Proc. Univ. Bristol Spelaeol. Soc., 1982, **16** (2), 143-159.

THE CLASSIFICATION OF AUTOGENIC PERCOLATION WATERS IN KARST AQUIFERS: A STUDY IN G.B. CAVE, MENDIP HILLS, ENGLAND

by

H. FRIEDERICH and P. L. SMART

ABSTRACT

A detailed examination of the possible sub-divisions of autogenic percolation cave inflows, employing data from G.B. Cave, Mendip Hills, generally supports previous classifications. Two major groups comprizing quickflow and baseflow can be further sub-divided into four classes which correspond with the general morphological descriptions: subcutaneous flow, shaft and vadose flow, percolation streams and seepage flow. The most important properties of percolation flow behaviour are maximum discharge, reflecting fissure transmission capacity, and discharge variability, reflecting available storage. Classifications based on carbonate hardness are considered of limited use due to the possible evolution of percolating water with depth, and to differences in the nature of recharge area. However, the variability of carbonate hardness is related closely to variability in discharge and functions equally well as a discriminatory variable.

INTRODUCTION

Recharge to karst aquifers can comprise either autogenic waters derived by direct infiltration from the exposed surface of the limestones, or allogenic waters which are derived from the surrounding rocks. In most situations the latter enter the limestone as discrete streams and are thus also described as concentrated recharge, while the former are predominantly diffuse or percolation recharge; "water which does not enter the channel of a surface stream either by direct run-off or through-flow prior to sinking underground" (Drew 1968, p. 107).

Autogenic percolation waters, when observed in caves, cover a wide range of flow characteristics, and a number of previous attempts at classification have therefore been made. Gunn (1974) defined 'slow' and 'fast' drips, in terms of the volume of water discharged per day. Smith, Atkinson and Drew (1976) proposed a quantitative classification into fast and slow percolation flow, for which they used the terms 'vadose trickle' and 'vadose seepage'. In a recent publication, Gunn (1981) used the physical size of the inlet as the criterion for three types of flow, which he labelled 'vadose seepage', 'vadose flow' and 'shaft flow', with increasing discharge.

In contrast to these quantitative classifications, Mangin (1975) proposed a functional classification of percolation flow, which was subsequently used by other French scientists (Bakalowicz 1979, 1981). He made the distinction between rapid percolation (*infiltration rapide*) and slow percolation (*infiltration retardée*). These two divisions are identical to Atkinson's (1977a) classes 'quickflow' and 'baseflow'. Atkinson's 'quickflow', however, incorporates swallet water (concentrated recharge) as well as rapid percolation flow. The last two studies are based on an analysis of the discharge hydrographs of karst resurgences. The present study attempts to achieve a classification on empirical grounds, from actual flow measurements within the unsaturated zone.

METHODS

Twenty percolation water inlets in G.B. Cave, Charterhouse-upon-Mendip, Somerset (entrance: ST 476.562) were monitored closely during the 1978/79 water year and the following months of the 1979 calendar year (Friederich 1981). G.B. Cave is within the catchment of Cheddar risings (ST 466.539), and has been described in detail by Ford (1964) and by Stenner (1973). A revised survey of the complete cave system was published by the University of Bristol Spelaeological Society in 1969 (Savage 1969). Recently the accuracy of this survey was confirmed to be within a spatial error of 5m (Friederich *et al.*, 1981). Figure 36 is based on the survey, with the sampling points added. These points are listed in Table 1.

TABLE 1

Percolation inflows measured in G.B. Cave from 1 November 1978 till 1 November 1979

Inflow Full name and abbreviation		Class	Depth below surface (metres)	Average discharge (l/hr)	Number of measure-ments
Entrance Passage Blockhouse	ENB	2	10	0.7	41
Entrance Passage	ENP	2	15	2.5	55
Entrance Chamber	ENT	1	27	1.9	74
Upper Grotto Slow	UGSL	3	27	1.2	28
Upper Grotto Fast	UGF	2	27	4.0	28
Ooze Aven	OAV	1	40	(30)	26
Top of the Gorge	GOTO	1	46	18	35
Mud Passage	MUD*	4	53	440	168
White Passage Percolation Stream	WPPC	4	50	140	69
White Passage Overflow	WPOV	2	53	200	50
White Passage Aven	WPAV*	1	55	58	114
White Passage New	WPNW	1	60	16	45
White Passage 4	WP4	3	47	0.4	130
White Passage 3	WP3	3	60	1.6	138
White Passage 2	WP2	3	60	2.6	217
White Passage 1	WP1	1	60	(13)	10
Rift Chamber	RI	3	63	0.6	33
Rhumba Alley	RA	3	63	1.2	24
Hall Aven	HAV	1	78	(40)	—
Hall Slow	HSL	3	82	0.23	24
Gorge Hall Junction	GOHA	3	82	0.53	32
Gorge, Top of the Pitch	GOPI	3	82	0.64	32
Gorge, Twisted Stalactite	GOTW	3	115	0.32	23
Great Chamber Fast	GCF	1	131	4.4	22
Great Chamber Slow	GCSL	3	135	0.86	21

Discharges in brackets are order of magnitude estimates only.

* discharges of 1979/1980 water year were used.

The simplest method of percolation flow measurement, which suffices if only changes in discharge are investigated, is to count the number of drops falling from a stalactite per unit of time (Pitty 1966; Halliwell 1970). Usually the counting is carried out by the investigator in person, but Gadoros (1966) describes a device consisting of two parallel copper wires which short an electric circuit when a drop passes between them, and which can be connected to a remote recording instrument. Stenner (1973) inproved this qualitative method by calibrating the number of drops against the total discharged volume of water, thus enabling quantitative measurements to be made. Gunn (1974) preferred to measure the time needed to fill a plastic container of known volume, a method which was also employed by Stenner (1973) for large percolation inflows, and by Habic and Kogovsek (1979). In a later study Gunn (1981) also used a standard recording raingauge to measure the flow of a number of percolation inlets continuously, but as Gadoros (1966) pointed out, a raingauge can only be used in large, easily accessible caves and only for short periods. Gadoros describes a specially designed percolation water measuring instrument, which is based on the tilting bucket principle. The major drawback with this instrument was the small volume of the collecting bucket, which was only 4-5 ml.

A variety of methods were employed in this study. During each visit to the cave, discharge at most inflows was measured manually, by recording the time required to fill a bottle of known volume. Timing was carried out with a stopwatch, and showers or multiple inflows were collected in a funnel. If this was not practicable, a fraction of the flow was measured, and the total discharge of the inlet was estimated as a multiple of the measured flow. A range of bottle sizes from 18 to 1080ml was used, the decreasing error in volume measurement being balanced by the increasing timing error associated with the larger inflows. The total error in each measurement is 3%-5%, although discharge in excess of 200l/hr may be less accurate. However, the additional error involved in estimating the total discharge from measurements of a fraction of the flow is large, a fact which will be discussed later.

