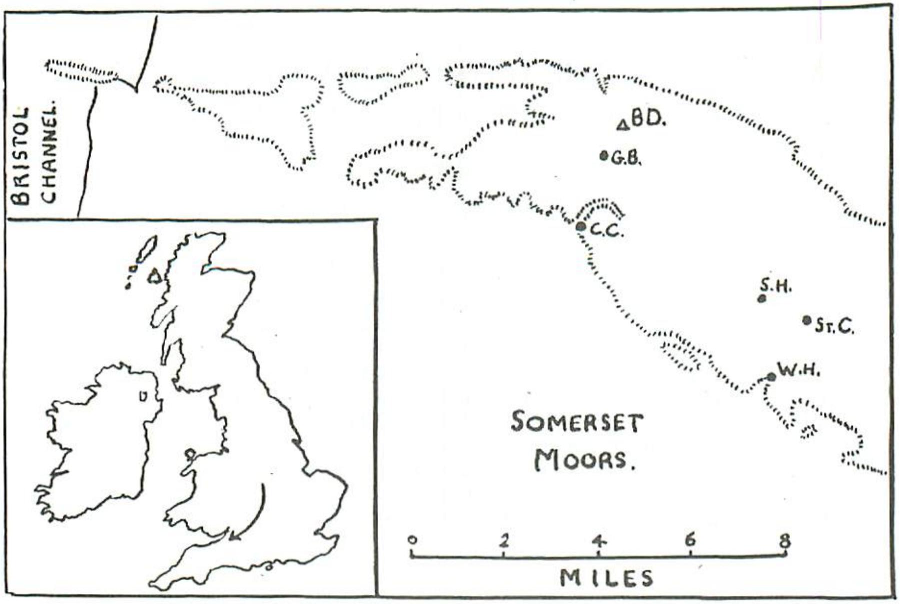
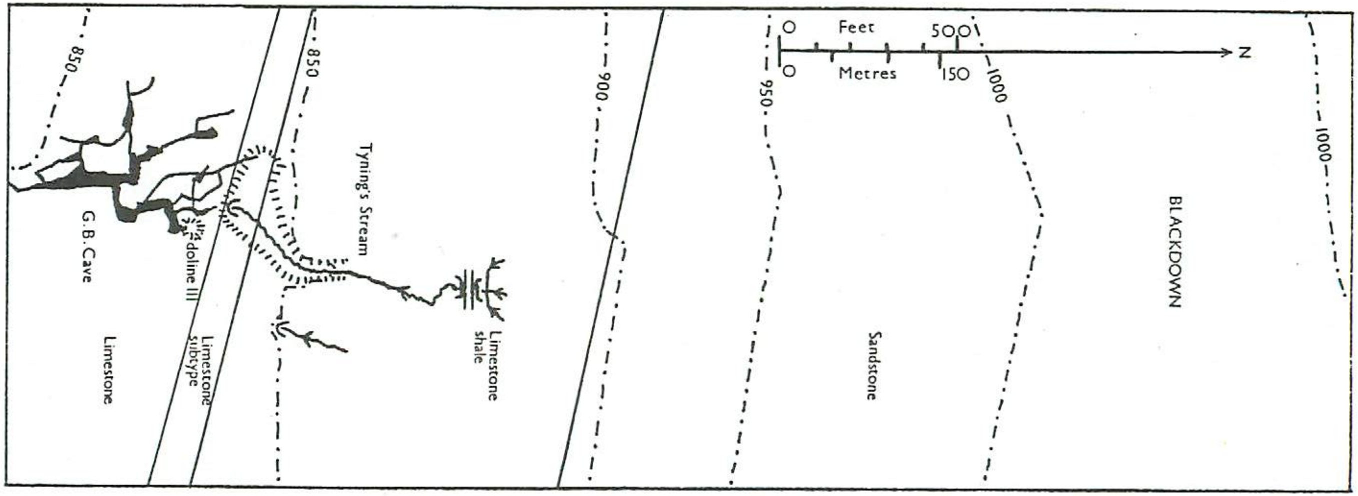


Fig. 43 The western Mendip Hills, showing location of caves referred to in this paper. B.D.—Blackdown. G.B.—G.B. Cave. C.C.—Cheddar Caves and springs.

measurements needed for the first purposes in a study of the hydrology of the cave and the related surface drainage. The original aim was to sample weekly for a year. After the Great Flood of July 1968, in week 22 of this study, sampling became slightly irregular, and in December 1968 illness put an end to the sampling programme.

The first aim of the work was satisfied first (Stenner, 1969, 1970(a), 1970(b), 1971). Here a summary of a large quantity of data gathered during this study is presented. 450 water samples were analysed, the majority of them in duplicate. More than 6,000 measurements or analyses were made, many being duplicated for increased precision. During the analysis of these results, the mean, standard deviation and 95% confidence limits of the mean were calculated for 179 groups of figures, correlation coefficients between 143 pairs of sets of data were calculated, as well as the significance of the difference between 29 pairs of mean values. In addition, time series analyses were made, investigating correlations of data with climatic conditions after varying time lags. This paper is only able to present the more significant results, and summaries of statistical findings. Copies of the complete results are in the libraries of the University of Bristol Spelaeological Society and the Bristol Exploration Club. The author will also be pleased to answer enquiries. If readers wish to pursue any of the suggestions for further work in the cave, they will find that the complete results contain detailed descriptions of the sample sites, with photographs showing precise locations.



·—·—·	Height above O.D., Feet.	o——	Spring
——	Geological boundary	——>	Swallet
—>—	Surface Stream		Doline III, survey, Crickmay and Bendall.
- ->-	Thalweg (dry valley)		

Fig. 44 · The geology of G.B. Cave and its Water Catchment Area.

The results obtained at sites S3, S6, S7, S10 (Fig. 45) and S11, are not included in this report. This is because their physical and chemical characteristics resulted from the admixture of varying proportions of other streams, a fact which was not known for certain before the study was made. This does not mean that the time used in their study was wasted since the sites were chosen to make it possible to use their results to calculate discharge values of tributary streams. The results also showed that changes in solute concentrations in the cave resulted only from the admixture of streams with different solute concentrations (Stenner, 1970(b)).

Results from the Read's Grotto Stream were obtained. They are not included since it is not known whether this stream enters the cave system. If a hydrological connection is found at some time in the future, these results are available for publication.

The estimated annual average of rainfall from 1916 to 1950 at the nearest suitable station, at Charterhouse, is 112 cm (Meteorological Office Hydrological Memoranda No. 16, undated). 4 days before the date of sampling of Week 22 of this study, a rainstorm of very unusual intensity fell on the region, and some of the consequences of the resulting flood are examined here. Following heavy showers in the afternoon of 10th July 1968, continuous heavy rain, interspersed with many violent downpours, fell for about two hours in the evening. The author's estimate of the total rainfall that day is 15.5 cm. This was based on the weekly rainfall recorded at Charterhouse, which had been noted as being subject to interference because of the considerable flood damage in the Velvet Bottom, where the station is located. The day after the flood, however, it was noticed that the recording equipment had not in fact been affected by the flood, and the figure was used. It is within the expected range for the rainfall in the locality (Hanwell and Newson, 1970, Fig. 5).

Opinions vary considerably as to the expected frequency of rainstorms of the magnitude of that of 10th July. Return estimates vary from between 60 and 100 years (Hanwell, 1969) to 100,000 years (Rodda, 1970). The lower value refers to the likelihood of such a storm occuring somewhere within a fairly large area, whereas the higher value refers to the likelihood of such a storm occurring at one specific site. Nevertheless, both figures show the storm to be a rare event.

The flood caused great physical changes in and around the cave. Some of these have been described elsewhere (Hanwell and Newson, 1970, Irwin, 1968, Savage, 1969). The flood changes described here are those not given by the authors cited.

2. THE LOCATION OF SAMPLING SITES (Fig. 45)

The figure also shows the distribution of streams between the surface and various passages in the cave and is based on the surveys of Crickmay and Bendall (1951) and Savage (1969). The sites are streams and drips.

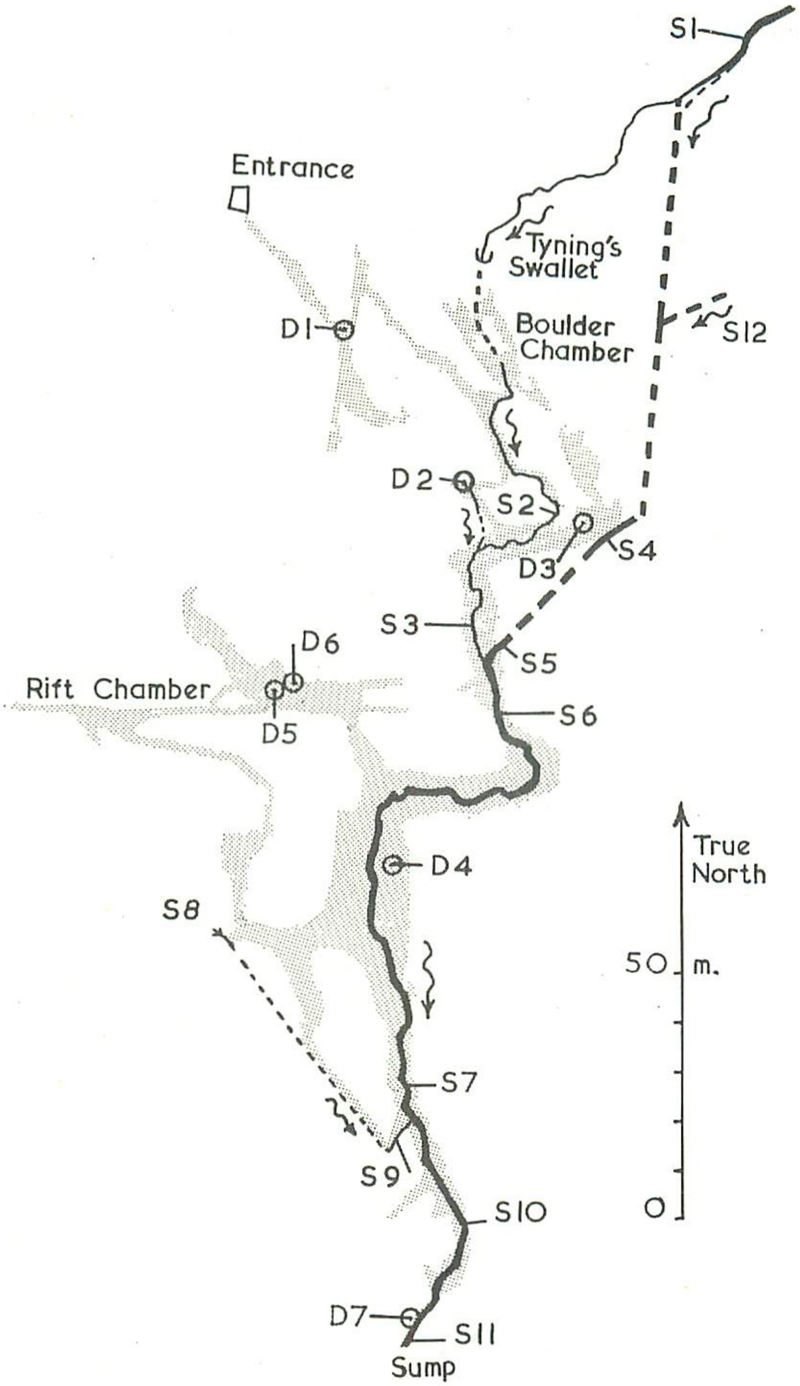

S1
Entrance
Tyning's Swallet
Boulder Chamber
S12
D1
D2
S2
D3
S4
S3
D6
S5
Rift Chamber
S6
D5
True North
D4
S8
50
m.
S7
S9
S10
0
D7
S11
Sump

Fig. 45

S1	Tyning's Stream, surface.
S2	Main Stream, Stream Passage at junction with the Gorge.
S3	Main Stream, Gorge, upstream of junction with N.E. Inlet Stream.
S4	N.E. Inlet Stream, Gorge.
S5	N.E. Inlet Stream, junction with Main Stream, Gorge.
S6	Main Stream, downstream of junction with N.E. Inlet Stream.
S7	Main Stream, upstream of the White Passage Stream junction.
S8	White Passage Stream, near the Oxbow.
S9	White Passage Stream, junction with Main Stream.
S10	Main Stream, downstream of White Passage Stream junction.
S11	Main Stream, Sump.
S12	N.E. Inlet Stream, the part not derived from Tyning's Stream.
D1	Drip from Stalactite at passage leading to Mud Passage.
D2	Drip inlet in Mud Passage.
D3	Drip inlet near top of Gorge.
D4	Drip inlet 25 m below the Bridge.
D5	Drip inlet, White Passage, main inlet in the Roof.
D6	Drip inlet, from a single stalactite.
D7	Very small drip inlet near the Sump.

3. THE MEASUREMENTS MADE AT EACH SITE

At all the sites, regular measurements were made of temperature, discharge, pH, total hardness, total hardness on saturation with $CaCO_3$ and aggressiveness to $CaCO_3$. At sites S1, 2, 3, 4, 5, 8/9, 11, D1, 2, 5, 6 regular determinations were made of alkaline and non-alkaline hardness, calcium and magnesium. These determinations were occasionally made at the remaining sites. Before the July 1968 flood regular measurements of free CO_2 were made at sites S1, 2, 4, 9, 11, D2, 5. This enabled aggressive CO_2, aggressiveness to $CaCO_3$ and pH change on saturation with $CaCO_3$ to be compared (Stenner, 1969). Before the July flood, analyses for minor and trace constituents were made occasionally at sites S1, 4, 5, 11, D2. These analyses were for sodium, potassium, lithium, strontium, chloride, sulphate, total anion, bromide, fluoride, phosphate, silica, aluminium and heavy metals. After the flood, the frequency of the minor and trace element analyses was increased. The results are given in the summaries of site characteristics.

Estimations of daily mean temperature and daily rainfall were made using records from three nearby weather stations to enable relationships between site characteristics and meteorological data to be investigated.

The methods used for the various measurements, analyses and statistical investigations are listed in Appendices 1 and 2.

4. SITE CHARACTERISTICS AND THEIR DISCUSSION

S1. *Tyning's Stream*

Tyning's Stream drains the extensive area of marshy land to the north of the road from Tyning's Farm to Charterhouse. The northern limit of this marsh is close to the junction between the Old Red Sandstone and the Lower Limestone Shales. Water drains from the marsh at a number of points, the trickles combining to make three main tributaries. They join close to the culvert which takes the stream under the road near the gate from which a private footpath leads to G.B. Cave. Between the road and Tyning's Swallet the stream bed is partly clay, and partly gravel and pebbles. Near Tyning's Swallet, occasional boulders of crinoidal limestone are prominent. 90 m upstream of Tyning's Swallet is a small 'rustic' bridge, and immediately above this bridge Tyning's Stream is joined by water draining the large field to the immediate North of the cave entrance. The volume of this water is very small compared with that of Tyning's Stream, and its study would be very difficult because the drainage is often entirely through the soil.

Downstream of the rustic bridge, water from Tyning's Stream starts to seep away through the stream bed. In low discharge conditions the shrunken stream sinks 50 m upstream of Tyning's Swallet. This sink in the stream bed is an 8 cm diameter hole between boulders, excavated shortly after the 1968 flood—the first time that a definite sink in the stream bed could be precisely located. The excavation of this sink coincided with a change in the distribution characteristics of the stream between Stream Passage and the N.E. Inlet Stream. After flowing through the cave, water from Tyning's Stream has been proved to reappear in the complex rising at Cheddar (Atkinson, Drew and High, 1967).

Table 1

The physical and chemical characteristics of Tyning's Stream, S1

Measurement	No[1]	Mean	95%Conf of Mean[2]	S.D.[3]	S.D.as % of Mean
Temperature, °C	39	8.82	1.51	4.62	52.4%
Discharge (Q), Galls/hour	49	1386	720	2480	179%
Alk.hard.p.p.m. $CaCO_3$	36	10.93	1.6	4.70	43%
Tot.hard.(uns.)p.p.m. $CaCO_3$	36	25.58	1.8	5.28	20.6%
Sat.tot.hard.p.p.m. $CaCO_3$	35	33.55	1.26	3.70	11%
Ca. 10^5 x M Ca^{2+}	34	18.59	1.53	4.42	23.8%
Mg. 10^5 x M Mg^{2+}	34	6.86	0.52	1.50	21.9%
Non alk.hard.p.p.m. $CaCO_3$	36	15.0	1.2	3.54	23.6%
Aggressiveness p.p.m. $CaCO_3$	35	8.44	1.55	4.54	53.8%
Na 10^5 x M Na^+	15	28.1	2.8	5.05	18%
K 10^5 x M K^+	15	4.00	0.66	1.19	29.8%
Cl 10^5 x M Cl^-	16	26.9	2.7	5.09	18.9%
SO_4 10^5 x M SO_4^{2-}	14	17.5	3.8	6.64	38%
Sr 10^5 x M Sr^{2+}	7	0.37	0.11	0.15	40%
F 10^5 x M F^-	5	0.2	0.14	0.15	70%

1. No. = Number of measurements.
2. 95% Conf of Mean = 95% confidence limit of mean.
3. S.D. = Standard deviation.

Table 2

Trace element concentrations in Tyning's Stream, S1.

Trace element	No.	Mean	S.D.
Zn, p.p.m	6	0.045	0.04
Cu, p.p.m.	6	0.02	0.015
Pb, p.p.m.	6	*	--
Fe, Mn, Ni, p.p.m.	6	N.D.	--
Al, p.p.m.	3	0.4	--
PO_4, p.p.m.	4	0.05	--
Br, p.p.m.	5	0.017	0.013

* N.D. in 5 samples, and 0.04 p.p.m. in 1 sample.

N.D. = Not detected.

Detection limits of Pb, Fe, Mn and Ni were 0.05, 0.02, 0.03 and 0.006 p.p.m. respectively.

