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KARST WATERS OF THE INGLEBOROUGH AREA, NORTH YORKSHIRE

by

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ABSTRACT

This introductory paper reviews the environmental factors influencing the karst geohydrology of the Ingleborough area. Subsurface water sampling revealed that although mean calcium carbonate hardnesses varied little with depth, variability of hardness did decrease with depth. The results of surface water sampling are used to classify the major risings in the area into major resurgences, smaller risings with mean calcium carbonate contents of 100 to 200ppm., risings with mean calcium carbonate contents in excess of 200ppm. with high calcium carbonate content variability and similar sites with low calcium carbonate content variability. Flowthrough times of around one day for most conduit-flow waters and 30 to 40 days for the majority of diffuse-flow waters are suggested and the importance of flood pulses is outlined. The results are drawn together to give a model of a typical karst system in the region and avenues for further work are outlined.

INTRODUCTION

The Yorkshire Dales have always been regarded as one of the best developed karst areas in Britain, especially with regard to underground drainage. Tiddeman (1890) states that "...The neighbourhood of Ingleborough presents examples of this kind of underground erosion which are second to none in the Kingdom for numbers, extent, and interest...". More recently Waltham (1974b) states "...The scenery is invigorating, the karst features are classic and the caves are fascinating...". However, in spite of this general acknowledgement of the importance of the area and its wide use for introducing students to limestone scenery, little work has been completed on its hydrology since the Yorkshire Geological Society undertook a programme of water tracing around the turn of the century (Carter & Dwerryhouse, 1905). This paper looks at the area within a 10 kilometre radius of Ingleborough and attempts to summarise recent work on its hydrology.

The Geological Structure of the area

The geological structure of the Three Peaks area "...is the key to much of its unique character..." (King, 1960) and general reviews of the work carried out on the area have appeared in Dunham et al (1953), Rayner (1953) and in slightly less detail in Waltham (1974c). In a much simplified approach the geology can be considered to consist of three elements, the pre-Carboniferous or 'basement' beds, the Great Scar limestone and the overlying beds. The basement beds consist of Ingletonian Series (Dunham, 1953; Leedal & Walker, 1950; Soper & Spears, 1974) and Silurian and Ordovician beds (McCabe, 1972) all separated

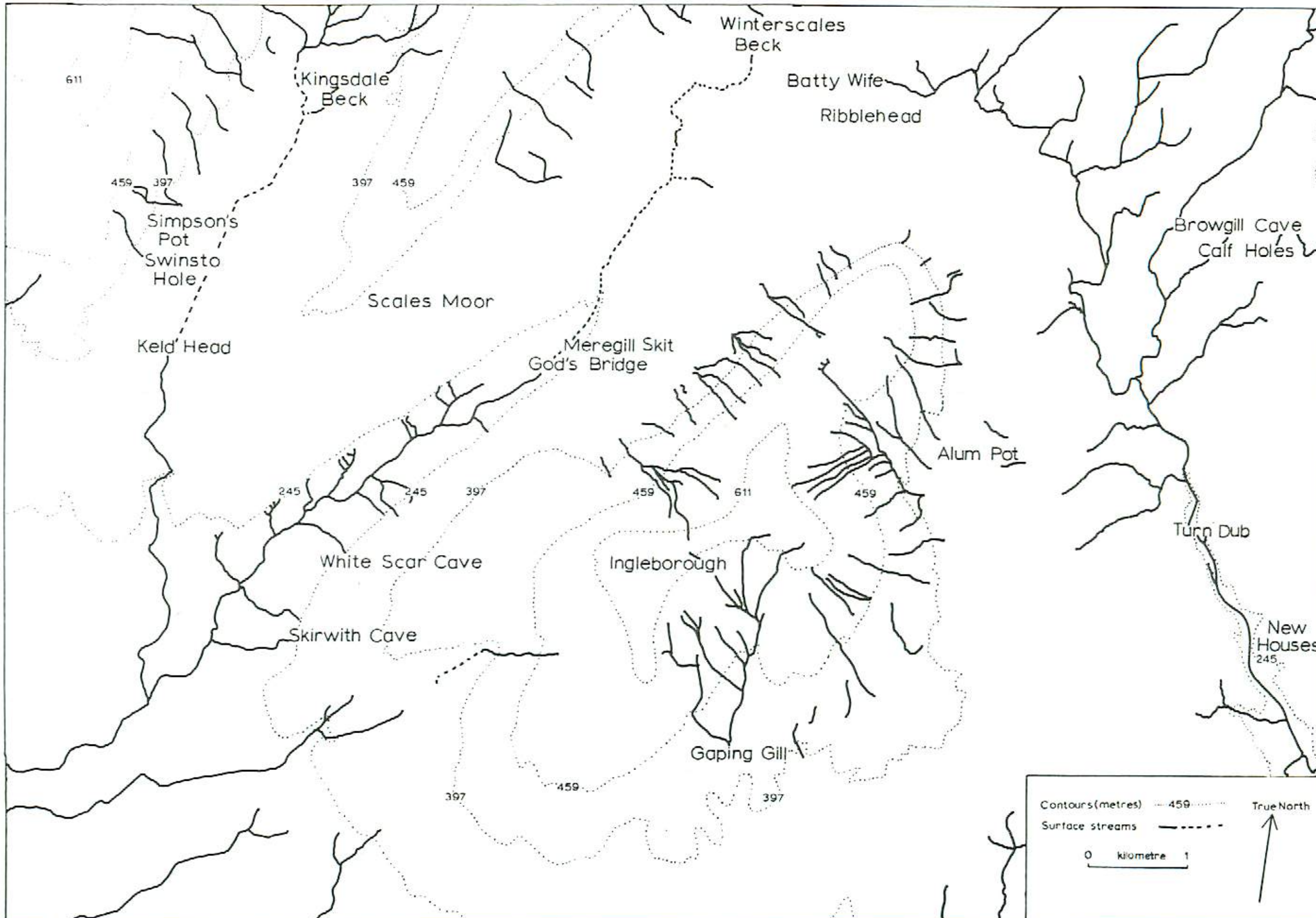

Fig. 39: Map of study area.