In addition to the manual measurements, several percolation inlets were monitored continuously during the period of research. Large inflows were measured by leading the total flow into a weirbox with a Munro horizontal waterlevel recorder (Type IH 125 and IH 126). Waterlevel was calibrated against discharge whenever this was measured manually. Small flows were measured with a tipping bucket system (Plate 9). Each bucket contained nominally either 150 ml or 200 ml, and the balance of the two buckets could be adjusted by calibration screws. Each instrument was calibrated individually, with accuracies varying from 1% to 3%. The buckets were eventually fitted with reed switches (R.S. Components Ltd.), and these functioned satisfactorily. The switches were mounted on the instrument with araldite (Ciba/Geigy Ltd.) but this two component epoxy adhesive became soft after two months underground. This problem was not solved, and instruments had to be taken back to the laboratory to be re-fitted after such a failure.

Each measuring unit was connected with to a clockwork driven, six channel event recorder (Edgecoombe - Peebles Ltd., Glasgow) or to a home-made recorder consisting of a solenoid mounted on a standard, single channel, battery chart recorder (Rustrak Instruments, Brighton; type 288). Every time the bucket tipped, the reed switch shorted a circuit, and the solenoid deflected, marking the chart. The spacing of these marks on the chart indicated the flow rate of the monitored inlet. The charts were linearized and digitized with the SCANS program of the PDP 8/DMAC system of the University of Bristol Computer Centre. Some gaps exist in the flow record, mainly due to exhaustion of the rechargeable, sealed, lead-acid batteries used for power. Tipping buckets were used to monitor WP2, WP3, WP4 and occasionally WP1 and WPNW. The combined flow of UGF and UGSL was also measured with a tipping bucket.

A long term record was obtained from the shower inlet in Mud Passage (MUD) by an unusual method. The water from the shower was collected in a natural hollow in the floor of the passage, behind a small concrete dam with an overflow pipe. A beaker of known volume, waterproof notepaper and a pencil were left behind, and a notice was installed urging fellow-cavers to measure the flow and to record the reading. Thus a semi-continuous flow record was obtained from MUD, from 24th October 1979 until 20th May 1980. The variation in discharge measured during any day was 5% or less, but the rapid variations in flow after heavy rainstorms suggested that peakflows were not always recorded. Comparison of this semi-continuous flow record with the discharge record from the previous

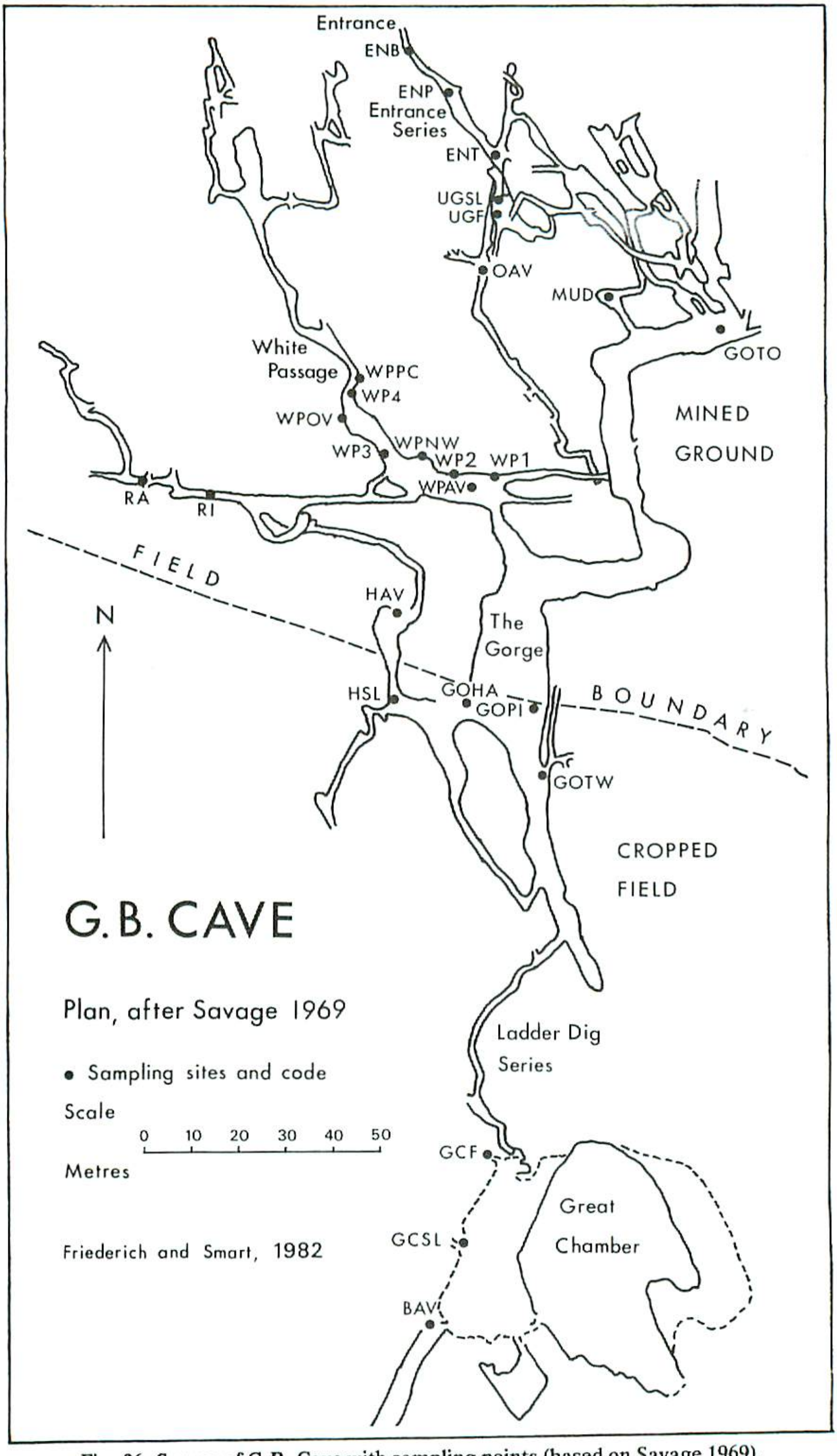


Fig. 36. Survey of G.B. Cave with sampling points (based on Savage 1969).