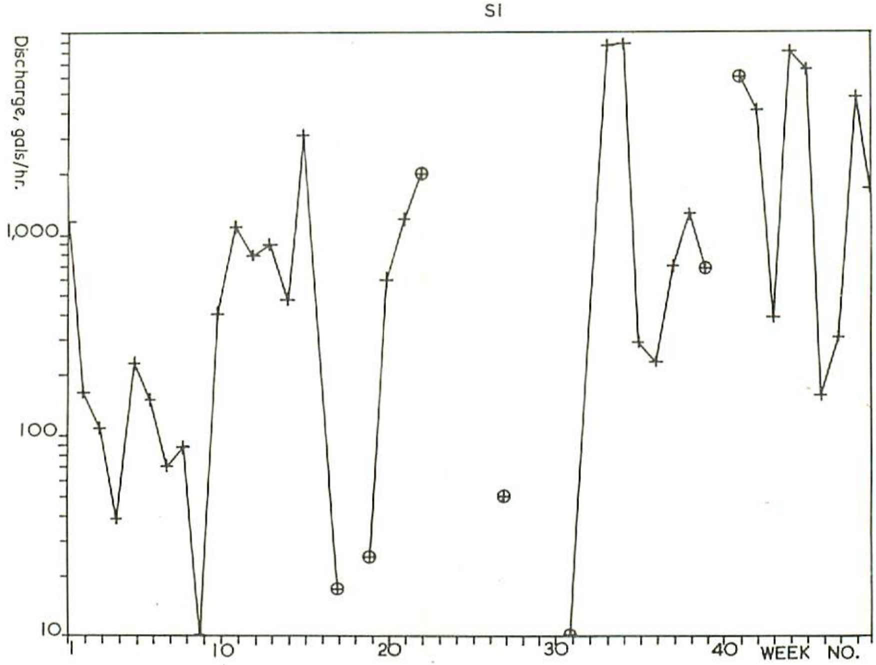


Fig. 46. Site Characteristics. Week 1 is February 11th, 1968.

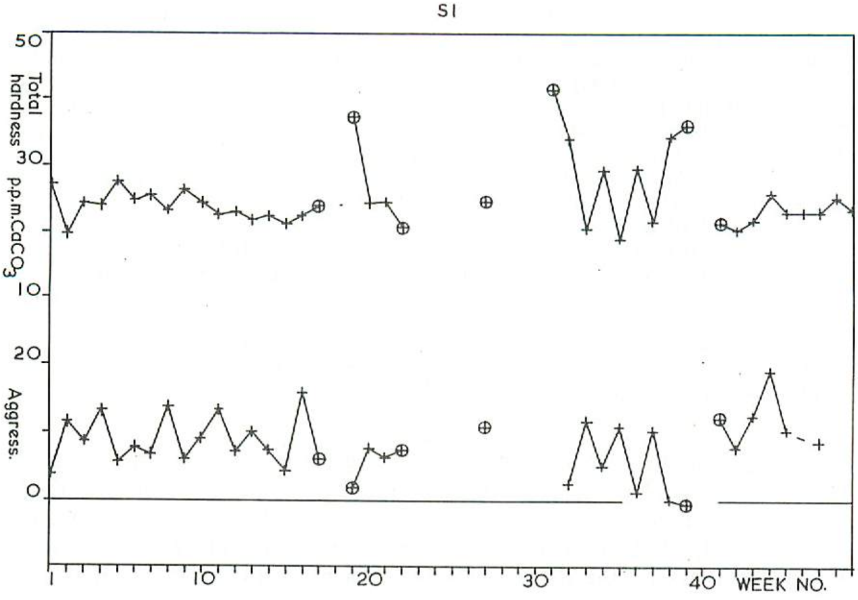


Fig. 47. Site Characteristics. Week 1 is February 11th, 1968.

Samples and measurements were taken 10 m downstream of the rustic bridge, where seepage through the stream bed was considered to be negligible. A portable rectangular-notch weir was used for discharge measurements, except in low discharge conditions, when the water was collected for a measured time in a polythene sack. The data is summarised in Tables 1 and 2, and Figs. 46 and 47.

Discussion of the results

Results of correlations. The significance of differences in the mean values of total hardness ,saturated total hardness, calcium, magnesium, non-alkaline hardness and aggressiveness before and after the July flood were calculated. In every case the significance of the differences was below 75%, and this means that for these parameters there was no significant change as a result of the flood.

Correlations with discharge. Alkaline hardness, total hardness, saturated total hardness, non-alkaline hardness, calcium, magnesium and aggressiveness showed no correlation with discharge. Alkaline hardness showed the highest correlation. The correlation coefficient for 35 pairs of results was; $r(35)=0.18$ which was insignificant.

Correlations between magnesium, sodium, chloride, sulphate, alkaline and non-alkaline hardnes.. Magnesium showed no correlation with calcium; $r(34)=0.05$. Magnesium showed the following correlation with sulphate;
$[SO_4]=1.5\ [Mg]+6.2$ $r(14)=0.47$ .... (i)
Although this correlation coefficient is less than the 5% probability value for 14 pairs, 0.54, it is still rather high in view of the poor precision of the sulphate determination.

Non-alkaline hardness showed no correlation with aggressiveness or with total hardness. However it showed a significant relationship with saturated total hardness, which is the combination of total hardness and aggressiveness.

Non-alk. hardness=0.52 [sat.tot.hard.]−2.6 r(35)=0.58 .... (ii)

With tot. hardness and aggressiveness the correlation coefficients were r(34)=0.30 and r(34)=0.14 respectively.

Non-alkaline hardness also showed a positive correlation with magnesium;

Non-alk. hardness=1.6 [Mg]+3.8 r(34)=0.68 ....(iii)

The Molar Ca:Mg ratio showed a high positive correlation with alkaline hardness, especially when two abnormal results (derived from an almost stagnant pool in the stream bed in drought conditions) were omitted.

Ca:Mg=0.12 [Alk.hard.]+1.4 r(32)=0.81 ....(iv)
=0.13 [Alk.hard.]+1.6 r(34)=0.44

The correlations listed above reveal a great deal of information about the source of the stream and the sources of the solutes. Chloride showed the following correlation with sodium;

[Cl]=0.77 [Na] +2.6 r(13)=0.69

This correlation was to be expected, since both ions may be considered to have largely the same source, rain-borne sea water.

The variability of total hardness was greater than that of saturated total hardness. This suggested that the CO_2 concentration absorbed during the passage of the water through the soil was fairly constant, being largely independent of precipitation, temperature or season. Factors influencing the degree of saturation have not been revealed, the lack of correlation between aggressiveness and discharge being an important consideration.

It is usual to regard a stream as having three contributory sources, (Ward, 1967) which have easily recognisable characteristics:

Surface runoff. This is water flowing over the surface of the soil. It causes solute concentrations to fall as it dilutes the salts dissolved in water of the other types. The hydrograph is very irregular in shape since surface runoff takes place only for relatively short times after heavy rainfall.

Interflow. This is drainage at a shallow depth in the soil. The hydrograph is irregular, with rapid response to rainfall, with an absence of response to light rainfall if there is a defficiency of soil moisture. Because of the shallow depth large changes in solute concentrations are caused by seasonal changes in biological activity.

Groundwater runoff. This is the runoff of water held at greater depth in the subsoil than interflow. It is characterized by relatively high and steady solute concentrations. The hydrographs are smooth, and in particular the falling limb of the hydrograph after a flood peak will show a gradual decrease in discharge.

Stream hydrographs are usually regarded as having contributions from each of the three types. The hydrograph of Tyning's Stream was examined together with solute concentrations in an attempt to assess the contribution of each of the three types to this stream. The following conclusions were drawn.

The variations in solute concentrations, especially the saturated total hardness, were so low that a single hydrological process was predominant. However, not one of the three types of runoff explained the site characteristics. Variations explicable in terms of dilution by surface

Table 3

The characteristics of Tyning's Stream and its tributaries

	E. Branch tributary	N. Branch tributary	W. Branch tributary	D.S.Bridge at the road	Weir	Swallet
Contribution to the Tyning's Stream Discharge, % of Tyning's Stream.(±5%)	71	18	11	--	--	--
Temperature, °C. (± 0.05°C)	5.8°	6.0°	7.3°	6.2°	6.35°	6.35°
Total hardness, p.p.m. $CaCO_3$(± 0.8)	14.6	15.7	39.0	18.6	19.3	18.6
Alkaline hardness, p.p.m.$CaCO_3$(± 2)	2.0	2.3	19.2	3.9	4.7	4.6
Mg $10^5 \times M\ Mg^{2+}$ (± 0.1)	5.8	5.4	4.6	5.6	5.7	5.5
Ca $10^5 \times M\ Ca^{2+}$ (± 0.9)	8.8	10.3	34.4	13.0	13.6	13.1
Non-alkaline hard, p.p.m. $CaCO_3$(± 2)	12.6	13.4	19.8	13.9	13.7	13.8
Aggressiveness to $CaCO_3$, p.p.m. $CaCO_3$(± 1)	12.0	12.4	7.3	10.9	9.5	9.1
Chloride $10^5 \times M\ Cl^-$(± 2)	16.0	16	19	18	18	18
Sulphate $10^5 \times M\ SO_4^{2-}$(± 3)	18	19	26	20	17	19
Na $10^5 \times M\ Na^+$(± 0.2)	24.2	25.6	27	26	26	26
K $10^5 \times M\ K^+$(± 0.1)	1.7	1.9	3.8	2.10	2.0	2.2
Sr $10^5 \times M\ Sr^{2+}$(± 0.05)	0.02	0.02	0.02	0.02	0.02	0.02

runoff were not detected, precluding the first type of source. Seasonal variations of solute concentrations, characteristic of interflow were absent, and there was no smoothing of the discharge hydrograph which is characteristic of groundwater runoff.

It is suggested that the single hydrological process operating was similar to interflow, taking place at a greater depth than is usual, where temperatures are approximately constant.

The absence of surface runoff (which took place at the height of the flood in July 1968 but at no other time during the study) shows that the soil has a high infiltration capacity.

The associations between non-alkaline hardness, sulphate and magnesium were unexpected. The relationships between non-alkaline hardness and saturated total hardness (regression equation (ii)), and between the Ca : Mg ratio and alkaline hardness (equation (iv)) were particularly revealing. The implication is that the water acquired both non-alkaline hardness and CO_2 at a relatively early stage of its journey through the soil. The non-alkaline hardness was in the form of sulphates of calcium and magnesium in the ratio of 1.4 : 1. The dissolved CO_2 subsequently dissolved limestone, resulting in an increase of alkaline hardness and a decrease of the proportion of magnesium. These conclusions support and amplify conclusions on p. 180.

The stream was studied from its sources in the marsh to Tyning's Swallet on 7th February 1971. The results are shown in Table 3.

The similarities of concentrations of magnesium, sodium, chloride and strontium in the three branches of the stream suggest that they have a common type of source. When under-saturated (i.e. aggressive) water was shaken with gravel from the stream bed close to Tyning's Swallet there was no significant increase in total hardness. The small decrease in aggressiveness in the stream between the road bridge and the swallet may have been due to biological activity.

The variability of major solute concentrations in absolute terms, as indicated by standard deviations, were considerably lower than those of some other inlets within the cave, namely S2, S4, S5, D3, D4, D5 and D7.

Potassium concentrations showed a very clear pattern of seasonal variation. This is probably due to the element's biological role.

S2. The Main Stream in Stream Passage.

This rises in Boulder Chamber and flows through Stream Passage into the Gorge. It only flows when the discharge of Tyning's Stream is sufficiently high for water to reach Tyning's Swallet, the lowest point of the blind valley. In unusually high discharge conditions, water also appears at two places upstream of the Devil's Elbow, giving the notorious pool a cleaning-out that is sometimes most welcome. Although the connections are not proven by dye testing, the results of chemical analyses indicate that the two streams are also derived from Tyning's Stream. Increased calcium bicarbonate concentrations that were noted in these two minor inlets resulted from greater time for the solution of CO_2 and limestone than the rest of the stream, flowing by a faster

Table 4

Characteristics of the Main Stream in Stream Passage, S2.

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as% of Mean
Temperature ^{o}C	18	7.90	0.80	1.62	20.5%
Discharge (Q) galls/hour	19	225.3	133	276	123%
Alk.hard.p.p.m. $CaCO_3$	17	32.5	7.0	13.76	42.3%
Tot.hard.(uns)p.p.m. $CaCO_3$	18	50.5	8.7	18.42	36.4%
Sat.tot.hard.p.p.m. $CaCO_3$	16	60.9	11.2	21.18	34.8%
Ca $10^5 \times M\ Ca^{2+}$	16	39.3	7.6	14.22	36.1%
Mg $10^5 \times M\ Mg^{2+}$	16	8.4	1.4	2.72	32.4%
Non alk.hard.p.p.m. $CaCO_3$	16	16.0	2.4	4.50	28.1%
Aggressiveness p.p.m. $CaCO_3$	16	11.8	3.4	6.42	54.4%

route to the normal rising in Boulder Chamber. A similar situation has been reported in St. Cuthbert's Swallet, where several small inlets with widely varying ranges of hardness have been shown to have the same source on the surface (Stenner, 1968).

The two inlets upstream of the Devil's Elbow follow older stream routes (which were captured by the present stream route) into the cave, and can only operate when water overflows the normal route in conditions of unusually high discharge.

The combined inlet stream was sampled in Stream Passage shortly before it entered the Gorge. The stream size was impossible to measure directly here, and the usual procedure was to measure the discharge upstream of the junction with the N.E. Inlet stream, and then to subtract the discharge of the Mud Passage Drip. Samples were collected at this point rather than in Boulder Chamber because of the need to complete sampling in the shortest time possible. Changes in temperature and hardness between the Boulder Chamber and the Gorge can be expected to be small under normal conditions.

Discussion of the results

1. The variations of solute concentrations were greater than those of Tyning's Stream, but much less than those of the N.E. Inlet stream. The results were examined to determine whether the variations were due to different rates of solution of calcium carbonate or to admixture with harder water. It was found that the increments were due to variations in the solution of CO_2 with discharge, and to high temperatures in Tyning's Stream. Important and considerable changes had therefore taken place in the short distance between the surface and Boulder Chamber. The implications of this statement are discussed at greater detail in Section 5 of this paper.

2. The high correlation between limestone solution and discharge (Section 5, p. 210) accounts for hardness changes between the surface and the cave with remarkable completeness. Admixture with water from another source was therefore negligible.

3. Sodium, potassium, chloride and sulphate were determined only twice, and their concentrations were then the same as in Tyning's Stream, which is to be expected because there is no other source, there is very little of them in limestone which was dissolved in the ruckle, between the Boulder Chamber and the swallet, and they do not interact with limestone.

S4 and S5. The North-East Inlet Stream.

The stream is first seen in the N.E. corner near the top of the Gorge, flowing in a narrow bedding plane and joins the stream in the Gorge. The N.E. Inlet stream normally is the largest of the inlet streams in the cave. The discharge of the stream was measured at S5, either from discharge ratios calculated from temperature or solute concentration measurements, or by collecting the water for a measured time in a polythene sack. It was not possible to measure the discharge at S4 by any of the chosen methods. (Appendix 1).

Table 5

Characteristics of Site S4,

together with some of the characteristics of Site S5

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	21	8.12	0.49	1.08	13.3%
Discharge (Q) galls/hour*	34	980	450	1350	138%
Alk.hard.p.p.m. $CaCO_3$	21	83.0	13.5	29.7	35.8%
Tot.hard.(uns)p.p.m. $CaCO_3$	21	95.6	12.8	28.2	29.5%
Sat.tot.hard.p.p.m. $CaCO_3$	20	102.5	11.7	25.0	24.4%
Ca 10^5 x M Ca^{2+}	19	84.9	13.2	27.4	32.2%
Mg 10^5 x M Mg^{2+}	19	9.60	0.82	1.71	17.8%
Non.alk.hard.p.p.m. $CaCO_3$	19	13.4	1.4	2.97	22.2%
Aggressiveness.p.p.m. $CaCO_3$	20	4.69	2.30	4.91	105%
Na 10^5 x M Na^+ *	14	30.2	2.5	5.0	16.5%
K 10^5 x M K^+*	14	4.1	0.5	0.9	22%
Cl 10^5 x M Cl^-*	11	28.6	3.0	5.1	17.8%
SO_4 10^5 x M SO_4^{2-} *	10	16.3	1.8	2.9	17.8%

* From site S5.

To determine whether changes in total hardness before and after the July flood were significant, the statistical procedure known as the t-test of significance was used. In this method, the means, standard deviations and numbers of measurements are used to calculate a value t, the significance of which can be found in statistical tables. If the significance of t is below 95%, the conclusion is that the two sets of figures do not differ significantly from one another.

The results were;

		Mean	(No.)	S.D.
Tot.hard.(uns.), p.p.m. $CaCO_3$	before flood	104.6	(20)	24.5
	after flood	94.3	(18)	46.7

$t=0.86$, significance of $t=75\%$.

The conclusions is that there was no significant difference in the total hardness before and after the flood.

Discussion of the results

The solute concentrations revealed unusually large variations that are characteristic of a stream formed by a combination of varying proportions of two different sources of water which have widely differing chemical composition. The total discharge of the N.E. Inlet stream and the Stream Passage stream consistently exceeded that of Tyning's Stream, and in mid-August 1968, the N.E. Inlet stream continued to flow three weeks after Tyning's stream had dried up altogether. The information all combines to show that there is an unknown source to the N.E. Inlet stream in addition to the contribution from Tyning's stream.

S12. *The part of the N.E. Inlet stream not derived from Tyning's Stream*

It has already been shown that water from an unknown source entered the cave in the N.E. Inlet stream, together with water from Tyning's Stream. Subtraction of the Stream Passage stream discharge from the Tyning's Stream discharge gave a measure of the size of the fraction of the stream coming from the Tyning's Stream. Subtraction of

Table 6

Characteristics of site S12

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as% of Mean
Temperature °C	8	9.0	0.12	0.17	1.9%
Discharge (Q) galls/hour	28	540	370	1000	185%
Alk.hard.p.p.m. $CaCO_3$	7	140.5	5.6	7.6	5.41%
Tot.hard.(uns) p.p.m. $CaCO_3$	7	149.1	4.9	6.6	4.4%
Sat.tot.hard.p.p.m. $CaCO_3$	7	152.8	5.1	6.9	4.5%
Ca $10^5 \times M\ Ca^{2+}$	7	139.6	4.4	5.9	4.2%
Mg $10^5 \times M\ Mg^{2+}$	8	10.1	1.7	2.3	23%
Non.alk.hard.p.p.m. $CaCO_3$	8	9.2	3.8	5.2	57%
Aggressiveness p.p.m. $CaCO_3$	7	3.7	4.1	5.5	150%

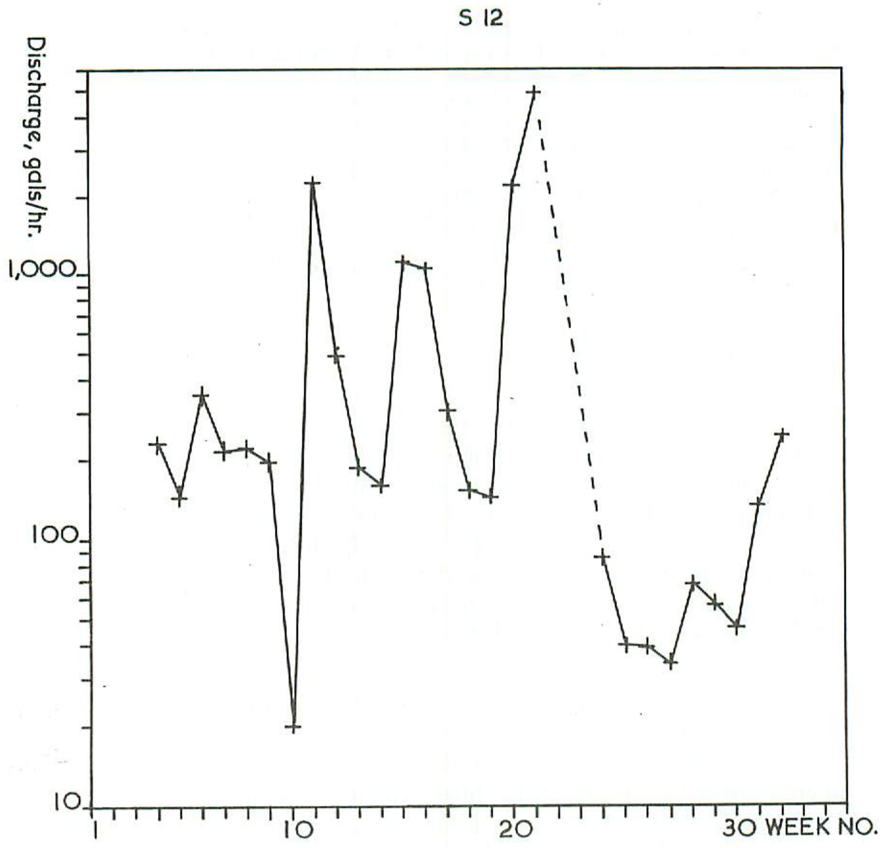


Fig. 48

this from the N.E. Inlet discharge figures gave an estimate of the size of the unknown fraction of the stream. By this means it was possible to study the discharge characteristics of the unknown source of part of of the N.E. Inlet Stream, in spite of the lower precision of the derived measurements (Fig. 48).