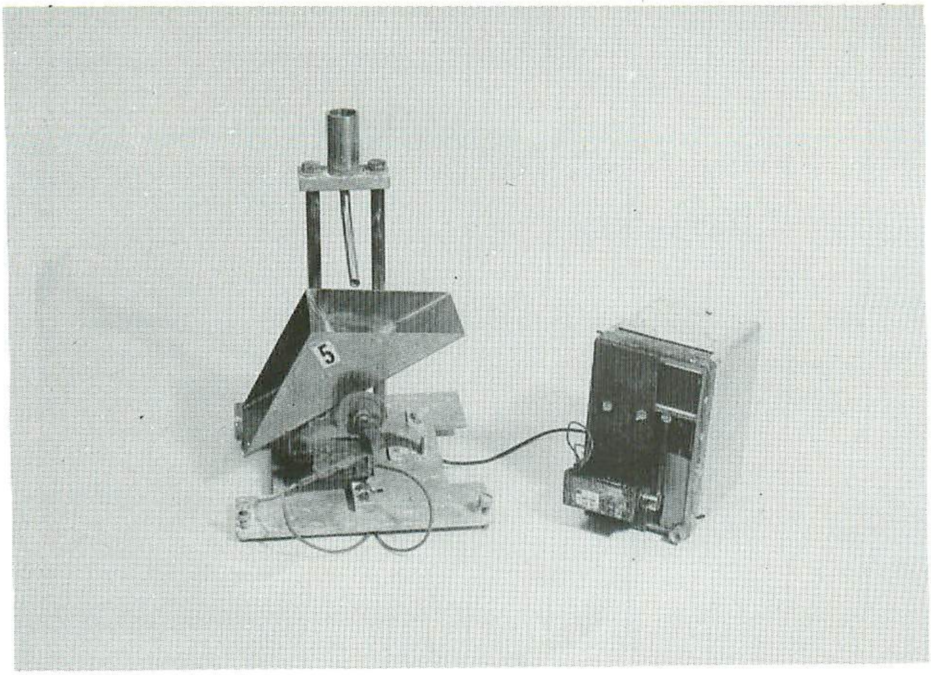


Plate 9 The tipping bucket and event recorder used for continuous monitoring of inflow discharge. The base of the bucket is 190 mm long.

winter, showed a marked lack of detail in the early record obtained by manually measuring a proportion of the flow from the shower, and estimating the total discharge. Figure 37 suggests that the infrequent manual measurements give rise to gross underestimates of the high discharges. Stenner (1973) used a similar method at this particular inlet. Consequently his figures for the maximum discharge, and the calculated drainage area for this inlet, are probably underestimates.

During the year 1979 water samples were collected from 20 inlets in G.B. Cave to be analysed for the major inorganic chemical species. The samples were collected in glass bottles at weekly intervals, but not every inlet was sampled during each visit. They were returned to the laboratory of the Department of Geography, University of Bristol, and within 24 hours alkalinity, pH and conductivity were determined. This procedure was shown to yield identical results to analyses made at the time of sample collection in the cave. Calcium was analysed at a later stage, after acidifying the water samples, usually within the week. The analyses were carried out by titration, using the methods described by Stenner (1969).

Rainfall was measured continuously on the surface above the cave using a Casella Tilting Siphon Autographic Raingauge. The potential evapotranspiration calculated from climate data provided by the Long Ashton Research Station (ST 534.695) was used to calculate weekly estimates of soil moisture deficit and effective precipitation using the method of Grindley (1967).

HYDROLOGICAL CLASSIFICATION OF AUTOGENIC PERCOLATION WATER

Figure 38 presents discharge data for the monitored inflows in G.B. Cave from October 1978 to June 1980. The smallest inflows measured had peak discharges of about 0.5 l/hr, while the largest exceeded 2000 l/hr. Despite these differences, similarities in behaviour are evident at this timescale. Many inflows show rapid response to rainfall, as can be seen by their behaviour following the heavy storm of 30 May 1979. This indicates a high transmission capacity in the fissures feeding the inflow, a property also partially reflected by the inflow discharge itself. Those sites showing the largest and most rapid response also exhibit an

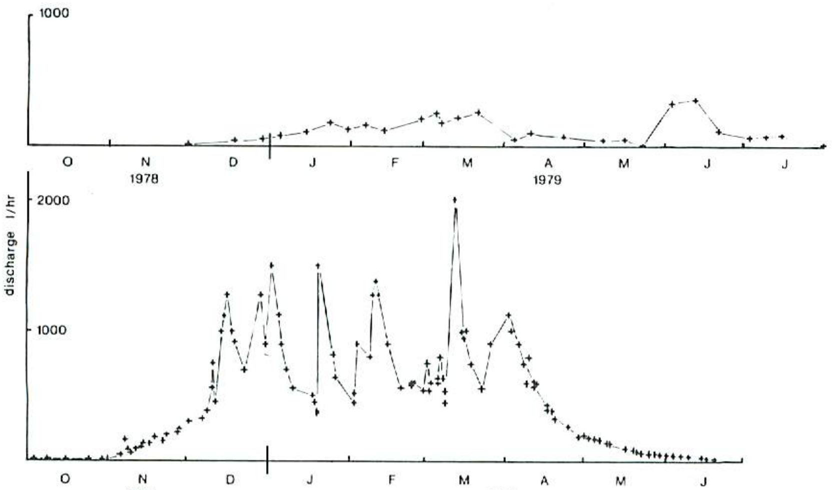


Fig. 37. Discharge record for MUD during 1978/79 (weekly observations) and 1979/80 (semi-continuous observations).

equally rapid recession, indicating they draw on limited storage. Some inflows, such as WPOV, stop completely during dry periods indicating insufficient storage to maintain discharge. In contrast, those inflows showing relatively little response to rainfall have long very gently sloping recessions, indicating a relatively large amount of storage. It is apparent that both transmission and storage characteristics are significant in controlling the behaviour of percolation inflows. The maximum discharge is here used to reflect the transmission capacity, while discharge variability is an indication of relative storage (stored volume relative to discharge). These two variables can now be used to group inflows.

The coefficient of variation (CV_Q the quotient of the standard deviation and mean discharge expressed as a percentage), provides a convenient dimensionless measure of discharge variability. For inflows with infrequent periodic manual estimation of discharge, CV_Q will be a minimum value due to underestimation of peak flows. For this reason WPAV and MUD data for the water year 1979/80 are employed, all other data being for the year 1978/79. Inflows which are periodically dry will conversely give very high values of CV_Q depending on the number of zero and non-zero observations. Figure 39 presents a graphical plot of maximum discharge and coefficient of variation for the sampled inflows. Several classes can be separated as follows:

Class 1. Inlets with moderate to high peakflows (more than 5 l/hr), and small relative storage (CV_Q more than 0.5). The range of discharge in this class is wide. The class corresponds morphologically to shaft flow in the form of showers from open avens, and vadose flows from smaller openings in the roof or wall, which are generally of lower discharge.

Class 2. Inlets which are dry during certain periods of the year, giving high CV_Q (more than 1.5). This class can be described as an extreme form of Class 1, with storage that is exhausted after a long period with no recharge.

Class 3. Inlets with low maximum discharges (less than 5 l/hr) and high relative storage capacities (CV_Q less than 0.5). Morphologically all these inlets represent water dripping from stalactites. GOTW, which has a CV_Q of 0.7, morphologically forms part of this class. The high CV_Q, which would exclude it from Class 3, is a result of one discharge overestimate in March 1979. Class 3 flow is here called seepage flow.

Class 4. WPPC (the only inflow in this class) is an inlet with a seepage flow behaviour, but with a maximum discharge which exceeds the flow of most inflows in G.B. Cave. It is here called a percolation stream. Possibly WPPC represents a collective discharge of many Class 3 seepage inlets, but percolation water traces indicate that it is not derived from local recharge. Analyses of the radon concentration in the water from several inlets in G.B. Cave, suggests that WPPC represents underground leakage from the Old Red Sandstone or Lower Limestone Shale aquifers (Friederich 1981).

When the hydrograph for MUD was analysed in detail, it was discovered that the storage capacity of this inlet is also considerable,

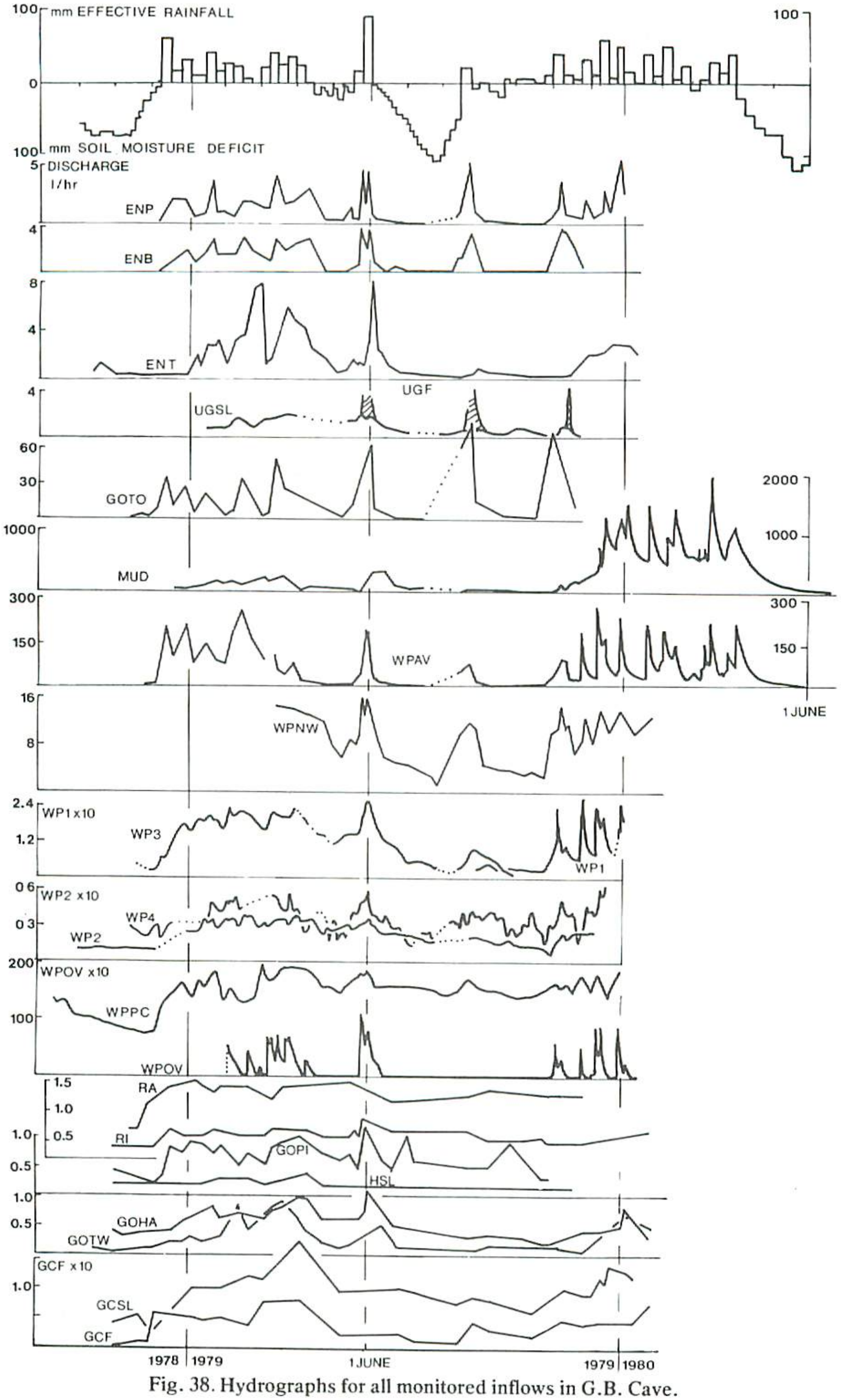


Fig. 38. Hydrographs for all monitored inflows in G.B. Cave.

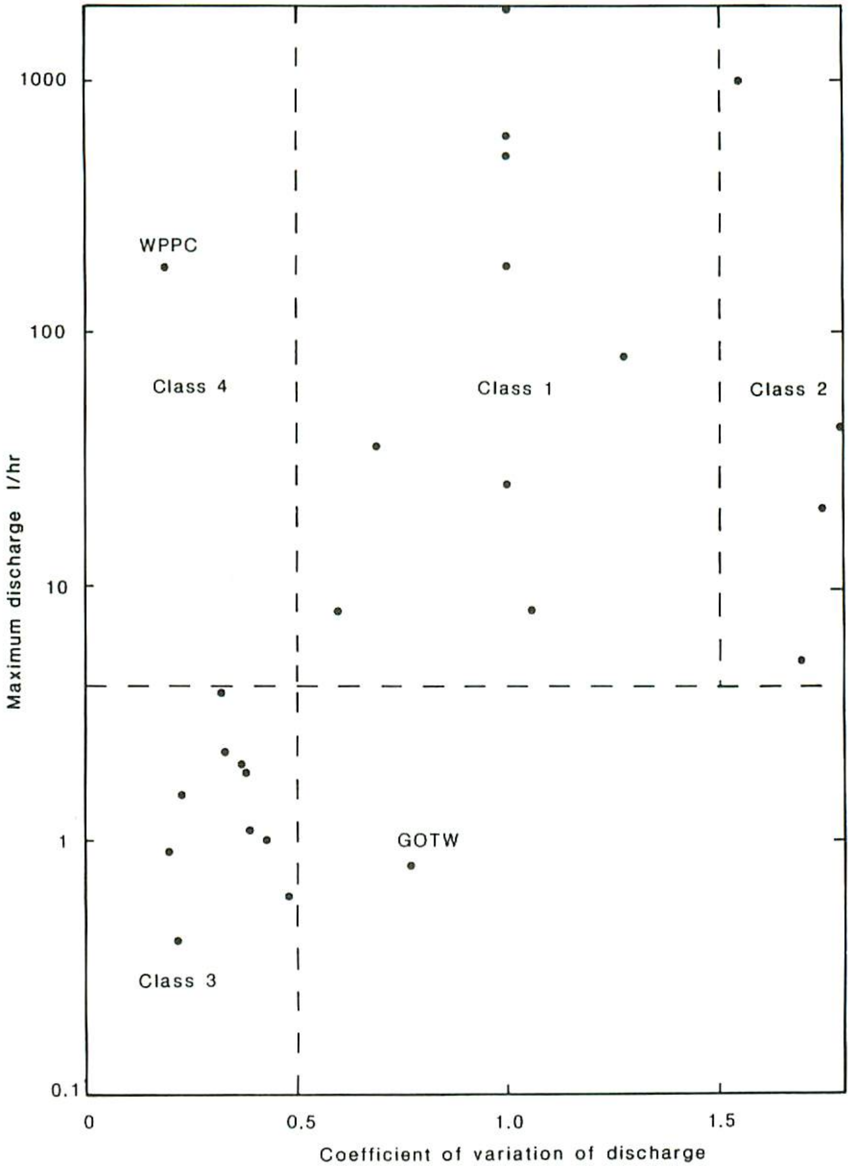


Fig. 39 Grouping of percolation inflows based on maximum discharge (Q_{max}) and variation in flow (CV_Q).