Temperature and solute concentration measurements of the unknown fraction could be studied only when Tyning's stream was dry. Unlike discharge measurements, these could not be estimated by subtraction, because changes in temperature and solute concentrations of the Tyning's Stream fraction can be expected (by comparison with Stream Passage results) to be large and variable.

Discussion of the results

The temperature and salt concentrations vary much less than those of the whole N.E. Inlet stream (S4 and S5), and the characteristics are those of a stream of percolation water.

The origin of the water is unknown.

The hardness and the aggressiveness of the stream showed variations which are similar to those seen in other inlets after the July flood.

D2. *The Mud Passage Drip Inlet*

In the Mud Passage route, 12 m before the Gorge is reached, this drip falls from a stalactite decorated opening in the roof onto dripstone-covered boulders 4 m below. The water once flowed into the roof of the Gorge, and the high-level passage was intersected by Mud Passage. The drip is dispersed over an area of 4 m^2, and the small stream flows through boulders to join the water from Stream Passage in the Gorge.

Water samples were collected by placing a bottle under the drip on the way into the cave, and collecting it on the way out. A polythene sack was used for a measured time to measure the discharge.

The characteristics of the site are shown in Figs. 49, 50 and 51, and in Tables 7 and 8.

Changes after the July Flood. No significant change was found in total hardness or magnesium, but there were changes exceeding the 99.8% probability in temperature (8.9 to 9.1°C), saturated total hardness (163.7 to 175.0 ppm $CaCO_3$), and aggressiveness to $CaCO_3$ (−11.5 to −4.6 ppm $CaCO_3$ even when the exceptional result of week 28 was omitted). Whether the changes were due to the flood or to normal seasonal changes is unknown.

Correlations between site characteristics. No correlations were found between total hardness and discharge. A significant inverse correlation was found between aggressiveness and discharge (Q).

Aggressiveness $= 0.76Q^{-0.4} + 121$ $\qquad$ $r(21) = -0.64$

Table 7

Characteristics of the Mud Passage Drip Inlet, D2

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as% of Mean
Temperature °C	39	8.98	0.052	0.159	1.77%
Discharge (Q) galls/hour	38	15.8	4.9	15.0	95%
Alk.hard.p.p.m. $CaCO_3$	37	161.4	3.7	11.0	6.84%
Tot.hard.(uns)p.p.m. $CaCO_3$	38	175.5	2.0	6.2	3.53%
Tot.hard.sat.p.p.m. $CaCO_3$	36	168.8	3.8	11.3	6.69%
Ca 10^5 x M	35	162.9	3.0	8.7	5.33%
Mg 10^5 x M	35	12.9	1.9	5.4	41.9 %
Non.alk.hard.p.p.m. $CaCO_3$	33	13.9	1.6	4.6	33.1 %
Aggressiveness p.p.m. $CaCO_3$	36	-7.3	3.3	9.8	135%
Na 10^5 x M Na^+	11	16.8	1.5	2.3	13.7%
K 10^5 x M K^+	11	2.10	0.48	0.72	34.3%
Cl 10^5 x M Cl^-	9	13.9	1.4	1.8	13.0%
SO_4 10^5 x M SO_4^{2-}	8	9.2	4.6	5.6	60.8%
Sr 10^5 x M Sr^{2+}	3	0.4	-	-	-
F 10^5 x M F^-	3	0.5	-	-	-

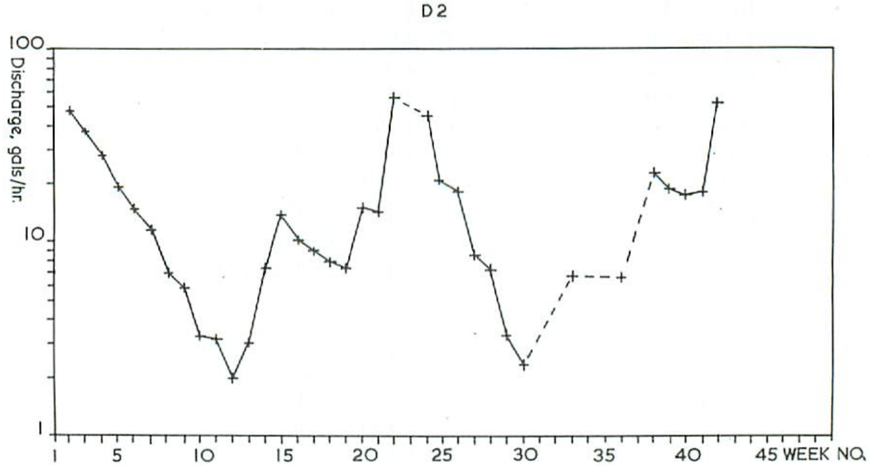

D2
100
10
1
Discharge, gals/hr.
1
5
10
15
20
25
30
35
40
45 WEEK NO.

Fig. 49

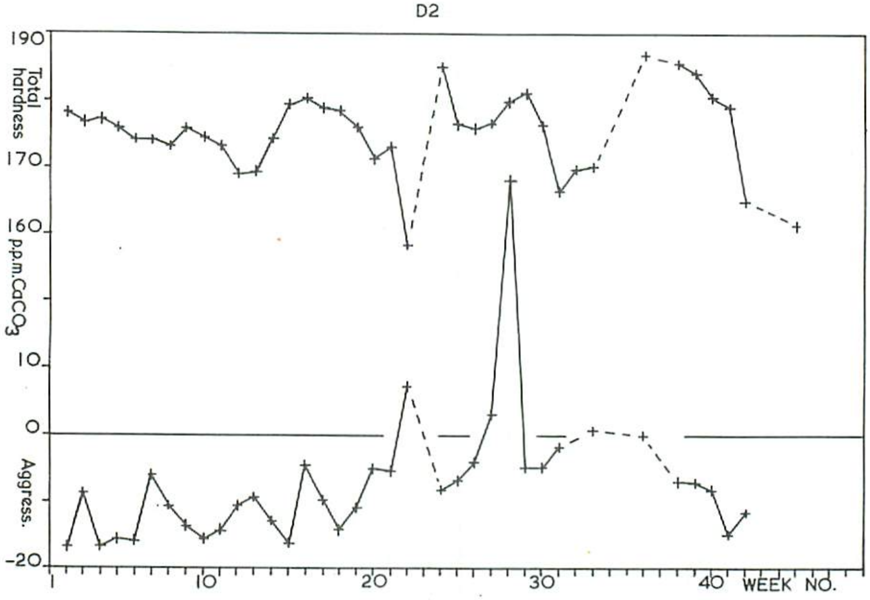

D2
190
170
160
10
0
-20
Total hardness
p.p.m. CaCO3
Aggress.
1
10
20
30
40
WEEK NO.

Fig. 50

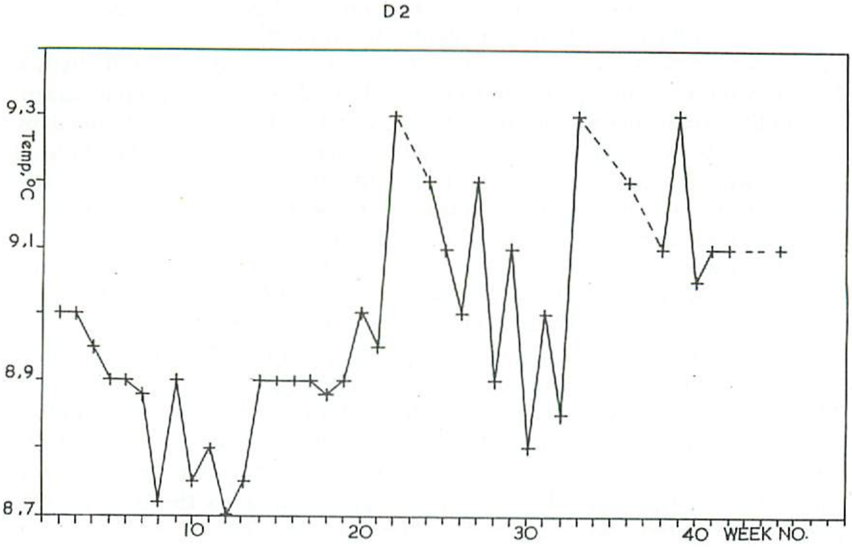


Fig. 51

Table 8

Trace concentrations in the Mud Passage Inlet, D2

Trace element	Mean before week 22 p.p.m.	week 22 p.p.m.
Zn	N.D.	0.02
Cu	N.D.	0.04
Fe	N.D.	0.02
Mn	N.D.	0.03
Ni, Pb, Br	N.D.	N.D.
Al	N.D.	1.3
PO_4	0.02	0.04

Discussion of the results

The comparatively low variations in most of the site characteristics are an outstanding feature of the results shown in Table 6.

The variablity of saturated total hardness exceeded that of the total hardness, reflecting variations in aggressiveness, which were related to the discharge. Related variations in losses of CO_2 between the roof and the sample bottle were likely, considering the excess of free CO_2 over the level in equilibrium with the CO_2 in air. However, the lack of variation in the saturated total hardness is a most significant feature.

There was a marked damping of discharge response to rainfall, the falling limb of the hydrograph having a gentle gradient. This is in marked contrast with stream sites and cetrain other drips, such as D3, 4 or 5, which have much more irregular hydrographs.

Solute concentration characteristics were those of a single hydrological source, either groundwater runoff or depression storage, draining 1,000 square metres of the surface. The last figure was obtained by two separate methods, first the total discharge and the total rainfall from 26th February 1968 to 8th December 1968, assuming a 50% evaporation loss, and secondly measuring the discharge resulting from a single large rainstorm followed by a long dry spell.

The figures for total hardness and aggressiveness suggests that limestone solution took place in conditions of *"equilibrium solubility"* (as defined by Smith and Mead, 1962) with respect to CO_2, with the solution of $CaCO_3$ tending to lag behind the solution of CO_2, this effect becoming apparent on rare occasions of very high discharge. Smith and Mead (1962) suggested that the high calcium concentrations found in the major risings around the Mendip Hills owe their origin to soil CO_2, and most of the limestone solution therefore takes place very close to the surface. Later work has tended to support this hypothesis. This site, and others in this cave and in St. Cuthbert's Swallet behave as if they are fed by reservoirs with very clear discharge characteristics. This fact, together with the explanation of limestone solution (above) suggests that site D2 is fed by depression storage, coming from an infilled depression close to the surface. This suggestion has many consequences, and is discussed more fully in Section 9.

During the July flood, and for two subsequent weeks the water carried a large suspension of a grey non-calcareous mud, (making it look milky). This is a sign of large changes having taken place in the sub-soil through which the water had drained.

These changes brought about by the flood are likely to have been accompanied by large quantities of organic material being carried into the sub-soil. This is a likely explanation of the changes in the pattern of aggressiveness and total hardness that took place after the flood. However, it is not possible to estimate whether these changes (and the temperature change) are due to the July flood entirely, or whether they also reflect regular seasonal variations. Further work in the cave will be needed to clarify this very important point.

Temperature variations at this site were interesting, and are discussed in Section 8.

The trace element results shown in Table 8 suggest that small traces were initially dissolved in the soil, and as the calcium concentration rose the metals were normally deposited on limestone, and only in very unusual high flood conditions do they reach the open cave in concentrations high enough to be detected by the method used in this study. The results are also consistent with laboratory studies of changes of trace metal concentrations in contact with solid $CaCO_3$. The detection of manganese during the flood is very interesting being consistent with its presence in the soil, and its participation in microbiological processes in the soil. It is not normally detected in cave water inlets because of its readiness to be deposited on calcium carbonate.

D1. *Drip near First Grotto*

The drip enters through stalactites in the roof of Entrance Passage at the junction with the short passage leading to Mud Passage. Because of the low discharge at the site, the samples were collected in a bottle (rinsed with water from the drip) left underneath the drip for the duration of the sampling trip. Slight losses of carbon dioxide may be expected in these conditions. Before the July flood, the drip fell four metres into the sample bottle. After the flood the distance was reduced to 1.5 m, increased later to 2 m during the digging to re-open the Mud Passage ruote. Site characteristics are shown in Table 9, and Figs. 52, 53 and 54.

Table 9

Characteristics of site D1

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	32	9.23	0.13	0.35	3.79%
Discharge (Q) galls/hour	32	0.097	0.058	0.162	167%
Alk.hard.p.p.m. $CaCO_3$	25	121.75	2.47	5.99	4.91%
Tot.hard.(uns) p.p.m. $CaCO_3$	29	141.09	1.33	3.50	2.48%
Sat.tot.hard.p.p.m. $CaCO_3$	22	138.00	2.64	5.95	4.31%
Ca 10^5 x M Ca^{2+}	18	133.92	2.18	4.37	3.26%
Mg 10^5 x M Mg^{2+}	18	6.78	2.30	4.62	68.2 %
Non.alk.hard.p.p.m. $CaCO_3$	18	20.91	2.16	4.34	20.8 %
Aggressiveness p.p.m. $CaCO_3$	22	-3.16	3.03	6.79	215%
Na 10^5 x M Na^+	10	32.84	3.98	5.42	16.5%
K 10^5 x M K^+	8	2.31	0.89	1.06	45.8%
Cl 10^5 x M Cl^-	9	29.87	2.52	3.27	10.9%
SO_4 10^5 x M SO_4^{2-}	7	19.71	6.37	6.87	36.7%

Correlations between site characteristics. There was no significant correlation between total hardness or aggressiveness with dicharge. The correlation between total hardness and aggressiveness was insignificant at the 5% probability level.

Total hardness $= -0.23$ [Aggress] $+ 131$ $\qquad$ $r(22) = -0.45$

Variations in site characteristics before and after the July flood. Changes in magnesium and aggressiveness were less than 75% probable, and changes of non-alkaline hardness and saturated total hardness less than 90% probable. These differences were therefore statistically insignificant. An increase of mean total hardness from 139 to 142.6×10^{-5}M was 99% probable, and an increase of mean temperature from 9.0°C to 9.5°C was higher than 99.9% probable. The increase in both total hardness and temperature after the flood were therefore highly significant.

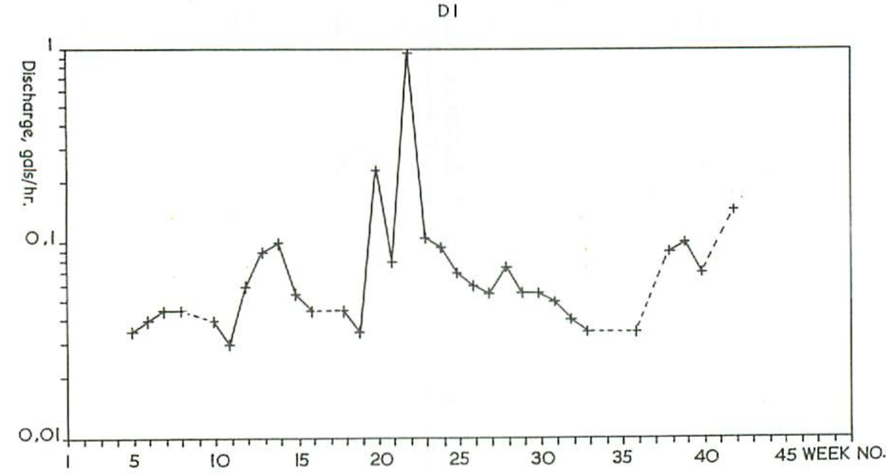

D1
Discharge, gals/hr.
1
0,1
0,01
1
5
10
15
20
25
30
35
40
45 WEEK NO.