compared to other Class 1 inflows. Despite the differences in coefficient of variation, the two inflows WPPC and MUD are therefore included in Class 4 as percolation streams.

It must be stressed that all the measured inflows in G.B. Cave merely represent points in a natural continuum; the exact boundaries between the defined classes are therefore somewhat arbitrary. However, the very low upper limit of 200 ml/hr adopted by Gunn (1981) for seepage flow cannot be accepted in this study because very few sites with such a low discharge were observed in G.B. Cave.

The ill-defined nature of the boundaries is particularly evident between Class 1 and Class 2, and between the two morphological subgroups within Class 1; vadose flow and shaft flow. When the cumulative discharge frequency distributions are presented for several inflows, this problem is highlighted (Figure 40). Seepage flow (Class 3) is readily separated from the combined Class 1 and Class 2 inflows, having mean flows which are approximately equal to half the maximum discharge. Class 1 or Class 2 inlets, in contrast, both have mean flows which are only 10% of the maximum measured discharge and cannot be readily separated. The lack of variation of flow from WPPC is illustrated by the mean flow of this inlet which is approximately 80% of the maximum measured flow. It is therefore suggested that the classes should be amalgamated into 2 groups, 'quickflow' and 'baseflow' (Atkinson 1977a). WPPC and Class 3 flow form the baseflow component, and the combined Class 1 and Class 2 flows represent quickflow (Figure 41).

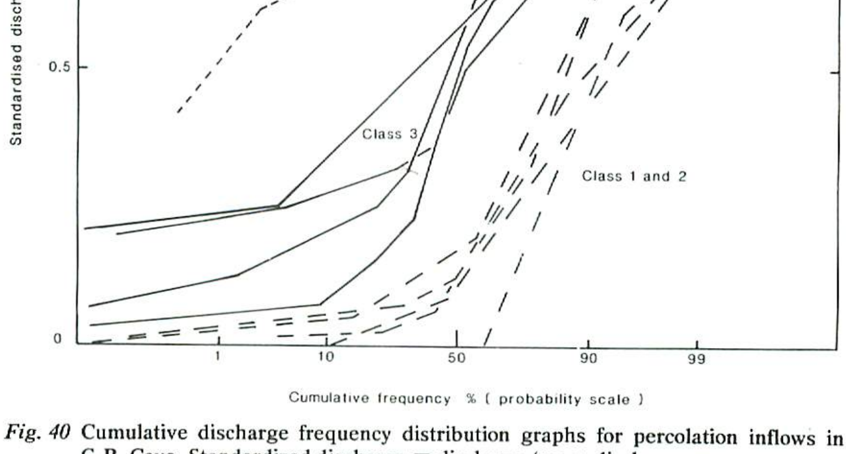


Fig. 40 Cumulative discharge frequency distribution graphs for percolation inflows in G.B. Cave. Standardized discharge = discharge/mean discharge.

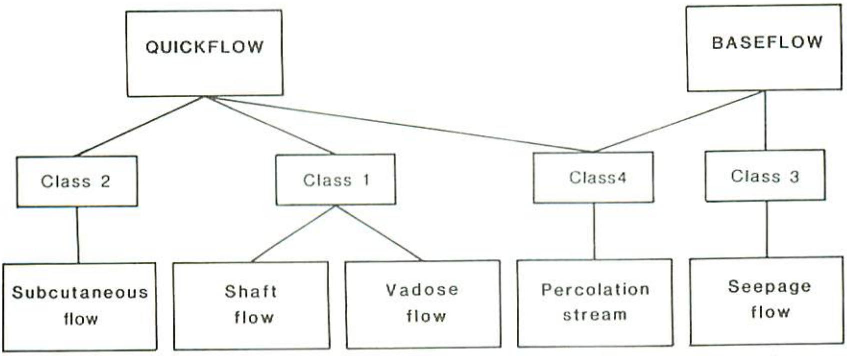
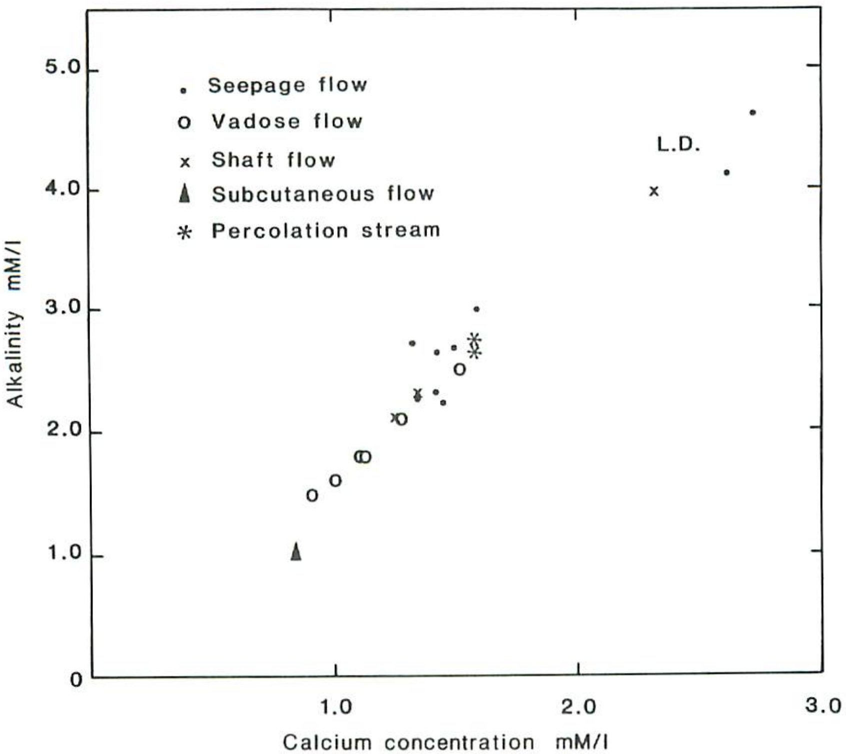


Fig. 41 Percolation flow types in G.B. Cave, based on hydro-dynamic grounds.

Class 2 inlets were grouped on account of their high variation in flow. This, in turn, was predominantly controlled by the fact that these inflows are dry during certain times in the year. However, close examination of the behaviour of the entrance inlets (ENB, ENP) showed that they respond differently from the deeper WPOV and UGF. The former inflows simply dry out after a long period of no recharge, and their flow decreases exponentially. In fact, these inflows may still have yielded minimal volumes of water, when they were considered to be dry. WPOV, in contrast, is dry for half of the year. During 334 days (7 February 1979 to 8 January 1980) the inlet only flowed for 131 days. The recession of flow at WPOV is nearly linear, and the ratio of storage capacity and peakflow for one storm is only 50, compared to 250 for ENP and 500 for ENB. The latter figures are similar to those for Class 1 inlets, again suggesting that Classes 1 and 2 are best amalgamated. WPOV will be described as 'subcutaneous flow' after Gunn (1981), because tracing experiments with fluorescent dyes suggested that the recharge for WPOV is concentrated in the upper 5 metres of the unsaturated zone (Friederich and Smart 1981). The five final flow types are summarized in Figure 41, together with their classes and groups.

CHEMICAL CLASSIFICATION OF PERCOLATION WATER

Gunn (1981) has shown that calcium hardness alone provides an adequate discriminator in separating various classes of percolation flow. However, the controls on the chemical evolution of percolation water are complex and involve factors not directly related to their hydrology. For instance Smith and Mead (1962), Ford (1966), Stenner (1973) and Atkinson (1977b) suggest that there is a positive relation between percolation water hardness of cave inflows and their depth below the surface, probably due to chemical evolution of the percolating waters. It is also widely recognized that soil carbon dioxide concentrations which vary between different soil and vegetation types even in the same climate are the dominant control on percolation water hardness (Bogli 1969, Jakucs 1973, Miotke 1974, Bögli 1978). Thus calcium hardness alone will only prove useful in providing a hydrologically significant grouping of percolation waters if both spatial variations in soil CO_2 and evolution with depth are unimportant.



L.D. : Inlets in Ladder Dig extensions.

Fig. 42 The relation between alkaline hardness and calcium hardness for all monitored inflows. The points represent yearly average values for 1979 water year.

When the average annual calcium concentrations and alkalinity of percolation waters sampled in G.B. Cave are plotted (Figure 42), it is apparent that there is some overlap between seepage flow and the shaft flow/vadose flow classes, but in general calcium concentration would be sufficient to separate the two groups baseflow and quickflow. However, it is also clear that the points labelled LD are exceptions to this general relationship. These points represent inflows sampled from the Ladder Dig series, which forms the deepest and most southerly portion of G.B. Cave. The carbon dioxide partial pressure (PCO_2) in equilibrium with each water sample was calculated using the WATSPEC water speciation program (Wigley 1977), and the average values for seepage flow are given in Table 2. It is clear that the Ladder Dig waters have evolved in equilibrium with a much higher PCO_2 than seepage flows from the remainder of the cave. This is due to the presence of deep loamy agricultural soils over the Ladder Dig Series, which have an annual average carbon dioxide concentration of 0.76% (range 0.1-2.6%), while the remainder of the cave underlies uncultivated shallow stony soils disturbed by mining activity in historic times. These soils have a much lower annual average carbon dioxide concentration of 0.32% (range

0.05-0.8%). Whilst it is known from dye tracing experiments that considerable spatial dispersion occurs during percolation of water from the surface (Friederich and Smart 1981), this difference in soil CO_2 is clearly reflected at depth in the percolation inflows.

TABLE 2

Annual mean calculated carbon dioxide partial pressures (PCO_2) for seepage inflows in G.B. Cave during 1978/79

Inlet	Average PCO_2 (%)	Standard deviation	Number of observations
WP2	0.138	0.02	6
WP3	0.125	0.06	22
RA	0.140	0.07	19
RI	0.083	0.07	24
HSL	0.088	0.02	19
GOHA	0.097	0.03	29
GOTW	0.127	0.04	10
GCF*	0.427	0.16	19
GCSL*	0.490	0.16	18

* inlets in the Ladder Dig extensions.

The spatial variation in the PCO_2 of recharge waters also affects the relation between calcium hardness of percolation waters and depth (Figure 43), because the deepest parts of the cave underly the cultivated soils. Furthermore, several of the shallower sites are intermittent vadose flows characterised by undersaturation with respect to calcite, and indicated by dye tracing tests to derive largely from sub-cutaneous flow. The remaining sites show only a limited range in calcium hardness from 1.2 to 1.5 mM/l and do not show a significant correlation with depth (correlation coefficient 0.05). There is thus little evidence from this data to support a gradual increase in calcium concentration with depth, although it is apparent that further evolution of sub-cutaneous flow waters would be expected.

Because hardness is controlled by non-hydrological factors it does not provide an unambiguous variable for the hydrological classification of percolation waters. However, the variability of hardness, which has been widely used to distinguish between quickflow and baseflow components in karst springs (Shuster and White 1971, Ternan 1972), as well as percolation water (Gunn 1981), may provide a more hydrologically sensitive alternative. A plot of the coefficient of variation of alkaline hardness (linearly related to calcium hardness; Figure 42) and maximum discharge in fact shows the same groupings as discussed for Figure 39. A cluster analysis was therefore carried out using these variables expressed as a fraction of the range of measurements to avoid bias in discriminatory power. The distance coefficient (D) is employed as an index of similarity (Bijnen 1969):

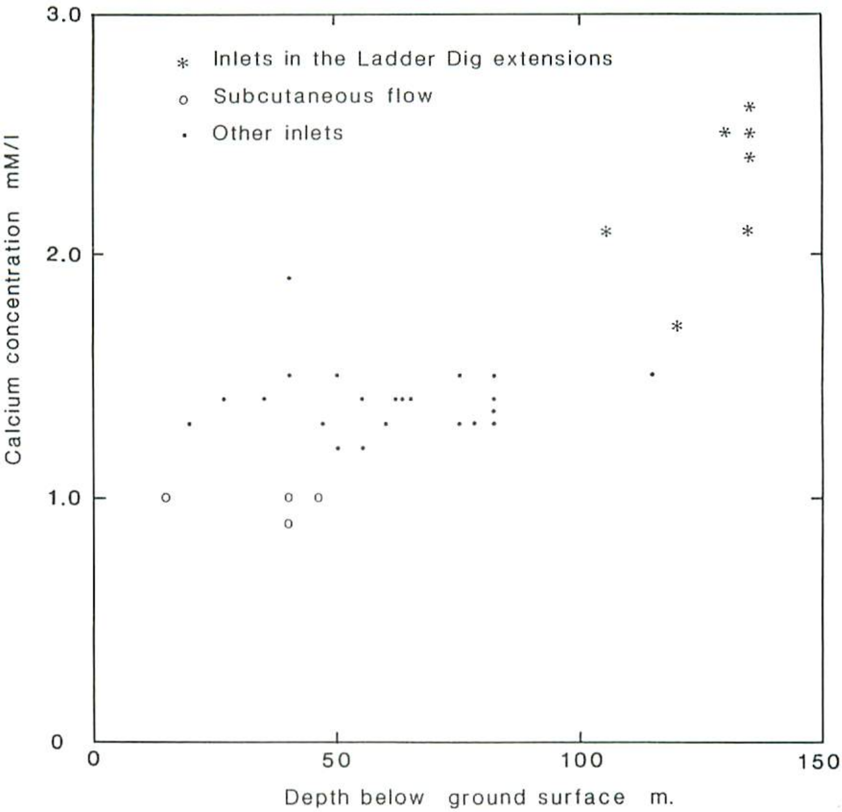


Fig. 43 Calcium hardness of percolation water related to depth of sampling point below ground surface. Samples collected on 14 November 1977 in G.B. Cave.