Fig. 52

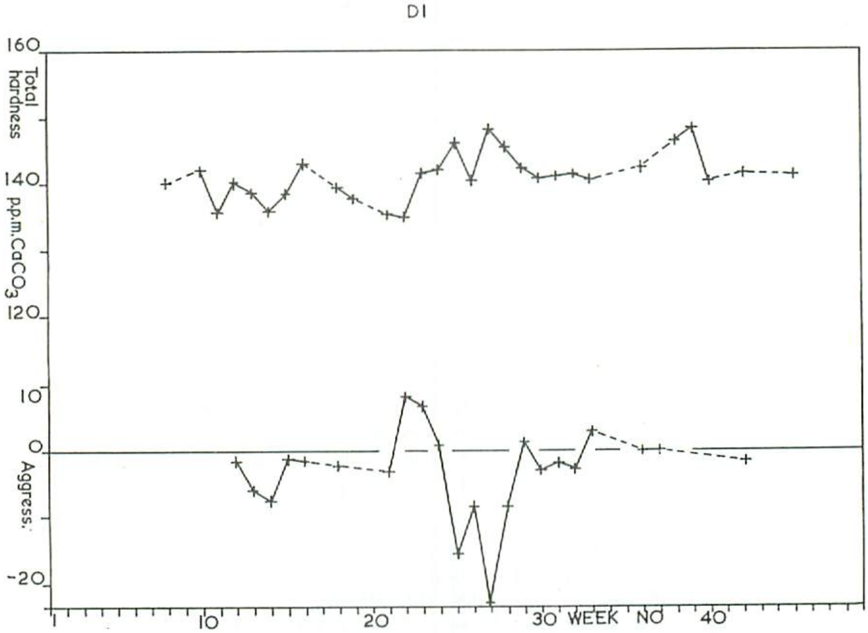

D1
160
Total hardness p.p.m.CaCO3
140
120
10
0
Aggress.
-20
1
10
20
30 WEEK NO
40

Fig. 53

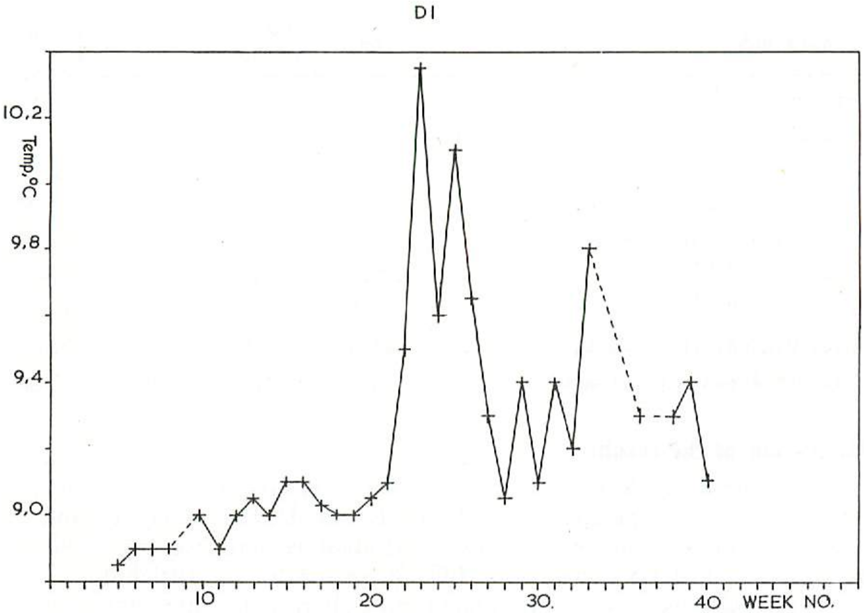


Fig. 54

Discussion of the results

The variability of site characteristics (apart from discharge) are sufficiently small to conclude that the water is derived largely from a single source.

The mean temperature was affected by the flood, the large influx of warm water raising the temperature of the drip for several weeks. Increases of hardness and aggressiveness may also be attributed to the flood and its side-effects. Further work will be needed to determine whether regular seasonal changes took place at the same time.

D3. Drip near the top of the Gorge

The water fell 11 m from a small opening in the roof onto a large boulder. The discharge was measured by collecting the water for a measured time with a polythene bag. In very low discharge conditions, the number of drops falling in a minute were counted, the volume of a drop being calculated. After the July flood, a huge quantity of mud, turf and boulders flowed into the top of the Gorge, and this site was then omitted from the sampling programme, because mud would have been spread unnecessarily to attractive parts of the cave. Site characteristics are shown in Table 10, and Figs. 55, 56 and 57.

Table 10

Characteristics of site D3

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	21	8.53	0.10	0.21	2.46%
Discharge (Q) galls/hour	18	1.43	0.63	1.27	89%
Alk.hard.p.p.m. $CaCO_3$	14	112.6	8.8	15.2	13.5 %
Tot.hard.(uns)p.p.m. $CaCO_3$	18	131.2	6.2	12.4	9.45%
Sat.tot.hard.p.p.m. $CaCO_3$	8	131.4	10.5	12.6	9.58%
Ca 10^5 x M Ca^{2+}	6	120.5	14.4	13.7	11.4 %
Mg 10^5 x M Mg^{2+}	6	11.0	5.2	4.9	44.6 %
Non.alk.hard.p.p.m. $CaCO_3$	6	21.4	4.9	4.7	22.0 %
Aggressiveness p.p.m. $CaCO_3$	8	-1.28	1.40	1.68	131%

Discussion of the results

The site characteristics show a relatively high degree of variability. Of other inlets of percolation water, only site D5 has a comparable degree of variation in total hardness and alkaline hardness, but it will be shown that at D5 there was a different reason for the variability.

The discharge responds to rainfall more sharply than any other drip inlet. The water runs through from the surface to the cave faster than at the other drips, and in high discharge conditions the water had insufficient time to reach equilibrium with the sub-soil air CO_2.

Temperature results can be interpreted in the following way. Discharge characteristics act in such a way that low discharge anomalies overlap with occasional high discharge anomalies, and the results do not permit the estimation of rock temperatures.

D4. *Drip in the Gorge opposite the Balcony*

This drip fell from stalactites in the roof, 16 m high at the point, onto dripstone encrusted boulders to the East of the stream 25 m downstream of the Bridge, opposite the Balcony. Discharge measurements were made by the same methods used for drip D3. During the flood, this part of the cave changed very greately, the whole bank of boulders being swept away. Sampling continued intermittently, but it was not for several months that it could be reasonably certain that the original drip had been re-located.

After the flood, the closure of the Mud Passage route made it essential to shorten the sampling route in the cave to enable the sampling to be completed as quickly as possible. So sampling at this site was not regularly done to avoid making a detour from the new route.

For 3 weeks after the flood, the water of this drip was clouded by a non-calcareous white suspension. Site characteristics are shown in Tables 11 and 12, and Figs. 55, 56 and 57.

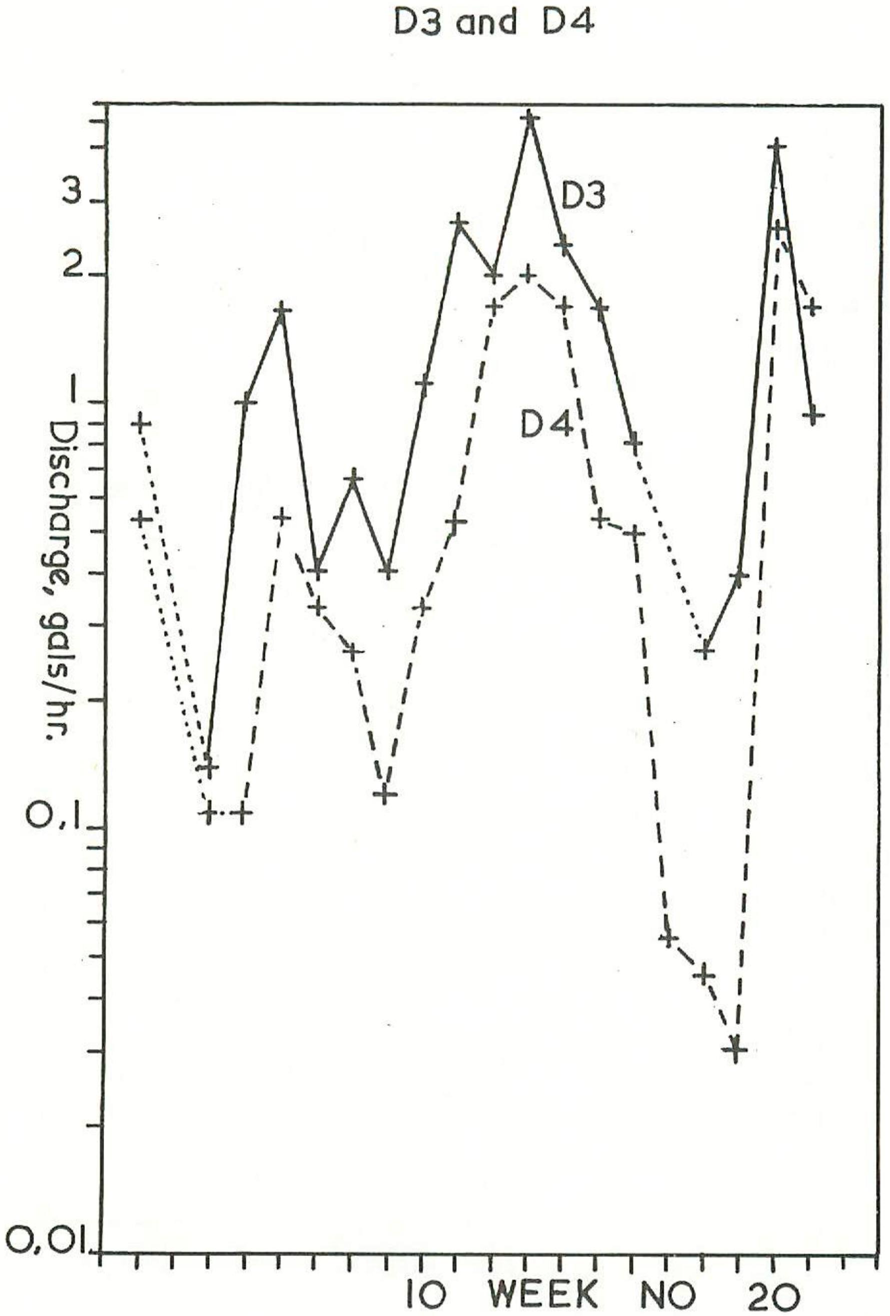


Fig. 55

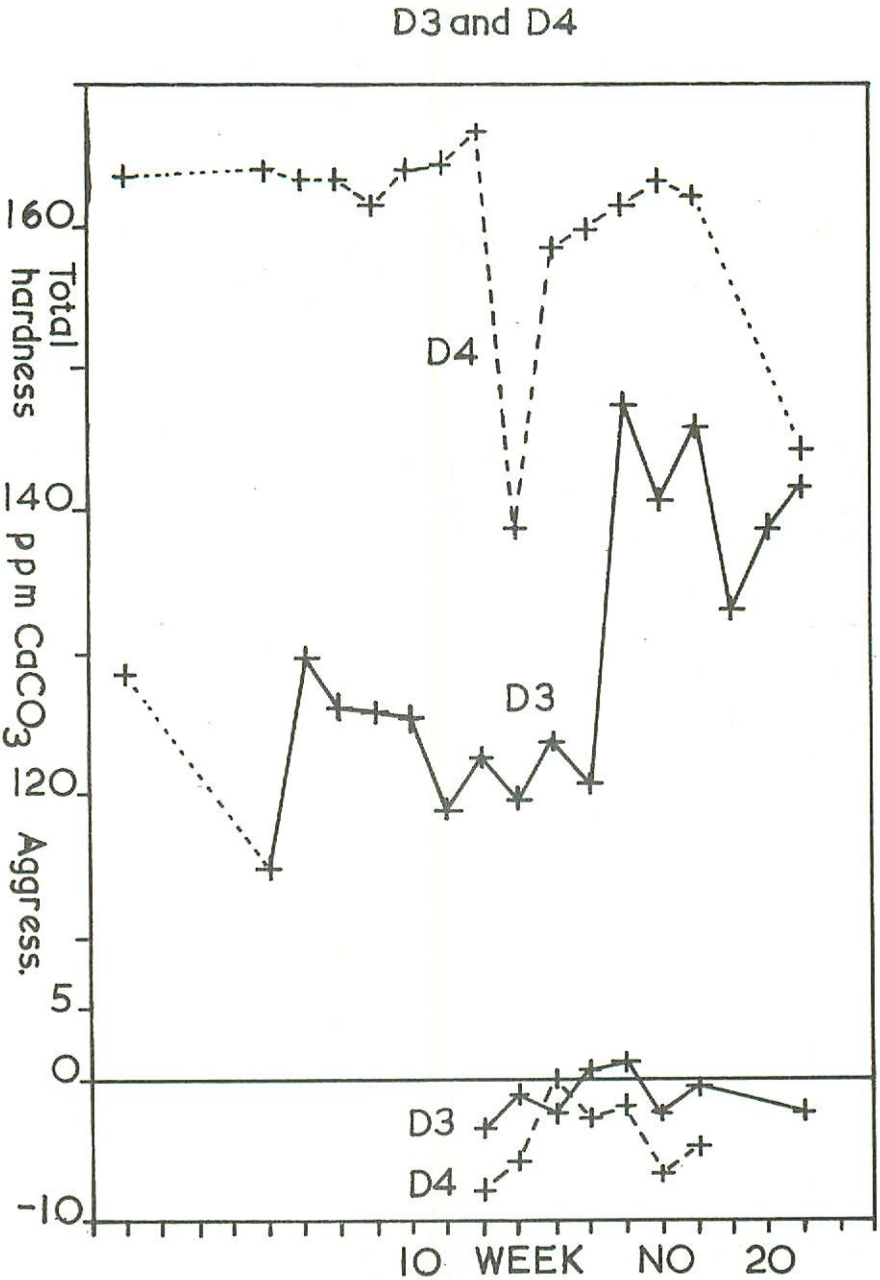

D3 and D4
160
140
120
5
0
-10
Total hardness ppm CaCO$_3$
Aggress.
D4
D3
D3
D4
10
WEEK NO
20

Fig. 56

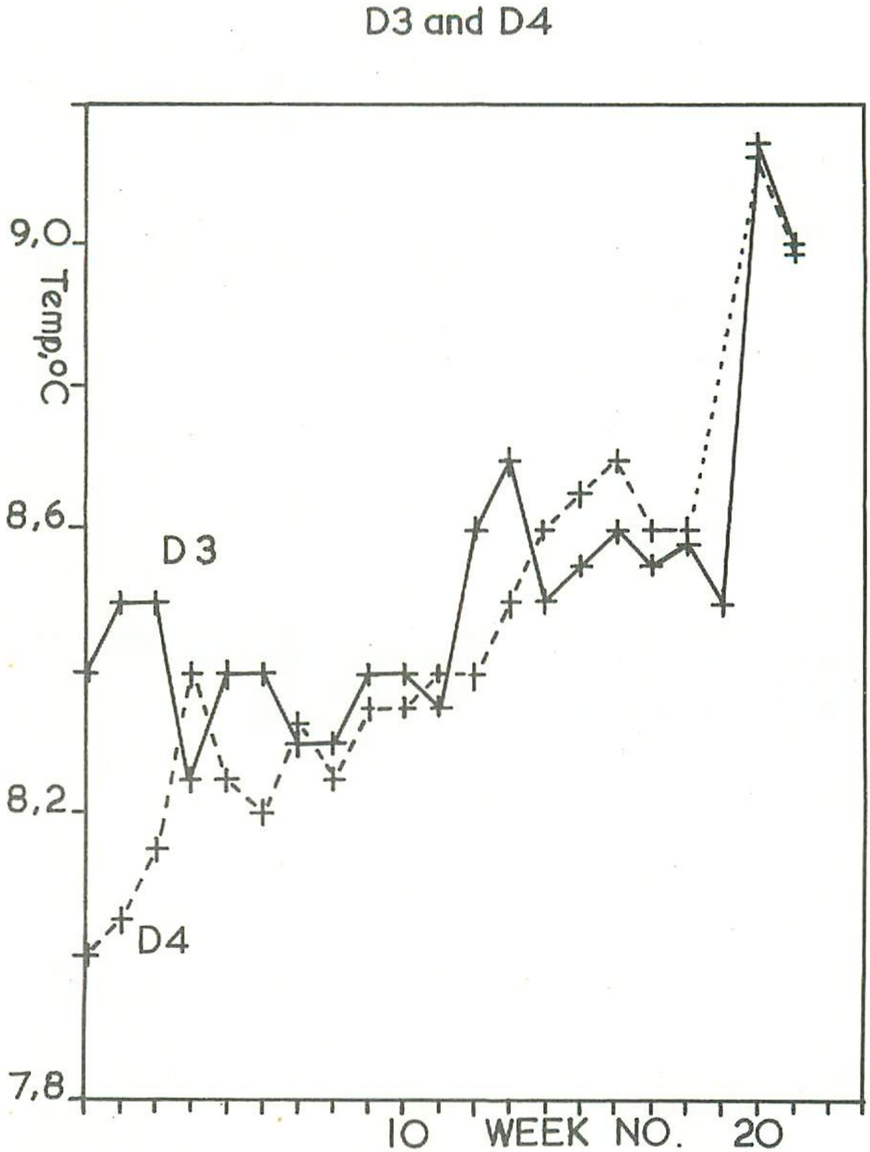


Fig. 57

Table 11

Characteristics of Site D4, weeks 1 - 21

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	20	8.43	0.13	0.28	3.32%
Discharge (Q) galls/hour	19	0.63	0.37	0.76	121%
Alk.hard.p.p.m. $CaCO_3$	11	139.9	5.4	8.0	5.71%
Tot.hard.(uns) p.p.m. $CaCO_3$	15	159.9	4.3	7.8	4.88%
Sat.tot.hard.p.p.m. $CaCO_3$	8	153.1	8.0	9.6	6.27%
Ca 10^5 x M Ca^{2+}	6	143.6	5.3	5.0	3.48%
Mg 10^5 x M Mg^{2+}	6	18.8	2.9	2.8	14.9%
Non.alk.hard.p.p.m. $CaCO_3$	6	19.2	3.2	3.0	15.6%
Aggressiveness p.p.m. $CaCO_3$	8	-3.75	2.59	3.10	82.7%

Correlations between total hardness with discharge (Q) and aggressiveness with discharge (before the flood) were investigated. The results were:—

Tot.hard. $= 8.94\ Q^{-0.4} + 148.2$ $\quad r(15) = 0.47$

Aggress. $= -1.031\ Q^{-0.4} - 2.84$ $\quad r(8) = -0.424$

The first value is close to the 5% probability value.

Table 12

Characteristics of Site D4 after week 22

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	10	9.49	0.12	0.20	2.1%
Discharge (Q) galls/hour	10	0.64	0.31	0.50	78%
Alk.hard.p.p.m. $CaCO_3$	4	144.0	3.6	3.7	2.6%
Tot.hard.(uns) p.p.m. $CaCO_3$	10	169.5	3.6	5.8	3.4%
Ca 10^5 x M Ca^{2+}	4	150.0	11.2	11.4	7.6%
Mg 10^5 x M Mg^{2+}	4	17.2	7.0	7.2	42%
Non.alk.hard.p.p.m. $CaCO_3$	4	23.4	3.5	3.5	15%
Aggressiveness p.p.m. $CaCO_3$	6	-0.8	2.1	2.6	320%

Discussion of the results

The temperature difference after the flood was very large indeed. It is possible that the shape of the Gorge at this point acted as a trap, holding warm air at roof level near the drip.

Large peaks of hardness and aggressiveness may have been due to after effects of the July flood, since seasonal variations were not indicated in the earlier study at the site (Smith and Meade, 1962 p. 201).

Site characteristics shown in Table 12 are sufficiently close to those in Table 11 to confirm that the site had been correctly re-located after the flood.

Temperature results must be interpreted as at site D3.

D7. The Drip at the Terminal Sump

This intermittent inlet was a few metres upstream of the final sump, at the end of the low pasage which comprised the final 10 m of the streamway until July 1968. The water trickled through a narrow muddy slot on the right hand wall. The 1968 flood blocked the passage leading to the drip. Site characteristics are shown in Table 13, and Figs. 58 and 59.