$$D = (Q_{max,A} - Q_{max,B})^2 + (CV_{A,A} - CV_{A,B})^2$$

when Q_{max} = maximum discharge

CV_A = coefficient of variation of alkaline hardness

and A and B are any two observations.

A dendrogram is then constructed (Figure 44) using the agglomerative weighted pair group method, discussed by Rhodes (1969, p. 226). The similarity matrix is searched for the smallest distance coefficient between two samples. These two samples are then combined to form a single sample, and the distance coefficients between this new sample and other samples are calculated, the search being continued until all samples have been related in this way. At a similarity level of 0.3, the dendrogram shows three main groups, with WPOV as a single member fourth group. Each group represents a flow class as defined earlier on purely hydrological grounds, although there is no differentiation between percolation streams and shaft flow. This finding may suggest that the classification adopted is robust, and therefore relatively insensitive to the variables used in its definition, because it is based on meaningful sub-divisions of the natural continuum of percolation inflows.

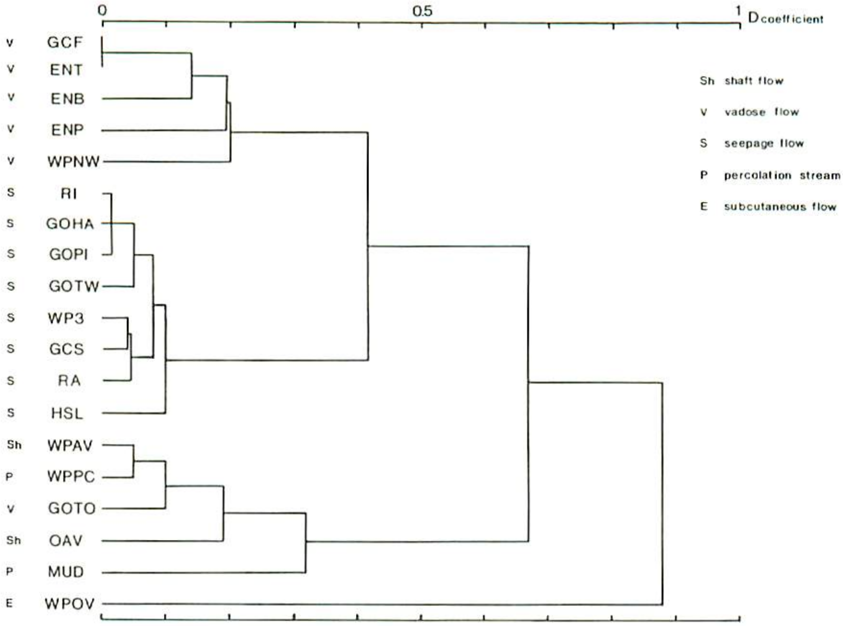


Fig. 44 Dendrogram of cluster analysis of percolation flow in G.B. Cave, using the D-coefficient as a measure of similarity.

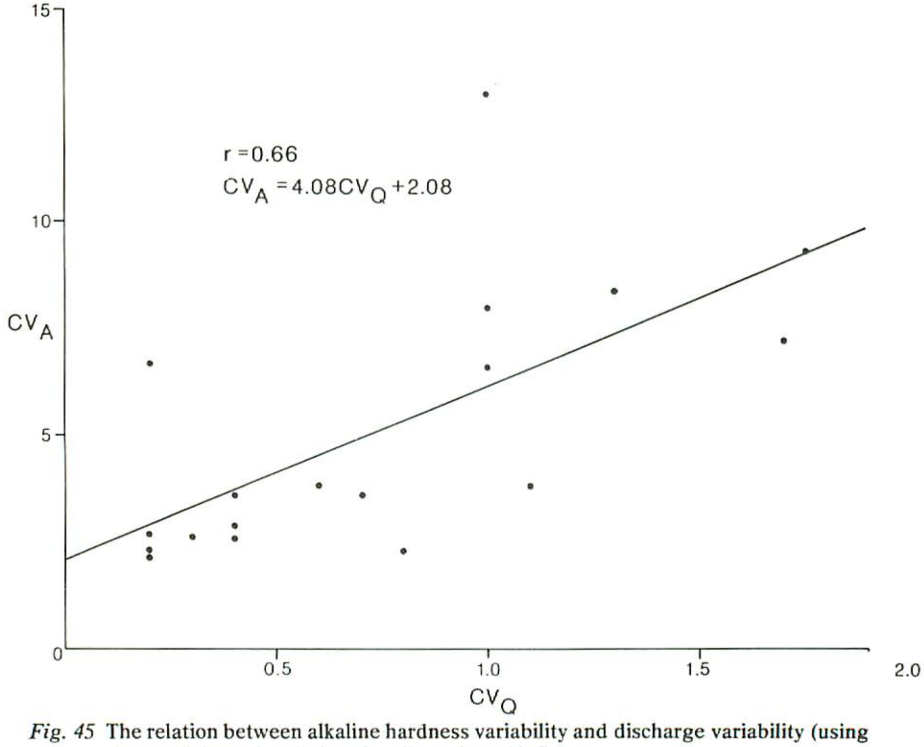


Fig. 45 The relation between alkaline hardness variability and discharge variability (using the coefficient of variation) for all monitored inflows.

However, there is also a strong positive relation between CV_A and CV_Q (Figure 45), which could equally explain the similarity of the hydrological and hydro-chemical groupings. This relationship suggests that variations in inflow carbonate chemistry through time are dominated by changes in discharge, which affect the residence time and surface contact of percolating waters. Other factors, such as seasonal variations in soil PCO_2, are therefore of less significance in G.B. Cave.

CONCLUSIONS

This paper has generally supported the sub-types of autogenic percolation water inflows to caves advocated by earlier workers. It has also shows that only differences in the numbers of sub-divisions result from a functional, hydrological or morphological classificatory base; the various groups and classes still being related in an essentially hierarchial manner (Figure 41). Earlier workers have employed chemical variables such as carbonate hardness in producing essentially hydrological classifications, but this is demonstrated to be unsatisfactory. The factors which govern the chemical evolution of autogenic percolation water interact in a complex manner, and are still only partially understood. There can therefore be little advantage in complicating the problems of classification by the inclusion of chemical variables.