Table 13

Characteristics of site D7

Measurement	No.	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	9	8.93	0.34	0.46	5.15%
Discharge (Q) galls/hour	20	0.38	0.27	0.57	150%
Alk.hard.p.p.m. $CaCO_3$	6	250.2	8.4	8.04	3.22%
Tot.hard.(uns)p.p.m. $CaCO_3$	7	261.6	6.9	7.47	2.85%
Sat.tot.hard.p.p.m. $CaCO_3$	7	232.2	8.8	9.46	4.08%
Ca $10^5 \times M\ Ca^{2+}$	3	249.5	8.9	3.6	1.44%
Mg $10^5 \times M\ Mg^{2+}$	3	12.8	14.0	5.6	43.8 %
Non.alk.hard.p.p.m. $CaCO_3$	3	11.5	7.5	3.0	26.1 %
Aggressiveness p.p.m. $CaCO_3$	6	-30.8	7.7	7.3	23.7 %

Correlations between site characteristics. The correlation between total hardness and discharge is quoted. Correlations between total hardness and aggressiveness, and aggressiveness with discharge were also calculated, but are inconclusive because of the small number of samples taken from the site. The results are:—

Tot.hard. $= -14.2Q^{-0.4} + 278.3$	$r(8) = -0.664$
$= -0.260$ Agg. $+254$	$r(7) = -0.24$
Aggress. $= 4.83Q^{-0.4} - 35.8$	$r(7) = 0.25$

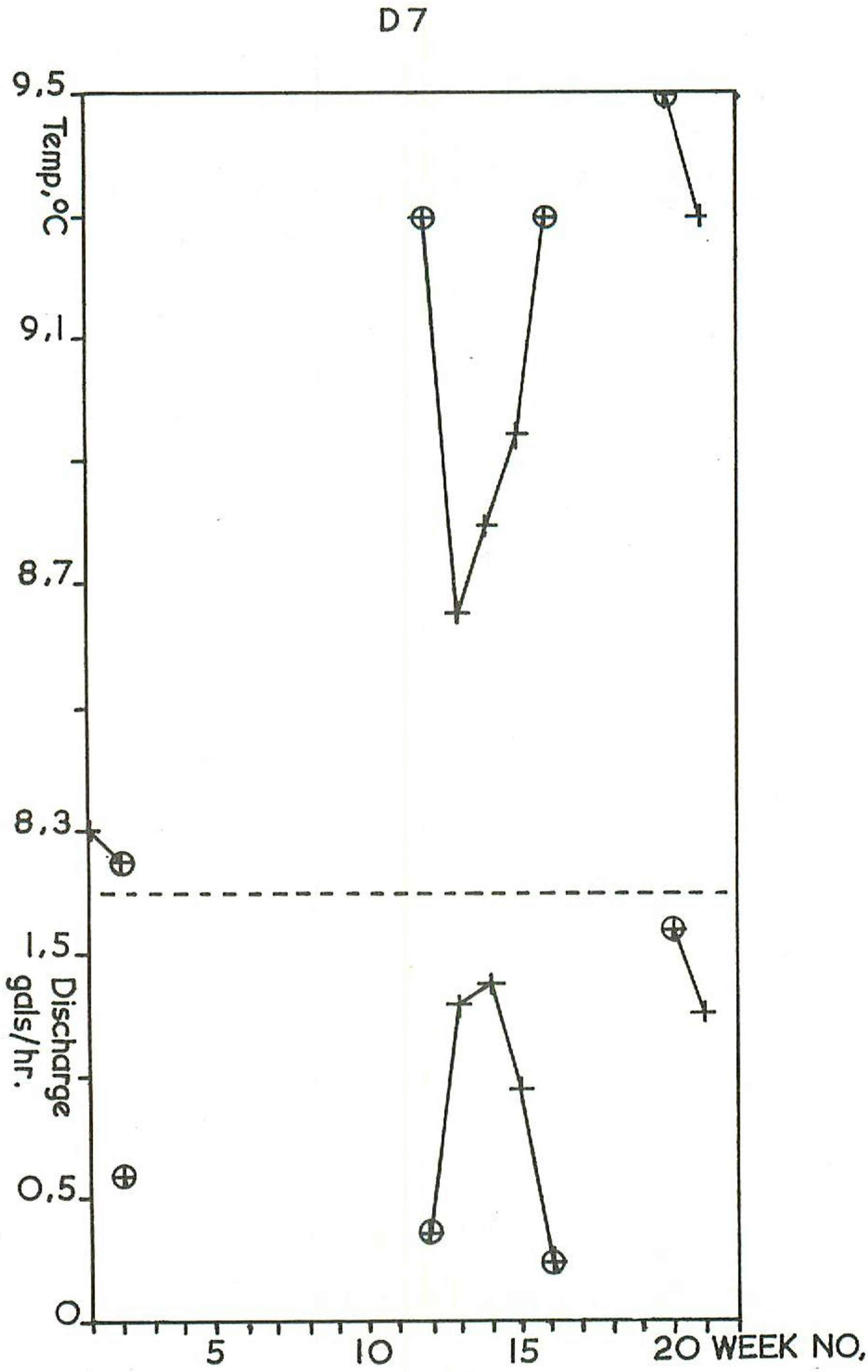


Fig. 58

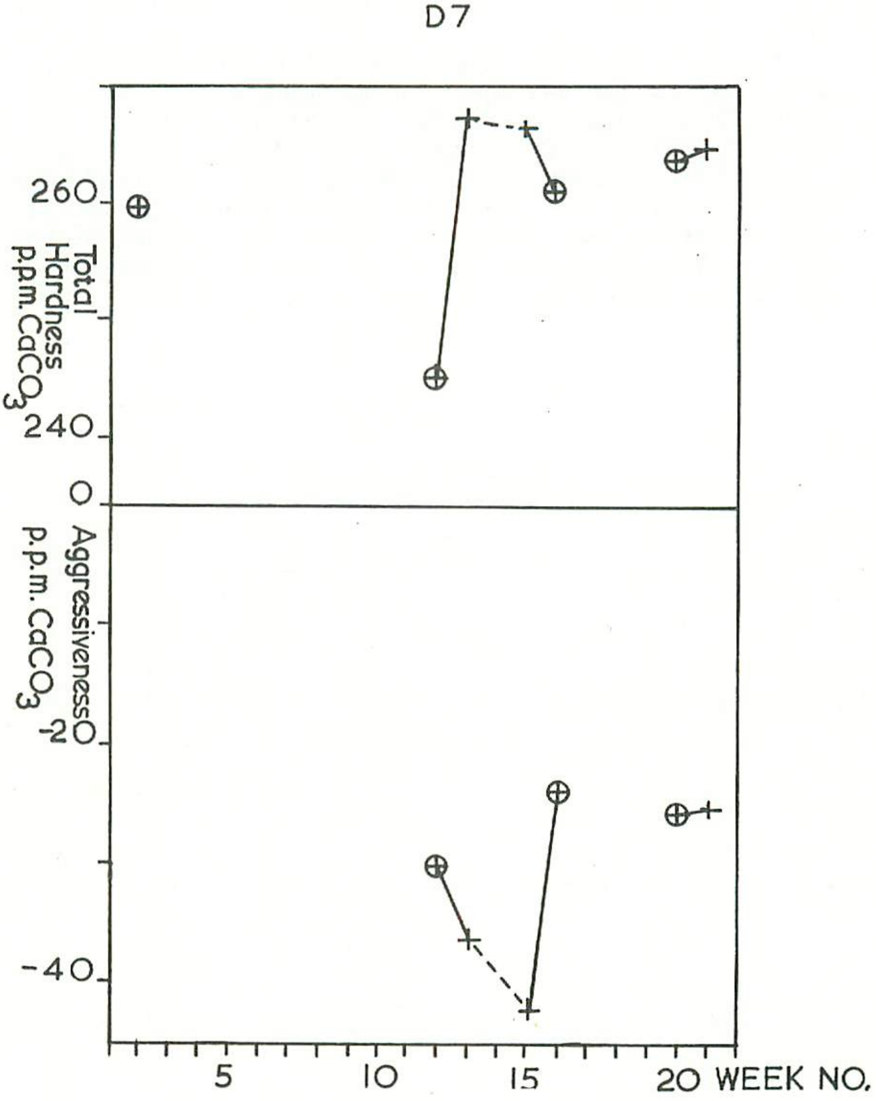

D7
260
240
0
Total Hardness p.p.m. CaCO$_3$
Aggressiveness p.p.m. CaCO$_3$
0
-20
-40
5
10
15
20 WEEK NO.

Fig. 59

Discussion of the results

The variability of the chemical characteristics is low. The hardness of the water is high, and the degree of super-saturation was very high. This supersaturation made it necessary to neutralise the bicarbonates before titrating with EDTA, otherwise, the addition of buffer solutions or E.D.T.A. solution caused solid $CaCO_3$ to be precipicated from solution.

The nature of the intermittent flow with an unusual hydrograph, and the high hardness and super-saturation leads to the following suggestion. The drip originated as percolation water entering the cave, probably through active stalactite formations. The large loss of CO_2 suggests a chamber with good air circulation, most probably in the Ladder Dig Extensions because of its topographical relationship to the site. The water normally drained through an alternative route leaving the End Drip dry. The water overflowed this route under high discharge conditions, causing the End Drip to start to flow.

Table 14

Characteristics of Site D5

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature ^{o}C	36	9.19	0.04	C.126	1.37%
Discharge (Q) galls/hour	35	4.76	1.20	3.49	73. 3%
Alk.hard.p.p.m. $CaCO_3$	28	130.8	4.11	10.6	8. 1%
Tot.hard.(Uns) p.p.m. $CaCO_3$	33	152.1	7.7	21.9	14. 6%
Sat.tot.hard.p.p.m. $CaCO_3$	26	146.5	5.4	11.2	7.64%
Ca 10^5 x M Ca^{2+}	21	140.0	6.1	13.3	9.50%
Mg 10^5 x M Mg^{2+}	21	11.5	1.7	3.72	32. 4%
Non.alk.hard.p.p.m. $CaCO_3$	21	19.8	2.4	5.3	26. 8%
Aggressiveness p.p.m. $CaCO_3$	26	-1.6	1.7	4.3	269%
Na 10^5 x M Na^+	8	26.7	4.4	5.3	19. 8%
K 10^5 x M K^+	8	4.0	1.2	1.42	35. 5%
Cl 10^5 x M Cl^-	4	23.3	1.5	0.94	4.03%
SO_4 10^5 x M SO_4^{2}	6	15.6	4.8	4.6	29. 5%

No correlation was found between total hardness and discharge, total hardness and aggressiveness, aggressiveness and discharge.

The significance of changes of temperature (9.15 to 9.25°) and total hardness (141.6 to 157.1 ppm $CaCO_3$) before and after the flood were 99% and >99.9% respectively. Again it is not possible to comment on this without first knowing the extent of normal seasonal variations.

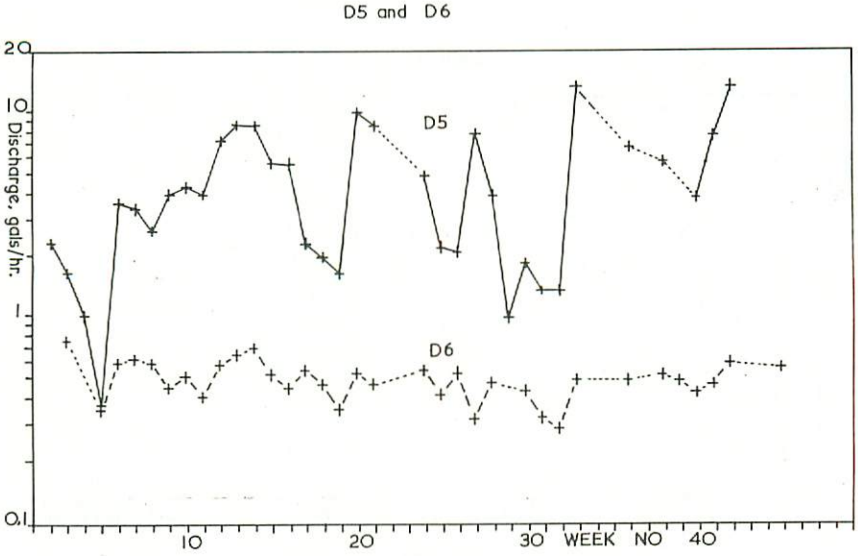

D5 and D6
20
10
Discharge, gals/hr.
1
0.1
D5
D6
10
20
30
WEEK NO
40

Fig. 60

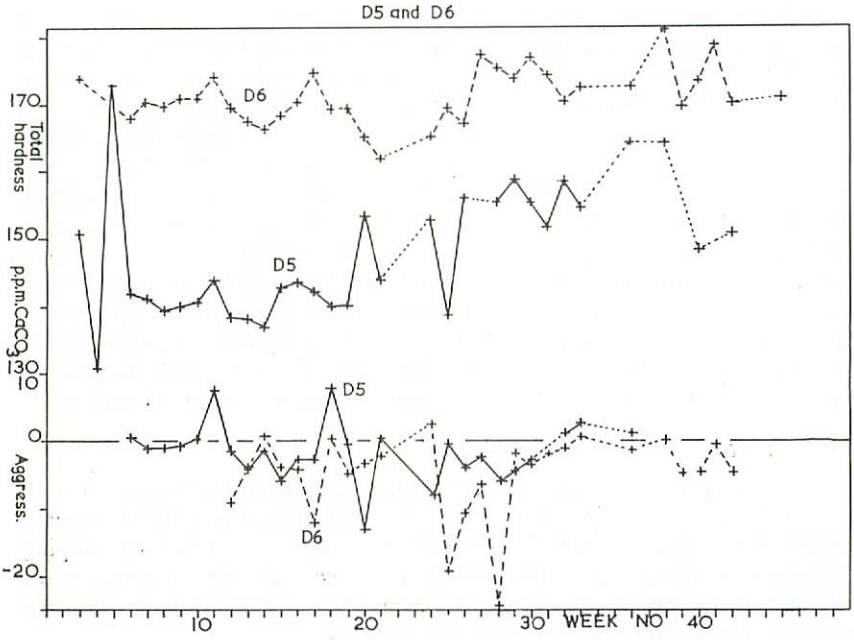

D5 and D6
170
Total hardness
150
p.p.m. CaCO3
130
10
0
Aggress.
-20
D6
D5
D5
D6
10
20
30
WEEK NO
40

Fig. 61

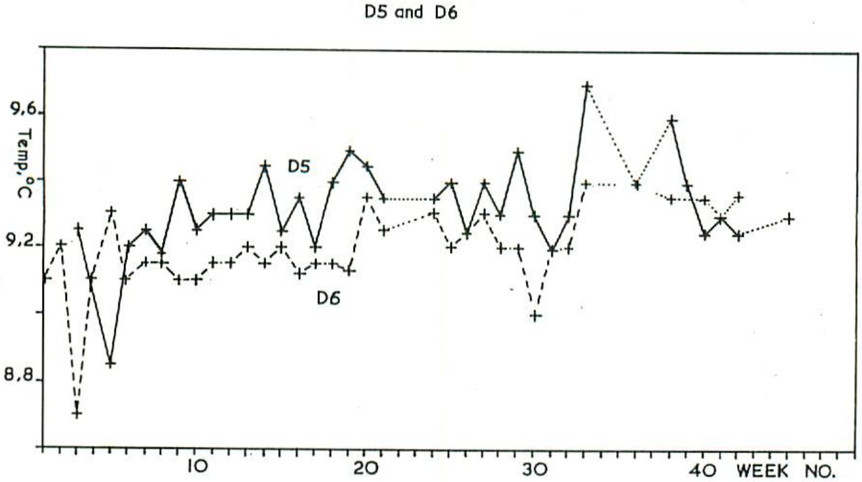


Fig. 62

White Passage Inlet

D5. *White passage fault inlet*

40 m from the Gorge, in the White Passage, is a large area decorated with active formations. The largest concentration of inlet drips is below a small stalactite-encrusted opening in the roof, 6 m high at that point. The inlet is on the line of a fault. The drip is fairly well dispersed, falling over an area of about 1 m^2, onto a large white stalagmite boss. Water collects in several crystal pools on this boss. Water samples were collected from one of these pools, and its temperature recorded. The discharge was measured by collecting the drip in a large polythene sack, two or three positions of the sack being used to ensure the collection of the large majority of the drip for the measured time. Since more water flows over and through a large number of stalactites in the roof, it was decided to study water dripping from a single stalactite, site D6, in addition to the principal drip, D5. Characteristics of the two sites are shown in Figs. 60, 61 and 62 and in Tables 14 and 15.

D6. *White passage stalactite drip*

The drip from a single stalactite was sampled for comparison with the larger inlet in the roof in White Passage. The water flows through rather than over this small stalactite, and falls 2 m onto the sloping stalagmite-covered wall. The temperature was measured directly (at the end of the stalactite) and the discharge was calculated from the time taken to fill a sample bottle of 67 cm^3 capacity.

Table 15

Characteristics of Site D6

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D. as % of Mean
Temperature °C	34	9.32	0.05	0.142	1.52%
Discharge (Q) galls/hour	34	0.498	0.035	0.100	20.1 %
Alk.hard.p.p.m. $CaCO_3$	25	153.3	1.6	3.84	2.51%
Tot.hard.(uns) p.p.m. $CaCO_3$	34	171.3	1.4	4.14	2.42%
Sat.tot.hard.p.p.m. $CaCO_3$	26	166.2	2.8	6.92	4.17%
Ca $10^5 \times M\ Ca^{2+}$	22	160.8	3.2	7.11	4.42%
Mg $10^5 \times M\ Mg^{2+}$	22	11.1	2.5	5.60	50.5 %
Non.alk.hard.p.p.m. $CaCO_3$	22	18.4	2.2	4.88	26.5 %
Aggressiveness p.p.m. $CaCO_3$	26	-4.8	2.5	6.11	127%
Na $10^5 \times M\ Na^+$	11	30.1	2.6	3.90	13.0 %
K $10^5 \times M\ K^+$	11	2.94	0.89	1.32	45.0 %
Cl $10^5 \times M\ Cl^-$	11	27.1	2.1	3.05	11.3 %
SO_4 $10^5 \times M\ SO_4^{2-}$	10	16.5	4.9	6.89	41.8 %

There was no correlation between total hardness and temperature, or aggressiveness and discharge. For total hardness and discharge the following correlation was obtained:—

Tot. hard. $= 10.4\ Q^{-0.4} + 157$ $\qquad r(32) = 0.28$

When results before and after the July flood were compared, the significance of temperature changes were less than 90%, and aggressiveness changes less than 75%. The significance of the total hardness change (169.5 to 173.2 ppm $CaCO_3$) was $>99\%$, thus a difference in total hardness before and after the July flood was again noted. As before, it is not possible to say whether this was due to the flood or to a seasonal change. The difference in temperature characteristics was revealing. For the small drip, coming through a stalactite and measured directly on emergence into the cave, no seasonal variation was found. The large drip did show a difference, and it seems likely that variations in air temperature in the cave played a part in this change.

Discussion of White Passage Drips, D5 and D6

The variability of dissolved solutes was in both cases low, although the variability of the total hardness of the fault inlet drip was appreciably higher than the other solute concentrations. Aggressiveness measurements showed that the water in the pool (fed by the fault inlet drip) was closer to equilibrium than the small inlet. Measurements taken from the pool under conditions of high discharge showed hardness values closer to those from the small inlet. Although this needs to be confirmed by analysis of water samples collected above the boss, it does seem likely that the lower hardness and aggressiveness closer to zero indicates that calcium carbonate had been deposited from the water of this inlet, the stalagmite boss has a very rough and irregular surface.

This roughness could be indicative of relatively rapid crystalline growth rather than of re-solution in this case.

The relatively small fluctuations in total hardness of the small drip, in contrast, suggested that calcite deposition was small, possibly because of the relatively high flow of the water through the stalagmite.

At each drip there was no correlation between solute concentrations and discharge.

At the stalactite drip, D6, the discharge varied much less than at any other site studied in the cave. It seems likely that the drip is part of a network of drips fed by the same source, and in high discharge conditions the extra water flowed through alternative routes.

The Oxbow Stream Inlet, S8 and S9

Small streams flowing in Rhumba Alley and Extension Passage join in Rift Chamber, and flow thence to the Loop, where a heavy drip enters from the roof. The stream then flows to the Gorge via the Oxbow. At the confluence with the Mainstream, it was not possible to measure the discharge of the Oxbow stream directly, and this figure was calculated from measurements of changes of temperature or solute concentration at the junction. It was possible on a few occasions to confirm these figures by measuring the discharge of the Main stream above and below the confluence, the difference being the discharge of the Oxbow stream. Samples and measurements were consequently taken at the point of the confluence, S9, until the July flood.

After the July flood, the stream for several weeks carried large concentrations of suspended sediment, making it impossible to measure the discharge at S9 from analyses of water samples. At the time, water temperature measurements could not be used either, and it was therefore decided to move the sampling point to the Hall, S8, where the discharge could be measured directly using a polythene sack. Site characteristics are shown in Figs. 63 and 64, and in Tables 16 and 17.

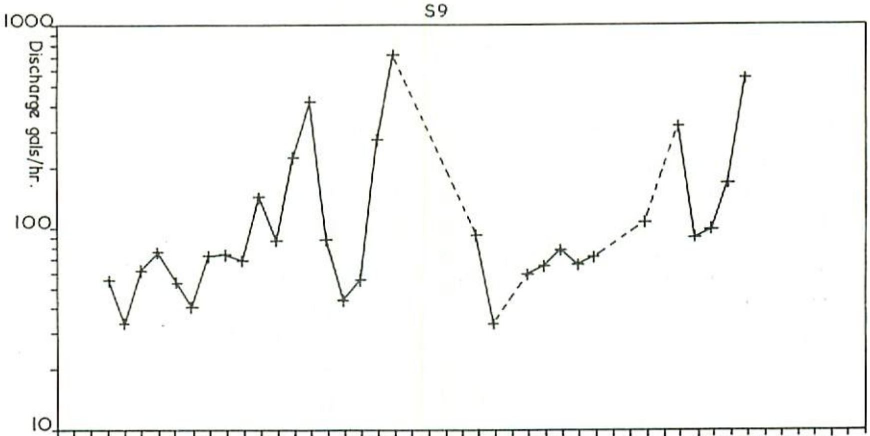


Fig. 63

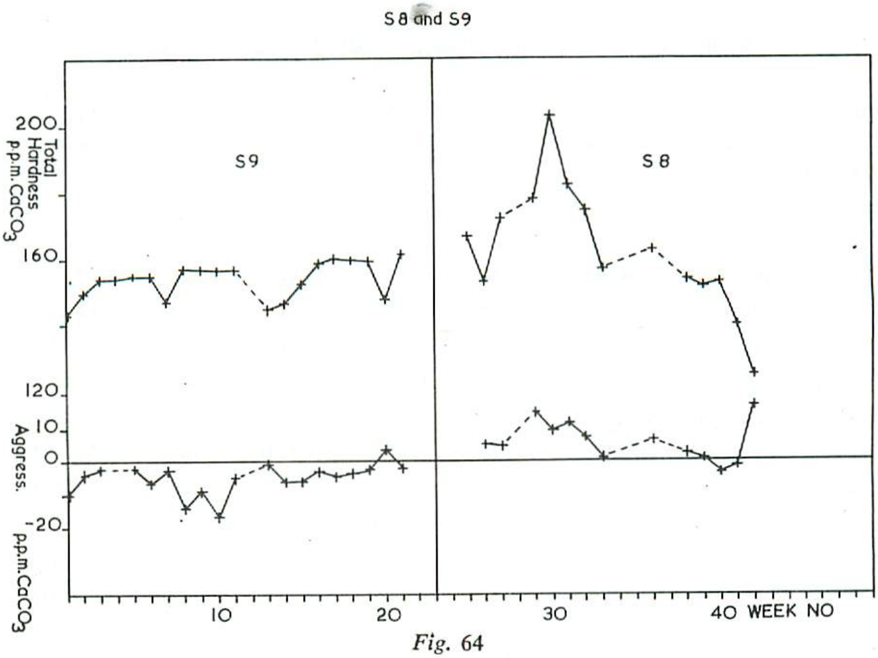


Fig. 64

Table 16

Characteristics of the White Passage stream at the junction with Main Stream, S9

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as % of Mean
Temperature °C	21	8.66	0.08	0.165	1.91%
Discharge (Q) galls/hour	18	142.9	85.5	172.2	120%
Alk.hard.p.p.m. $CaCO_3$	19	140.0	4.2	8.80	6.3%
Tot.hard.(uns) p.p.m. $CaCO_3$	19	154.4	2.5	5.24	3.4%
Sat.tot.hard.p.p.m. $CaCO_3$	18	149.6	2.9	5.85	3.9%
Ca 10^5 x M Ca^{2+}	15	140.4	6.6	5.34	3.8%
Mg 10^5 x M Mg^{2+}	16	13.6	0.78	1.46	10.8%
Non.alk.hard.p.p.m. $CaCO_3$	15	14.6	2.2	3.90	26.7%
Aggressiveness p.p.m. $CaCO_3$	18	-4.78	2.08	4.19	87.8%

Table 17

Characteristics of the White Passage stream, Oxbow, S8

Measurement	No	Mean	95%Conf of Mean	S.D.	S.D.as% of Mean
Temperature °C	14	9.27	0.11	0.191	2.06%
Discharge (Q) galls/hour	13	137.9	82.0	144.2	104%
Alk.hard.p.p.m. $CaCO_3$	14	143.1	12.8	22.0	15.4 %
Tot.hard.(uns) p.p.m. $CaCO_3$	14	162.6	11.2	19.4	12.0 %
Sat.tot.hard.p.p.m. $CaCO_3$	13	167.7	13.5	22.4	13.4 %
Ca 10^5 x M Ca^{2+}	14	152.3	9.9	17.1	11.2 %
Mg 10^5 x M Mg^{2+}	14	10.6	3.1	5.39	50.7 %
Non.alk.hard.p.p.m. $CaCO_3$	14	21.3	6.1	10.6	49.6 %
Aggressiveness p.p.m. $CaCO_3$	13	5.51	3.16	5.81	57.4 %
Na 10^5 x M Na^+	11	33.0	3.5	5.22	15.8 %
K 10^5 x M K^+	11	3.96	0.68	1.02	25.8 %
Cl 10^5 x M Cl^-	11	29.6	4.1	6.04	20.4 %
SO_4 10^5 x M SO_4^{2-}	10	13.1	6.9	9.70	74%

Correlations of site characteristics. The correlations listed below were calculated. At the Oxbow site, S8, the aggressiveness was abnormally high on week 42 of the study (1.12.1968). In spite of the long time delay, it is considered that this abnormality was a result of the July flood. When this abnormal result was omitted from the data being compared, the coefficients of correlation altered very considerably. Many other sites showed unusual results after the flood, with varying time delays. These unusual results will be considered in greater detail in Section 7.

White Passage Stream at the Main Stream Junction
Total hardness $= 11.8\,Q^{-0.4} + 153$ — $r(17) = 0.11$
$= -0.24$ Aggress $+ 154$ — $r(18) = -0.22$ .... (i)
Aggress. $= -34\,Q^{-0.4} + 0.72$ — $r(16) = -0.39$
White Passage Stream at the Oxbow
Total hardness $= 330\,Q^{-0.4} + 108$ — $r(13) = 0.70$
$= 2.5$ Aggress $+ 154$ — $r(12) = 0.78$ (excluding week 42) ......(ii)
Aggress. $= 60\,Q^{-0.4} - 5.6$ — $r(12) = 0.41$ (excluding week 42)
$= -4.0\,Q^{-0.4} + 6.2$ — $r(13) = -0.03$ (including week 42)
(the 5% probability value for 12 pairs of readings is 0.58).

There is a similarity between the regression equations linking the total hardness with aggressiveness (equations (i) and (ii)) which is very striking, and is in agreement with the hypothesis that CO_2 should be lost by the water between the two sites. The other regression equations show differences which cannot be explained so easily.

Discussion of the results

When the site characteristics of S8 and S9 are compared, a large difference in some solute concentrations is apparent. The differences of total hardness, aggressiveness, magnesium, and non-alkaline hardness need to be explained. As the stream flows from site S8 to S9, loss of

CO_2 to the cave air is to be expected, together with a consequent fall in total hardness. The total hardness at S8 was on several occasions so much higher than the figures recorded at S9 that it was decided to measure the size of the changes resulting from the CO_2 loss. In late November 1969 the White Passage Stream was sampled at both sites, under average discharge conditions, and the following results were obtained.

	White Passage Stream	
	S8, Oxbow	S9, M.S. Junction
Temperature, °C	9.30	9.00
Total hardness, $10^5 \times$ M Ca	155.2	151.6
Aggressiveness, $10^5 \times$ M	−7.8	−8.0
Magnesium, $10^5 \times$ M	14.5	14.6

If these changes of concentrations between the two sites were normal, they are insufficient to explain the differences in total hardness and aggressiveness seen in Tables 16 and 17. It may also be seen that the figures were close to the mean values at S9 (Table 16), rather than the mean values at S8 (Table 17). This suggested that if it had been possible to study the stream at the same site, a significant difference in solute concentrations before and after the flood would have been recorded. Such a change was reported in the work by Smith and Mead (1962), so normal seasonal variations undoubtedly occur in this inlet. It also seems probable that the figures were also influenced by after-effects of the July flood. Further work is needed. The characteristics of the various inlets which contribute to the White Passage Stream also need to be investigated, because changes in stream ratios may be a contributary cause of the seasonal changes which have been noticed.

5. CHANGES IN TYNING'S STREAM BETWEEN TYNING'S SWALLET AND STREAM PASSAGE

A. *The solution of limestone by the stream in the boulder ruckle between Tyning's Swallet and Stream Passage*

A comparison of the site characteristics of the stream in Stream Passage (S2) with those of Tyning's Stream (S1) shows a considerable and variable increase in total hardness. Increases in total hardness were numerically equal to increases in alkaline hardness.

Increments in calcium and magnesium were totalled separately. The average value of the molar Ca : Mg ratio of the increment was calculated. For thirteen results, the mean molar Ca : Mg ratio was 20.1 : 1. The standard deviation was 6.0.

A sample of rock was taken from the Gorge near Mud Passage. It was from the beds in which much of the cave is developed. The Ca : Mg ratio of this sample was 30 : 1, but samples taken from outcrops on the surface have a ratio closer to 15 : 1. The mean increment found in the stream lies between the two extremes, and it is safe to conclude that the increase in hardness noted between the swallet and Stream Passage is due to the solution of limestone, which reacts with carbon dioxide to produce calcium bicarbonate.

The solution of limestone between the swallet and Stream Passage was investigated by considering,

1. the increase in total hardness between the surface and Stream Passage, ($\triangle$tot in the statistics below)
2. the increase in dissolved carbon dioxide ($\triangle CO_2$ below) by subtracting the saturated total hardness of Tyning's Stream from the saturated total hardness of the stream in Stream Passage. This procedure ignores changes in equilibrium free carbon dioxide, which may be calculated but not measured directly. This reduces the values of added carbon dioxide slightly.

These two factors were compared with Q, the discharge of the stream at S2, and with the temperature of Tyning's' Stream at the surface. The results are shown in Fig. 65.

Other factors were then taken, and the results examined statistically. These results are quoted below. A third quantity, the increase in the stream's potential for dissolving limestone ($\triangle X$ in the results below) was examined at the same time.

The following symbols have been chosen (hardness in ppm $CaCO_3$).

$\triangle$tot : Total hardness, Stream Passage—Tot. hard Tyning's stream
$\triangle CO_2$: Sat.tot.hard, Stream Passage—Sat.tot.hard., Tyning's stream.
$\triangle X$: Sat.tot.hard, Stream Passage—tot.hard. Tyning's stream.
Q : Discharge of Stream Pasage, gallons per hour.
T_1 : Temperature of Tyning's stream, °C.
T_2 : Temperature of Stream Passage stream, °C.
Agg. : Aggressiveness to $CaCO_2$ at Stream passage.

$\triangle$tot $= 0.74\triangle CO_2 + 5.3$ r(16) = 0.96 .... (i)
$= 0.72\triangle X - 1.4$ r(16) = 0.98
$= 0.73T_1 + 19$ r(16) = 0.21
Agg. $= 0.06\triangle tot + 8.0$ r(16) = 0.29
Tot. hardness (Stream pass) $= 58Q^{-0.4}$ r(15) = 0.73

Considering only the figures when Tyning's stream was below 12°C, with no apparent elevation of limestone solution, the following correlations were calculated.

$\triangle$tot $= -0.032\ Q + 30$ r(10) = −0.82
$= 115Q^{-0.4} + 0.81$ = 0.99 .... (ii)
$= 0.67\triangle CO_2 + 6.4$ = 0.95 ....(iii)
$= 0.66\triangle X + 1.2$ = 0.94
$\triangle CO_2$ $= 124Q^{-0.4} + 1.25$ = 0.95 ....(iv)
Agg. $= 34Q^{-0.4} + 4.4$ = 0.67
$= -0.12T_1 + 11.4$ = −0.053
=0.46 (Agg. of Tyning's stream) +6.1 = 0.24
$= 0.32\ \triangle CO_2 + 2.9$ = 0.83 .... (v)

The 5% probability value for 10 pairs of figures is 0.64. Correlation coefficients above 0.95 are most unusual in this type of work, revealing extremely close agreement.

Discussion of the results

When the temperature of Tyning's Stream was below 12°C, the addition of CO_2 (regression equation (iii)) and the increase of total hardness (equation (iv)) were both dependent on the discharge of the stream. The correlation coefficients were so high that it must be concluded that the discharge alone was responsible for variations in the concentration of limestone dissolved.

When the temperature of Tyning's Stream exceeded 12°C, the addition of CO_2 and the increase of total hardness were both enhanced

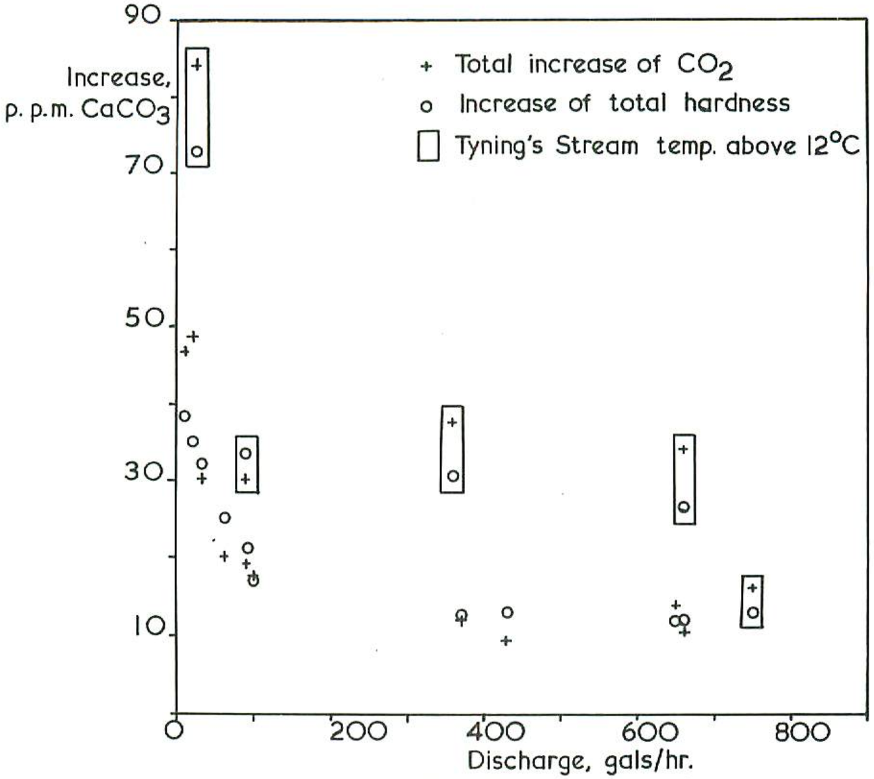


Fig. 65

(Fig. 65). This temperature effect was quite sharp. Every time 12°C was exceeded, enhancement was noted, and not once was there significant enhancement below the temperature. This enhancement was the only effect temperature had on the solution of limestone.

The correlation between the increase in total hardness and the addition of dissolved carbon dioxide (equation (i)) was very high, so the solution of limestone was dependent on the uptake of carbon dioxide, which was in turn dependent on discharge, apart from enhancement when the surface stream temperature exceeded 12°C.

The source of the carbon dioxide is unknown. It may be produced either in the water itself by biochemical oxidation of dissolved organic matter, or in the air in the ruckle by biochemical decomposition of stream-borne organic matter, or by a combination of the two. The temperature-independent relationship with discharge suggests the second source, but work in this field of limestone chemistry is still in the preliminary stage. The enhancement of dissolved CO_2 above 12°C is typical of a biochemical process, as opposed to a purely chemical reaction.

The relationship with $Q^{-0.4}$ implies a relationship with the time of passage through the ruckle, since this is the power of Q which is most closely associated with the time of the passage of a stream of water between two points with varying discharge conditions.

Although the correlation between the aggressiveness of the stream in Stream Passage with the total uptake of CO_2 (equation (v)) was high, it was decided to investigate in greater detail the factors which influenced the aggressiveness of the water emerging into the cave. The results form part B below.