ACKNOWLEDGEMENTS

We would like to thank the University of Bristol Spelaeological Society and Bristol Waterworks Co. Ltd., for access to G.B. Cave, and for the practical assistance which several U.B.S.S. members gave occasionally underground. Thanks also to the many unknown Mendip cavers, who helped to construct the semi-continuous flow record for the inlet in Mud Passage in G.B. Cave.

Richard Head of the Physics Department Workshop of the University of Bristol constructed the tipping buckets, and Simon Godden of the Department of Geography drew some of the diagrams.

During the research H.F. was supported by a grant of the Philips-van der Willigenfonds, Eindhoven, The Netherlands.

Finally Dave Drew made many helpful comments on an earlier version of this paper which are duly acknowledged.

REFERENCES

ATKINSON, T. C. 1977a Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *J. Hydrol.* **35**, 93-110.

ATKINSON, T. C. 1977b Carbon dioxide in the atmosphere of the unsaturated zone: an important control of groundwater hardness in limestones. *J. Hydrol.* 35, 111-123.

BAKALOWICZ, M. 1979 *The contribution of water chemistry in the understanding of the karst aquifer and limestone dissolution* (in French). Ph.D. thesis, Universite Pierre et Marie Curie. Publ: Laboratoire souterrain de CNRS, Moulis, France.

BAKALOWICZ, M. 1981 Percolation water in the karst aquifer (in French). *Proc. 8th Int. Congr. Speleol.* **2**, 710-713.

BIJNEN, E. J. 1969 *Cluster analysis* (in Dutch). Ph.D. thesis, Katholieke Hogeschool, Tilburg, The Netherlands.

BÖGLI, A. 1969 CO_2 concentrations of air in alpine karst soils and in caves (in German). *Proc. 5th Int. Congr. Speleol.*, Stuttgart, West Germany, **28**, 1-9.

BÖGLI, A. 1978 *Karst Hydrology and Physical Speleology* (in German), Springer-Verlag, Berlin.

DREW, D. P. 1968 A review of the available methods for tracing underground waters. *Proc. Brit. Speleol. Assoc.* **6**, 1-19.

FORD, D. C. 1964 On the geomorphic history of G.B. Cave, Charterhouse-on-Mendip, Somerset. *Proc. Univ. Bristol Spelaeol. Soc.* **10** (2), 149-188.

FORD, D. C. 1966 Calcium carbonate evolution in some central Mendip caves. *Proc. Univ. Bristol Spelaeol. Soc.* **11** (1), 46-53.

FRIEDERICH, H. 1981 *The hydrochemistry of recharge in the unsaturated zone, with special reference to the Carboniferous Limestone aquifer of the Mendip Hills.* Unpubl. Ph.D. thesis, University of Bristol.

FRIEDERICH, H. and SMART, P. L. 1981 Dye tracer studies of the unsaturated zone recharge of the Carboniferous Limestone aquifer of the Mendip Hills, England. *Proc. 8th Int. Congr. Speleol.*, Kentucky, USA, 283-286.

FRIEDERICH, H., PREWER, B. and SMART, P. L. 1981 Radiolocation in G.B. Cave, Charterhouse-on-Mendip, Somerset. *Proc. Univ. Bristol Spelaeol. Soc.* **16** (1), 59-61.

GADOROS, M 1966 Measuring instruments for observation of drip-water in caves. *Problems of speleological research II.* Ed. Stelcl, O. Czech. Acad. of Sci., Brno, Czechoslovakia. 115-127.

GRINDLEY, J. 1967 The estimation of soil moisture deficits. *Meteorol. Mag.* **96**, 97-108.

GUNN, J. 1974 A model of the karst percolation system of Waterfall Swallet, Derbyshire. *Trans. Brit. Cave Res. Assoc.* **1** (3), 159-164.

GUNN, J. 1981 Hydrological processes in karst depressions. *Z. Geomorph. N.F.* **25** (3), 313-331.

HABIC, P. and KOGOVSEK, J. 1979 Percolating water karst denudation in the case of Postojnska Jama and Planina Jama. *Actes Symp. Int. Erosion Karstique, U.I.S.*, France. 49-60.

HALLIWELL, R. A. 1970 An elementary study of the cave morphology and seepage in the Reyfad-Pollnacrom system, Northern Ireland. *Trans. Cave Res. Grp. (G.B.)* **12** (4), 271-281.

JAKUCS, L. 1977 *Morphogenetics of Karst Regions*, Adam Hilger, Bristol.

MANGIN, A. 1974-1975 Contribution to the study of the hydro-dynamics of karst aquifers (in French). *Annales de Speleol.* 29 (3), 283-332: **29** (4), 495-601; **30** (1), 21-124.

MIOTKE, F. D. 1974 Carbon dioxide and the soil atmosphere. *Abh. Karst u. Hohlenkunde Ser. A.* **9**, 1-49.

PITTY, A. F. 1966 An approach to the study of karst water, *University of Hull occ. papers in geography* **5**.

RHODES, J. M. 1969 The application of cluster and discriminatory analysis in mapping granite intrusions. *Lithos* **2**, 223-237.

SAVAGE, D. 1969 A revised survey of G.B. Cave, Charterhouse-on-Mendip, Somerset. *Proc. Univ. Bristol Spelaeol. Soc.* **12** (1), 126.

SHUSTER, E. T. and WHITE, W. B. 1971 Seasonal fluctuations in the chemistry of limestone springs: a possible means for characterizing carbonate aquifers. *J. Hydrol.* **14**, 93-128.

SMITH, D. I. and MEAD, D. G. 1962 The solution of limestone, with special reference to Mendip. *Proc. Univ. Bristol Spelaeol. Soc.* **9** (3), 188-211.

SMITH, D. I., ATKINSON, T. C. and DREW, D. P. 1976 The hydrology of limestone terrains. In *The Science of Spelaeology*. Eds. Ford, T. D. and Cullingford, C. D. H., Academic Press, London, 179-212.

STENNER, R. D. 1969 The measurement of aggressiveness of water towards calcium carbonate. *Trans. Cave Res. Grp. (G.B.)* **11** (3), 175-200.

STENNER, R. D. 1973 A study of the hydrology of G.B. Cave, Charterhouse-on-Mendip, Somerset. *Proc. Univ. Bristol Spelaeol. Soc.* **13** (2), 171-226.

TERNAN, J. L. 1972 Comments on the use of calcium hardness variability index in the study of carbonate aquifers; with reference to the central Pennines, England. *J. Hydrol.* **16**, 317-321.

WIGLEY, T. M. L. 1977 WATSPEC: a computer programme for determining the equilibrium speciation of aqueous solutions. *Brit. Geomorph. Res. Grp. Tech. Bull.* **20**.

University of Bristol
Department of Geography
Bristol BS8 1SS
England