The results shown in this study of the changes which took place in a short time and in a short distance may help to clarify the understanding of the chemical changes which give percolation waters their solute characteristics. Fig. 65 shows that if the water was given sufficient time, the solution of limestone in the ruckle would be high and approximately constant, and the solution would be enhanced when the temperature of the water exceeded 12°C. Temperature effects on percolation water inlets are considered again in Section 8.

B. *The limestone dissolved compared with the stream's potential for dissolving limestone*

Of the factors considered in the previous sections, $\triangle X$ represents the total potential of the stream for dissolving limestone. It follows that $\frac{\triangle \text{tot}}{\triangle X} \times 100$ represents the limestone dissolved by the stream expressed as a percentage of its potential capacity for dissolving limestone. This percentage was examined, and the following correlations were found:—

$$\begin{array}{lll}
\frac{\triangle \text{tot}}{\triangle X} \times 100 = -0.023Q + 73 & r(10) = -0.64 & \ldots\ldots\ldots\ldots\ldots\ldots \text{(i)} \\
\qquad = 27Q^{-0.4} + 63 & \qquad = \ \ 0.32 & \\
\qquad = 0.064\triangle X + 65 & \qquad = \ \ 0.10 & \ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)} \\
\qquad = -2.2\ T_1 + 87 & \qquad = -0.60 & \ldots\ldots\ldots\ldots\ldots\ldots \text{(iii)} \\
\qquad = -4.8\ T_2 + 104 & \qquad = -0.45 & \\
\qquad = 1.9 \times (\text{tot. hard Tynings}) + 24 & \qquad = \ \ 0.24 &
\end{array}$$

Discussion of the results

The percentage was dependent on the discharge, (but not, apparently, on the time in the ruckle), and on the temperature of the ruckle, shown by equations (i) and (iii) respectively. This latter correlation may at first sight appear to contradict the findings in section A, where the temperature had no effect on the limestone dissolved. There is, however, an important if subtle difference between actual quantity of limestone dissolved and the limestone dissolved as a percentage of its potential, and the two conclusions are not contradictory.

Much more interesting is the absence of dependence on the potential capacity for dissolving limestone (equation (ii)) and it is likely to be important to try to find an explanation for this.

C. *Changes in water temperature between Tyning's Swallet and Stream Passage*

When the water temperature of Tyning's stream was greater than 7.5°C, the water temperature fell as it entered the cave. On the other hand, if the temperature of the stream at the surface was less than 7.5°C, its temperature rose as it entered the cave. This indicates that the effective rock temperature between the surface and Stream Passage was 7.5°C.

Using this value it was possible to compare the temperature change between Tyning's stream and Stream Passage, $[T_1\text{-}T_2]$ (the square brackets indicate that only the numerical value of the difference is significant) with the potential change in temperature, $[T_1\text{-}7.5]$.

The change in temperature, expressed as a percentage of its potential temperature change was therefore:—

$$\frac{[T_1\text{-}T_2]}{[T_1\text{-}7.5]} \times 100$$

This value was compared with various factors, and the following correlations calculated:—

$$\frac{[T_1\text{-}T_2]}{[T_1\text{-}7.5]} \times 100 = -0.035Q + 93 \qquad r(10) = -0.61 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

$$= 80Q^{-0.4} + 70 \qquad r(10) = 0.58$$

$$= -24{,}000\ T_1 + 106 \qquad r(10) = -0.39$$

$$= -8.0\,[T_1\text{-}7.5] + 104 \qquad r(10) = -0.75 \qquad \ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

Discussion of the results

It is interesting to compare these figures with those for the solution of limestone expressed as a percentage of the potential. In both cases the discharge is an important factor (equation (i)). Equation (ii) revealed the expected relationship with the potential temperature change, $[T_1\text{-}7.5]$. This contrasts sharply with the absence of a correlation between the percentage solution of limestone with the potential for limestone solution. The views of a physicist on these findings would be most welcome.

6. THE DISTRIBUTION OF TYNING'S STREAM BETWEEN STREAM PASSAGE AND THE N.E. INLET STREAM.

Water seeps away through the stream bed of Tyning's Stream in a section between 80 and 50 metres upstream of Tyning's Swallet. This water joins a stream of unknown origin to reappear in the cave as the N.E. Inlet stream (S4). Water sinking in Tyning's Swallet reappears in Boulder Chamber, and flows through Stream Passage to the Gorge. The water in Stream Passage has only the single source, and stream flow ceases when Tyning's Stream does not reach Tyning's Swallet. The distribution of Tyning's Swallet between the N.E. Inlet and Stream Passage was calculated, and compared with the total discharge value of Tyning's Stream. The figures are known to be subject to errors because of the time difference between the surface measurements and the measurements inside the cave on those occasions when discharge values were changing rapidly. Nevertheless, Fig. 66 clearly shows that there was a definite relationship between the discharge of Tyning's Stream and its distribution between the two routes.

Fig. 66 shows that a very marked change took place in the distribution of the stream as a result of the flood of July 1968. Before this, Tyning's Swallet and Stream Passage became active when the discharge of Tyning's Stream exceeded 15 gallons per hour. After the flood the stream only reached the swallet when the discharge value reached a

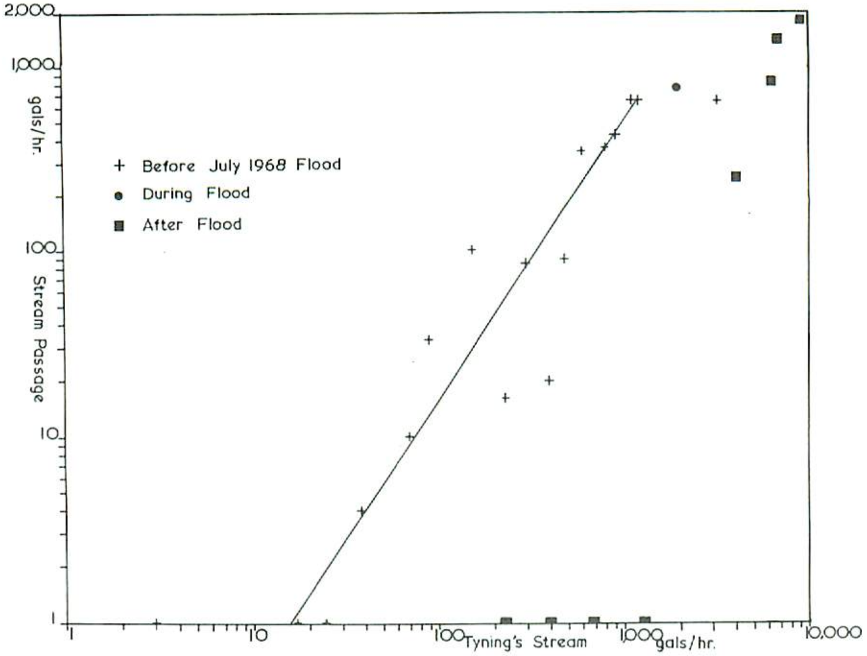


Fig. 66

much higher value, 1,100 gallons per hour. The change is thought to be due to the excavation of a definite sink 50 m upstream of the swallet. The figure recorded during the final stage of the flood still fits the pre-flood part of the graphs. This suggests that the excavation of the new sink took place after the flood, when the stream cut a new trench in the much modified stream bed, channeling the stream to the site of the new sink.

The change in stream distribution was predicted by Dr. D. C. Ford (1964), and it demonstrates one aspect of the variability of the hydrology of limestone areas. It will be interesting to repeat some measurements at a future date to find whether the change in distribution was a temporary feature, or part of a progressive trend.

7. EFFECTS OF THE GREAT FLOOD OF JULY 1968 ON THE COMPOSITION OF STREAM INLETS

After the July flood in 1968, a number of changes took place in the characteristics of the majority of the stream and drip inlets in the cave. The scale and significance of these changes are difficult to assess, because some were undoubtedly reflecting normal seasonal fluctuations. More must be known about such variations before the conclusions presented in this section can be anything more than preliminary in nature. Indeed, part of the original aim of the study was to investigate seasonal variations in the cave in a year's study. Nevertheless, it is the author's opinion that many of the changes in site characteristics that have been found represent changes which resulted from the flood. In addition to the many changes which have been noted and discussed elsewhere in this paper, the following aspects of the changes merit discussion.

Until the July flood, variations in site characteristics at several sites were remarkably small during the 21 week period between February and early July. After the flood, considerable variations were seen in many of the characteristics at these sites. By the end of the period of the study, the site characteristics had returned to their normal values. Among the site characteristics which showed considerable variation after the flood were concentrations of non-alkaline hardness (sulphate), and magnesium. These indicate that the soil chemistry above these sites had been considerably disturbed by the flood. Table 18 presents a summary of some of the changes of site characteristics which took place after the flood.

Table 18

Peaks of Aggressiveness following the Flood of July 1968 (Week no. 22)

Site no.	Aggress. weeks 1-21 Mean, (S.D.)		Aggress. week 22	Aggress. peaks, (week no. of peak)		
S1	8.65	(3.74)	7.6	N.D.		
S5	-	-	14.4	39.2(27)	24.1(33)	
S8	-4.78	(4.19)	-	14.4(29)	11.3(31)	
D1	-3.57	(2.51)	8.0	1.2(29)	3.0(33)	
D2	-11.7	(4.24)	7.2	3.2(27)	38.4(28)	0.9(33)
D5	-	-	-	N.D.		
D6	-4.15	(3.94)	-	2.4(24)	0.5(33)	
D4	-3.75	(2.59)	-	2.8(24)		

Site	Tot.hard. weeks 1-21 Mean, (S.D.)		Tot.hard., week 22	Tot.hard. peaks, (week no. of peak)	
S1	24.6	(3.50)	21.0	N.D.	
S5	104.6	(24.5)	72.2	157.2(24)	159.5(30)
S8	154.4	(5.24)	-	203.0(30)	
D1	138.7	(2.49)	134.9	148.0(27)	
D2	175.3	(3.22)	158.3	185.2(24)	181.2(29)
D5	141.6	(4.93)	-	187.2(27)	
D6	169.5	(3.30)	-	177.6(27)	
D4	159.9	(4.30)	-	177.2(25)	

Total hardness and aggressiveness figures are p.p.m. $CaCO_3$

After the flood, many of the inlet drips were milky in appearance due to a suspension of a non-calcareous material. This was known because the suspension, which passed through a Whatman No. 541 paper, did not affect the stability of the end-points of EDTA titrations, as would be the case with a calcareous suspension. Although no conclusive analyses were carried out, the suspension was probably an aluminium silicate. This was the only time such a deposit was seen in the water of these drips, and indicates that considerable and abnormal disturbances had taken place in the infilled depressions which feed the drip inlets.

Values of aggressiveness and total hardness reached unusual peaks at many sites during and after the flood. Although it is possible that some of these could be associated with a "spring burst" of microbiological activity, such as Pitty (1966) has reported in a study in Derbyshire, it is the author's opinion that the delayed peaks were much more likely to be due to two factors; a large influx of warm water into an infilled depression, and a large quantity of organic material carried into the depression by the abnormal flow of water, and subsequently broken down by biochemical processes to liberate abnormally high concentrations of CO_2. These two factors are likely to take place simultaneously. The results shown in Section 5 demonstrate that an elevated stream temperature can result in an increase in limestone solution, and temperature anomalies at drip inlets show that the temperatures in infilled depressions were likely to have been abnormally high for several weeks after the July flood.

The size of the aggressiveness and hardness peaks are shown in Table 18, in which the size of these peaks are compared with the means of data gathered at the sites in the 21 weeks prior to the flood.

Discussion of the changes in total hardness and aggressiveness during the flood

The results in Table 18 show certain important features. At sites D1 and D2 the total hardness was below the normal value, and the water was aggressive. This means that in the unusually high discharge conditions the water did not have sufficient time for the dissolved CO_2 to be saturated. At D2 the total uptake of CO_2 was slightly lower than usual, but that was not the case at site D1. Under highly abnormal discharge conditions the water at this site still had sufficient time to absorb its normal total quantity of CO_2, and the total quantity of limestone dissolved was only very slightly lower than the usual figure.

These results help to explain the solution of limestone by the waters of these sites under normal conditions. Carbon dioxide and limestone are dissolved together under conditions which approximate to equilibrium saturation of the CO_2. The water is not highly aggressive because as the aggressiveness increases the rate of solution of limestone increases rapidly.

Discussion of changes of total hardness and aggressiveness following the flood.

Table 18 shows that in many of the inlets of percolation water, large peaks of total hardness and aggressiveness followed the July flood. The size of the peaks were sometimes far beyond the range to be expected from the figures obtained before the flood. The time lag between the flood and the peak varied, and there was sometimes more than one peak. It is interesting to note that two very large peaks in aggressiveness (week 28 at site D2, week 29 at S8) were followed the next week by large peaks of total hardness.

The peaks of aggressiveness and hardness suggest that the extra CO_2 was absorbed by the water at a greater depth below the surface than is the normal case. This suggestion is consistent with organic matter from the soil being carried deeper into infilled depressions than is the normal case, and subsequently broken down by microbiological agencies to liberate CO_2.

No abnormalities were noted in the surface stream. Those noted in the N.E. Inlet stream (S5) are similar to those seen in the streams of percolation water. They probably reflect changes in the unknown branch of this stream, which has already been shown to have the discharge characteristics of a stream of percolation water.

8. THE TEMPERATURE VARIATIONS AT DRIP INLETS

The temperature variations recorded at several drip inlets need to be discussed in greater detail, especially with regard to the physical laws of heat transference. Luckwill (1965) calculated that a small stream in contact with both rock and air will tend to reach the temperature of the rock, because the thermal conductivity and the thermal capacity of limestone are much higher than those of air. The study of Tyning's Stream between the surface and Boulder Chamber (Section 5) are in accordance with his conclusions, and studies in St. Cuthbert's Swallet (Stenner 1968) showed the usefulnes of applying Luckwill's findings. There are two conditions when a small stream will fail to record the temperature of the rock. The first, (see section 5), is when the stream has insufficent time to reach the rock temperature. The higher the discharge, the greater the potential difference between the water and rock temperatures. A second condition is if the water flows slowly onto a rock projection or stalactite and is surrounded by air with a large temperature difference from the normal rock temperature at the site.

When temperatures before and after the July flood were compared, at many sites there was a statistically significant difference between the means. When the weekly temperature records were examined at sites D1, D2, D3 and D5 it was noticed that the temperatures showed large variations from the mean when the discharge was very high, and when the discharge was very low. Thus, in high discharge the water did not have time to reach equilibrium with the rock, and the drip temperature fell in winter, or rose in summer. In low discharge the drips remained on the surface exposed to air for a long enough time for their temperatures to change. This conclusion is supported by the results from site D6, where the water temperature was measured at its point of emergence into the cave, and no seasonal variation was found.

The situation in low discharge conditions is more complicated than it may seem in the preceding paragraph. First, relatively little is known about air temperatures in the cave. Until the recent development of thermistors and associated circuits, it has been difficult to measure air temperatures in a cave reliably. Air flow patterns in caves are complex, but a generalization which can be applied to a cave with a single entrance is that when atmospheric pressure rises, surface air flows into a cave system. Cold air in winter, or warm air in summer can then be clearly felt deep in large caves. In such conditions the largest temperature variation at a drip under low discharge may be expected. On the other hand, when atmospheric pressure falls, air from deep in the cave flows out of the cave. This has a temperature closer to rock temperatures, and may therefore have little effect on drip temperatures.

It seems likely that barometric records of 1968 may help the understanding of temperature records, especially in low discharge conditions.

At sites D1 and D2, very large discharge peaks were followed by peaks of temperature abnormalities, with a time lag of approximately one week. This will be discussed in section 9. Similar time lags were not found at sites D3 and D5 (the time is approximate since sampling was weekly, and larger peaks may have occured before or after sampling).

Temperature anomalies at low discharge conditions appear to overlap with high discharge anomalies at sites D3 and D4. These sites cannot be used to estimate the rock temperature through which the water had recently passed.

9. INFILLED DEPRESSIONS AND KARST HYDROLOGY

A preliminary discussion of infilled depressions has been published (Stenner 1970). Further information which supports the earlier suggestions was noticed during the compiling of this paper, making it necessary to expand the earlier speculative ideas.

In a study in Derbyshire, Pitty (1966) suggested that rainwater, entering the soil after rainfall, pushed into the caves 'older' water already present in the fissures between the surface and the cave. Results from sites D1 and D2 suggest that at these sites this suggestion does not adequately explain the site characteristics. During the July flood in 1968, when discharge values were very high, solute concentrations were depressed well below normal values, and this depression was largely compensated by increased aggressiveness. At these sites the hydrographs and temperature records show a clear time lag of one week between large hydrograph peaks and the consequent temperature peaks. Aggressiveness and solute concentration peaks followed after even bigger time lags (Section 7, Table 8). The sources of the drips also respond to rainfall in such a way that they act as reservoirs with definite time-determined discharge rates, discharging water with solute concentrations which show remarkably little variation.

The hydrological characteristics of the sites can be explained by the hypothesis of drainage via infilled depressions. A large volume of water can be held in such a depression, and the air spaces can hold large volumes of CO_2-rich air, and temperatures will vary very little except in very unusual circumstances. These conditions satisfy the requirements of the stable solute concentrations noted in percolation water in this cave and others in the Mendip Hills (Stenner, forthcoming 1974) since the majority of the solution of CO_2 and limestone would take place in the depression.

Using the concept of drainage via infilled depressions, the following account of the sequence of changes following an abnormally high summer rainstorm can be made. The heavy rainfall resulted in a very large volume of water entering the depression. This ejected the water already present in the depression, including water which had not yet reached equilibrium with the air CO_2 and the limestone, the water at first being at the stable temperature of the depression. The hydrograph peak and solute concentrations were therefore recorded by water already in the depression. The fresh input of water was big enough to significantly raise the temperatures throughout the depression, the effect being gradually passed downwards by the decreasing discharge from the base of the depression, reaching the cave after a week as a peak in the drip temperature. Meanwhile the elevated temperature in the depression increased bio-chemical activity there, producing the peaks of aggressiveness and solute concentrations with a still greater time lag. Such increases of bio-chemical activities have also been shown to be important in the boulder ruckle between Tyning's Swallet and Boulder Chamber, (Section 5).

The explanation proposed in the preceding paragraph also removed a difficulty in accepting correlations between solute concentrations and antecedent air temperatures. The paradox between the facts that temperatures can affect solute concentrations while the temperature of the subsoil does not vary with the season has been resolved.

In any limestone area the frequency and character of infilled depressions will depend very much on the geological history of the limestone. Their frequency on the Mendip Hills is still a matter of speculation, but it is a problem which could be solved easily by using modern geophysical techniques. The experience of several generations of diggers searching for caves suggests that in Mendip at least, they are very common. Because limestone solution is concentrated in the infilled depressions, subsidences, which attract the attention of diggers, are relatively frequent. Once the digging starts, the familiar conditions are met; very wet mud and gravel, intermixed with water-worn limestone boulders; frequent air spaces which enable many live toads to be dug out at 10 m depths; the whole dig bounded by fluted limestone. This may break into a pot-hole. Juvenile pots are boulder-filled, older ones will have ladder-pitches. Both types again show very marked fluting, signs of intense solutional activity in the past. If digging is continued the shafts dwindle to tiny crevices which mark the end of the accessible cave, unless, by extremely rare good fortune, the pot-hole had cut into a pre-existing cave system.

The list of such digs and small caves is great, comprising a very large proportion of the sites listed in guides for caving on the Mendips. Typical examples are Alfie's Hole, Tankard Hole, Vole Hole (Stenner 1961), Cow Hole and Ubley Hill Pot (Barrington and Stanton 1970). Infilled depressions explain the observed physical and chemical characteristics of drip inlets and risings on the Mendip Hills so well that it can be predicted that they are very much more numerous than has been suspected hitherto, and are of great hydrological importance.

10. A COMPARISON OF STREAMS IN G.B. CAVE

The discharge hydrograph of the Mud Passage inlet (D2) was smoother than that of any other inlet in the cave (Section 4, p. 188). The hydrograph was used as a basis for calculating the area drained by this inlet. The calculation for this inlet should be more accurate than any similar calculation for other inlets because of the regularity of response. However errors arise for no allowance was made to allow for the many peaks that occurred between readings. These errors will always act in the same direction to give a low value for the total area drained by the inlet. To improve the precision of the estimate, more will need to be known about the detailed short-term response of the hydrograph of the site to precipitation. It may be then possible to correct the discharge hydrograph, by estimating the size and shape of peaks between weekly readings, and so get more accurate results.

Having shown the limitations in the accuracy of the estimate for the surface area drained by site D2 (Table 19), it is nevertheless the best figure for use for comparing the surface areas drained by other inlets in the cave, using the ratio between the mean discharge of the site and the mean discharge of D2 for the same period of time (usually the time up to the flood, when records were more regular). Although it may later be found necessary to revise the figures upwards by a factor of perhaps two or more, the ratios should remain relatively unchanged, apart from the surface stream which responded so quickly to rainfall. Similarly, estimates of the volume of water held as depression storage by each of the inlets may need to be revised upwards (as has been already necessary at site D2).

Table 19

Drainage characteristics of stream and drip inlets

Site No.	Mean Discharge Gal/hr	Mean tot. Hardness p.p.m. $CaCO_3$	Est. rock temp. °C.	Depth of inlet metres	Area drained by site m^2.	Time for discharge to halve, days.	Max.vol. held by site, gals.
S1	1400	26	(i)	(i)	90,000	(ii)	(ii)
S8/9	140	154	(ii)	(ii)	10,000	4	50,000
S12	540	149	9.0	62	50,000	6	900,000
D1	0.10	141	9.1	24	6	21	160
D2	16	176	8.9	46	1,000	20	30,000
D3	1.4	131	(iii)	43	100	3	450
D4	0.6	160	(iii)	67	50	10	550
D5	4.8	152	9.3	50	300	11	4,000
D6	0.50	171	9.2	56	(iv)	(iv)	(iv)
D7	0.38	262	(ii)	131	(iv)	(iv)	(iv)

(i) Not applicable.

(ii) Not possible to estimate from the results.

(iii) Not possible to estimate because high and low discharge anomalies overlap.

(iv) Not valid to estimate from the results since the inlets are part of a linked network.

Discussion

Smith and Mead (1962) noted a relationship between the hardness of a drip inlet with its depth below the surface. This study shows this relationship is not so pronounced as they thought. However, the apparent relationship is in conflict with the hypothesis that limestone solution is dependent on soil-air CO_2 concentrations. Smith and Mead therefore suggested that the drip inlets in the shallower parts of the cave were not saturated with calcium carbonate in respect of the CO_2 content. Aggressiveness measurements, in spite of the need for care in their interpretation becaue of CO_2 losses to the air, nevertheless show clearly that this idea is untenable.

The water at site D7 was considerably harder than at other sites. The chemical and physical nature of the soil above the limestone close to the edge of the limestone is known to be considerably different to the nature of the soil farther from this boundary (Findlay, 1965). The soil, close to the boundary, through which water drains into the shallower parts of the cave, is derived largely from Lower Limestone Shales and Old Red Sandstone, transported from higher up the hillside. The soil above the limestone farther from the boundary is derived largely from the weathering of limestone. It is therefore tempting to try to explain sub-soil air CO_2 variations, responsible for variations in hardness between inlets, in terms of soil differences. The situation, however, is more complicated than has been indicated. This is because it is known that infilled depressions may be filled with material of much more recent origin, and this complication prevents any further speculation.

ACKNOWLEDGEMENTS

The research for this paper was carried out with the help and approval of the Scientific Research in Schools Committee of the Royal Society, supervised by Professor D. H. Everett and Dr. G.Nickless of the School of Chemistry of Bristol University. The author also wishes to thank D. Ingle Smith, Dr. T. Atkinson, Dr. B. Leake and Dr. D. Drew for help and advice, and many members of the Bristol Exploration Club, particularly B. Britton and R. Voke, for help in the collection of samples and data, and for help from sixth formers in the analysis of certain water samples. Technical assistance by G. Davies, D. Roberts and A. Senior is gratefully acknowledged. The author wishes to thank the U.B.S.S. for permission to work in the cave, and Professor Tratman for assistance and advice in the presentation of this paper. Finally the author wishes to thank his wife and family for encouragement and assistance during the work.

APPENDIX 1

Methods of analyses and data collection

Water temperature

Mercury-in-glass thermometers, −10 to 50×0.1°C, checked with a more accurate instrument, were used to estimate temperatures to 0.05°C. The measurement of drip temperatures with such an instrument present difficulties which were solved in the following ways. Drips with a sufficient size (D2, D6 and D7) were measured directly, allowing the water to fall onto the thermometer bulb. At D5, the water temperature of a small gour pool fed by the drip was measured. At the remaining drips, the temperature of water collected in a polythene bottle was measured. The possible effects of temperature gradients between the water and either the air or the rock supporting the bottle in the last method was looked at. Four times the temperature was measured directly at site D1, and when sufficient time was allowed for a stable reading to be reached, it agreed with the temperature of the water in the bottle.

Stream discharge

(a) *Tyning's Stream.* A portable rectangular notch weir was used. It was not installed permanently to avoid damage or loss, and to reduce the likelihood of errors due to leakage through the bank. The stream discharge was calculated from a graph published by Donnan (1952). The calibration was checked by the method (b) (below), and found to be satisfactory. In low discharge conditions, when a weir would be likely to be inaccurate, method (b) was used.

(b) *Main Stream at site S2, White Passage Stream at S8, Drips D2 and D5.* The discharge was measured by collecting the stream for a measured time in a large polythene sack, and the volume which was collected was measured with a polythene measuring cylinder. This method was sometimes used at Main Stream sites S6, S7 and S10 to check the accuracy of method (c), and it was used at site S6 whenever the discharge at S2 was too small to enable it to be used to calculate the stream sizes in the rest of the Main Stream.

(c) *Main Stream at sites S5, S6, S7 and S10, White Passage Stream at S9.*

The discharge at these sites was calculated from stream discharge ratio measurements, which were derived from water temperature or solute concentrations around the two major stream junctions. Before the July flood, the time taken to move from one stream junction to the other was sufficiently short to assume that the stream discharge at S6 was equal to the discharge at S7. The discharge values at S5, 6, 7, 9. 10 and 11 were all dependant on the accuracy of the direct measurement; by method (b), at site S3. This was checked many times by direct measurements at sites S6, S7 and S10, and method (c) was found to be satisfactory. Not only was it sufficiently accurate, but it used results and measurements made for other purposes. Furthermore it was the only method which could be used to find the discharge of the White Passage Stream, which trickles over a wide area of irregular steeply sloping rock, at its junction with the Main Stream.

(d) *Drips D3, D4 and D7.* Under normal discharge conditions method (b) was used. In low discharge conditions the number of drops falling in a measured time was counted. On one occasion the drops were collected in a small polythene bag and transferred to a measuring cylinder. The results were used to enable the drip counts to be converted to discharge measurements.

(e)*Drip D6.* The time taken to fill a container with a capacity of 67 cm^3 was measured.

(f) *Drip D1.* The number of drops falling in one minute was counted. Assuming the drop volume to be approximately constant, the numbers were converted to discharge measurements by collecting 100 drops in a 10 cm^3 capacity measuring cylinder.

Water sample collection

The majority of the water samples were collected in 250 cm^3 narrow neck, screw-capped polythene bottles. Two samples were collected simultaneously after both bottles had been thoroughly washed with the water being sampled. To one of the samples, approximately 4% AnalaR $CaCO_3$ was added, and to ensure that the sample became saturated, and the sack of sample bottles was inverted frequently. If the water was cloudy, the unsaturated sample was filtered through a Whatman No. 541 filter paper. Small drips were collected in 67 cm^3 or 130 cm^3 bottles, reducing the information that could be obtained from these samples. When sampling the surface streams, 1 litre capacity glass bottles were frequently used.

To avoid contamination of water samples, small drips were sampled on the journey into the cave, and sampling of the stream started at the Sump and continued upstream.

Chemical analyses. Determinations made with all samples

Brief details are given of the chemical techniques used. Complete practical details and a list of references consulted are available elsewhere (Stenner 1969, 1970a, 1970b, 1971).

Total hardness

25 cm^3 of the sample were titrated with 0.02 EDTA solution. The NH_4OH/NH_4Cl buffer solution contained Mg/EDTA. The Eriochrome Black T indicator solution contained hydroxylamine hydrochloride. The indicator blank reading, obtained with 25 cm^3 distilled water, was subtracted from the burette readings. 10 × 0.02 cm^3 Grade A twin-tap burettes were read to 0.01 cm^3. The EDTA solution was standardized frequently with a calcium chloride solution of known concentration made from AnalaR Ca CO_3. This solution was later checked using a standard magnesium iodate solution, and the difference was 0.02%. The standard error was estimated to be 0.8 ppm $CaCO_3$. Until the July flood, determinations were made in duplicate to ensure precision, except for the samples collected from some of the small drips. After the flood, most of the samples were not titrated in duplicate.

Calcium

25 cm^3 of the sample were titrated with 0.02 N EDTA solution. Most of the EDTA was added before adding the NaOH buffer solution and the screened murexide indicator. The standard error of the determination was 1.5 ppm $CaCO_3$.

Magnesium

This was found by subtracting the calcium concentration from the total hardness. The standard error was $1.8 \times 10^{-5}M\ Mg^{2+}$.

Alkaline hardness

25 cm^3 of the sample were titrated with 0.02 N HCl using a 10 × 0.02 cm^3 Grade B burette which was checked with a Grade A instrument. The sample was titrated to pH 4.5 using a pH meter or B.D.H. 4.5 indicator. The HCl was standardized frequently using a standard borax solution. The standard error of the determination was 1.5 ppm $CaCO_3$.

Non alkaline hardness

This was measured by subtracting the alkaline hardness from the total hardness. The standard error was 1.5 ppm $CaCO_3$.

Aggressiveness to calcium carbonate

This was the difference in total hardness between the unsaturated sample and the sample which had been saturated with $CaCO_3$. To evaluate the procedure, the change in pH on saturation with $CaCO_3$ and the concentration of dissolved CO_2 were also measured, but since the direct measurement was considerably more accurate than the other two methods, only the results of the direct method are included in this paper. The comparison of the three procedures has been discussed elsewhere (Stenner 1969, 1970). The standard error of the procedure was 1.1 ppm $CaCO_3$.

pH

Portable battery operated pH meters were used. This was done within 48 hours of the sample collection—in most cases within twelve hours. Although readings were made to 0.1 units, these types of meter are known to be inaccurate when solute concentrations are low.

Chemical analyses. Determinations made at irregular intervals

Sodium, potassium, lithium and strontium. Concentrations of these metals were determined by flame emission photometry. A Unicam SP920 spectrophotometer was used, burning mixtures of either air and acetylene or air and propane.

Chloride. 25 cm^3 of the sample were titrated with 0.02 N $AgNO_3$ using

5% potassium chromate indicator, subtracting the indicator blank from the volume of silver nitrate added.

Sulphate. 1 cm^3 of the sample in the acid form (see total anion) was shaken with 4 cm^3 propan-2-ol and 12.5 mg purified barium chloranilate. After centrifuging, the absorbance was measured at 310 nm with a Unicam SP800 u.v. spectrophotometer calibrated with standard H_2SO_4 solutions.

Fluoride. The absorbance of the ternary complex formed by the fluoride and cerous ions with Alizarin Complexone reagent in a buffered solution was measured at 617 nm with a Unicam SP800 spectrophotometer calibrated with standard NaF solutions.

Phosphate. Assuming metaphosphates to be absent, the Denigé method was used. The absorbance was measured at 670 nm, the spectrophotometer being calibrated with standard potassium dihydrogen phosphate solutions.

Total anion. 25 cm^3 of a sample were converted to the acid form using a 12 × 1.5 cm column packed with Dowex 50 W-X-8 resin (100-200 mesh) in the H^+ form. After boiling off CO_2, samples were titrated to pH 4.3 with 0.02 N NaOH using a Pye Dynacam pH meter.

Dissolved silica. A colorimetric procedure using ammonium molybdate was chosen. The absorbance at 400 nm was measured in 4 cm cells using a spectrophotometer calibrated with standard solutions of sodium fluorsilicate.

Trace elements determined by X-ray fluorescence spectrometry following concentration in disks of ion exchange papers. Trace elements, both cation and anion, were extracted from 100 cm^3 samples into 3.5 cm diameter disks of SA2 and SB2 Amberlite ion exchange paper (in H^+ and OH^- forms respectively).

After drying the disks were analysed using a Phillips Universal Vacuum X-ray Spectrometer PW 1540, with a tungsten X-ray tube, and either a lithium fluoride crystal with a scintillation counter or a pentaerithriotol crystal and a gas-flow proportional counter, depending on the Atomic Number of the element.

Analysis for S, P, Si and Al were made using a Phillips Automatic X-ray Spectrometer PW 1212, with a chromium X-ray tube and a pentaerithritol crystal and a gas-flow proportional counter.

APPENDIX 2

The Presentation of the Results; Chemical Units and Statistics

Units chosen for solute concentrations. In Table 1, the calcium concentrations are presented as $10^5 \times$ M Ca^{2+}, which is 10^5 times the calcium concentration in gram ions per litre of the water. The molecular concentration of calcium carbonate is 100.09, so within the precision of the practical methods, this unit is numerically equal to the calcium concentration expressed as parts per million (ppm) of calcium carbonate, which is a unit in wide use by hydrologists.

The large quantity of data embodied in this paper would be incomprehensible without methods for making detailed summaries of the results. This is done by using statistical procedures. Readers with no prior knowledge of statistics will be able to learn a great deal from the tables and correlations in the report, once they have learned the basic conventions of the subject. These are outlined.

In Table 1, temperature results are presented. The mean, 8.82°C, is the arithmetic mean (or average) of the 39 measurements. The 95% Confidence of the mean shows that there is a 95% probability that the *true* value of the mean (such as would have been given by continuous measurments rather than periodic measurements) would be within 1.51°C of the arithmetic mean. The Standard Deviation (S.D.) is the measure of the scatter of the measurements about the mean. In this case, the value 4.62°C shows that 68% of the measurements lay between 13.4°C and 4.2°C (the mean ±4.62°C); 95% of the readings lay between the mean ±9.24°C, and 99.7% between the mean ±3 × S.D. The values of the S.D.s are also shown as a percentage of the means, and this shows at a glance the degree of variation of a parameter at a site. Thus it is noticed from Table 1 that the saturated total hardness (the total hardness of a sample that had been saturated with pure $CaCO_3$) showed a very much smaller degree of variation than the alkaline hardness.

It is often very useful to compare two sets of data to find if there is any relationship between them. This can be done graphically, but it is both clumsy and expensive to publish the results of a large number of such comparisons pictorially. There is a statistical procedure for reducing the information to a regression equation and a coefficient of correlation. The regression equation is the equation of the line best fitting the data. The line may be curved or straight. The coefficient of correlation, r, is a measure of the spread of the measurements around the "best fit" graph. With 10 pairs of results, if $r = 0.65$ there is only a 5% probability that the correlation could be due to chance, so the correlation is probably true. With 20 pairs of samples, the correlation is significant at the 5% level if $r = 0.45$. For 100 pairs of results, the correlation is significant at the 5% level if $r=0.20$. Conversely, if r is less than 0.65 with 10 pairs of results, there is a greater than 5% probability that the correlation could be due to chance, so the correlation is doubtful. Two correlations, one very high and one low, are shown graphically in Fig. 67.

When data collected before and after the July flood was compared, a procedure known as the t-distribution test of significance was used. This is a test to determine whether the difference between two mean values is significant or not, considering the standard deviations and the numbers of the measurements, using a formula worked out for small numbers rather than an approximation valid for large numbers only. The use of the test is illustrated in the site characteristics of the North-east Inlet Stream, S4 and S5.

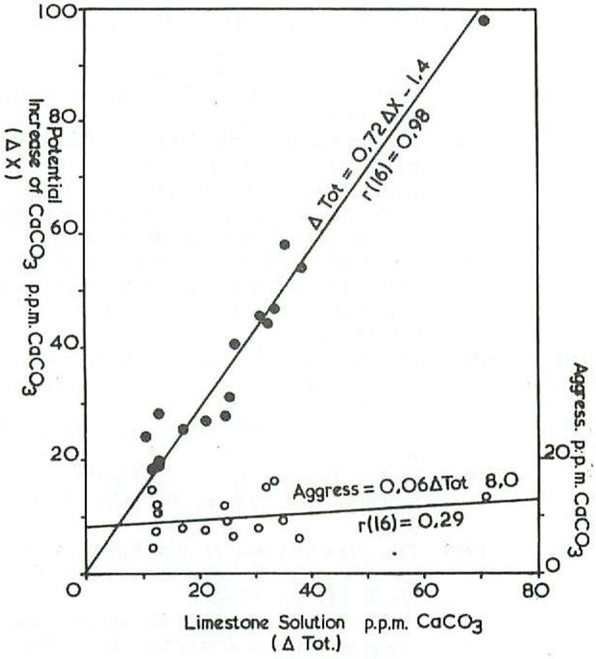


Fig. 67

APPENDIX 3

The collapse in Doline III, caused by the flood of 10*th July* 1968

[This has been withdrawn together with Fig. 68. The total collapse of Doline III into the cave has made the major part of the appendix obsolete.—*Editors.*]

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