from each other and the limestone above by unconformities. It is the presence of this impermeable basement close to the surface which distinguishes the Yorkshire Dales karst from that in other parts of Britain. "The magnificently developed unconformity between the older rocks exhibiting Caledonoid folding, and the flat lying Carboniferous rocks is one of the best known in the British Isles" (Dunham, 1953, p78). Wilcockson (1927) stresses the variability in altitude of the unconformity with the fossil topography having led to variations in the basement beds of the overlying limestone. These variations include changes in bed thickness, percentage of impurities, and the total omission of beds from the succession in some places.

The main body of the near-horizontal limestone is of variable thickness ranging from 100 to 205m. thick around Ingleborough as a consequence of the variation in altitude of the unconformity (Waltham, 1974c). The limestone is mainly of Asbian and Holkerian age (former zonal divisions D1 and S2) but locally the lower beds may be of Arundian age (formerly C2S1). The stratigraphy of the Great Scar limestone has been described in detail by Garwood and Goodyear (1924). Lithologically it consists mainly of fine grained bioclastic limestones of a pale grey to cream colour with around 50% micrite and sparite matrix and only 2% insoluble residue. The proportion of sparite to micrite has been shown to influence the type of solutional features developed (Sweeting & Sweeting, 1969) and the dense micritic *Porcellaneous* band has been shown in the Gaping Gill region to be an important factor in cave formation (Glover, 1974). Work in the area has also demonstrated the importance of shale beds within the limestone for cave development (Simpson, 1935; Waltham, 1970). Similarly the early work of the Yorkshire Geological Society (Carter & Dwerryhouse, 1905) showed how joint directions in the limestone exerted a strong influence on the direction of underground water flow.

In the higher parts of the region the limestone is overlain by the Yoredale beds, a series of cyclic repetitions of a limestone, shale, sandstone unit (Hicks, 1959) reaching a thickness of around 300m. in the Ingleborough area. The summit of Ingleborough consists of a coarse grit, probably of Millstone Grit age but the palaeontological evidence is inconclusive.

The geological structure of the limestone is basically simple with a gentle dip of approximately 1 in 50 to the north, interrupted by a number of very gentle folds with east-west axes. The area is sharply delimited to the south by the Craven Faults which as well as having a downthrow to the south of between 300 and 600 metres also reveal evidence of having been active as tear faults (Wager, 1931). There are also many smaller faults throughout the area which are roughly parallel to the Craven Faults and which often exert a strong local influence on the hydrology.

The present-day hydrology is strongly influenced by past glaciations. This influence is both large scale with the deepening of the valleys allowing vadose action through a greater depth of limestone, and on a smaller scale with the introduction of large volumes of unconsolidated debris both enhancing mechanical erosion and occasionally blocking older passages. This latter effect may also be seen on the surface where boulder clay deposits can strongly influence the entry, and in the case of Turn Dub where the Alum Pot water crosses under the River Ribble, the exit of water from the limestone mass. The larger areas of bare limestone pavement, e.g. Scales Moor, greatly influence the present day hydrology with the grikes acting as active sinks. Thus the risings at the base of Scales Moor show a rapid rise in discharge shortly after rainfall even though they are not fed by stream sinks (Figs. 39 and 44).

The Climate of the area

Within a 10 kilometre radius of Ingleborough there are seven raingauges which are read on a monthly basis and three which are read daily. However, the bulk of this network was only established in 1969 and in a region which is notorious for very localised weather events and where much of the land is at an altitude in excess of 400m., the mean altitude of the monthly gauges is 345m. and of the daily gauges 125m. The available information shows that precipitation is fairly evenly distributed throughout the year with only a slight peak in autumn as shown for Ribblehead (SD766789, alt.310m) in Figure 40. Heavy rainfalls are common with 31% of the rainfall at Sedbergh (SD656921) occurring on days when the precipitation was in excess of 20mm. (1965-72). Other noteworthy examples of very heavy precipitation include 53mm. in one hour at Barbon (SD639829) and 38mm. in 20 minutes at Casterton (SD623796) (Rowsell, 1963). There is some evidence of increasing precipitation at higher altitudes but the effect is difficult to quantify because of local rain shadow effects.

Even less data is available on air temperatures than on precipitation. Records were collected for 20 years at Ribblehead Station but this ceased in 1972 and the nearest comparable site is Malham Tarn House (SD894672, alt.405m.) some 17 kilometres distant. The average air temperature at Ribblehead is just below 8°C. At Malham the average monthy temperatures only exceed 10°C on four months of the year and the mean monthly minimum temperature is below freezing for eight months of the year (Manley, 1956). The temperature data can be used to estimate potential evapotranspiration losses but these approximate to only 600mm. a year. It is rare for monthly potential evapotranspiration to exceed precipitation as may be seen in Figure 40 and thus the caver may be reassured that there should always be sufficient runoff to keep the caves sportingly wet.

In an attempt to assess the chemical input to the region, precipitation samples were collected from Malham Tarn House between February 1974 and January 1975. On all but two occasions, the monthly samples were found to have a pH of less than 7.0. Sweeting (1966, p198) suggests that as a consequence of air pollution originating in the industrial regions of Greater Manchester and West Yorkshire, the "...pH of rainfall is distinctly lower when the wind is from the east or south east than when it is from the northwest...". The samples were found to have a mean conductivity of 55 μmhos but the amounts of calcium present

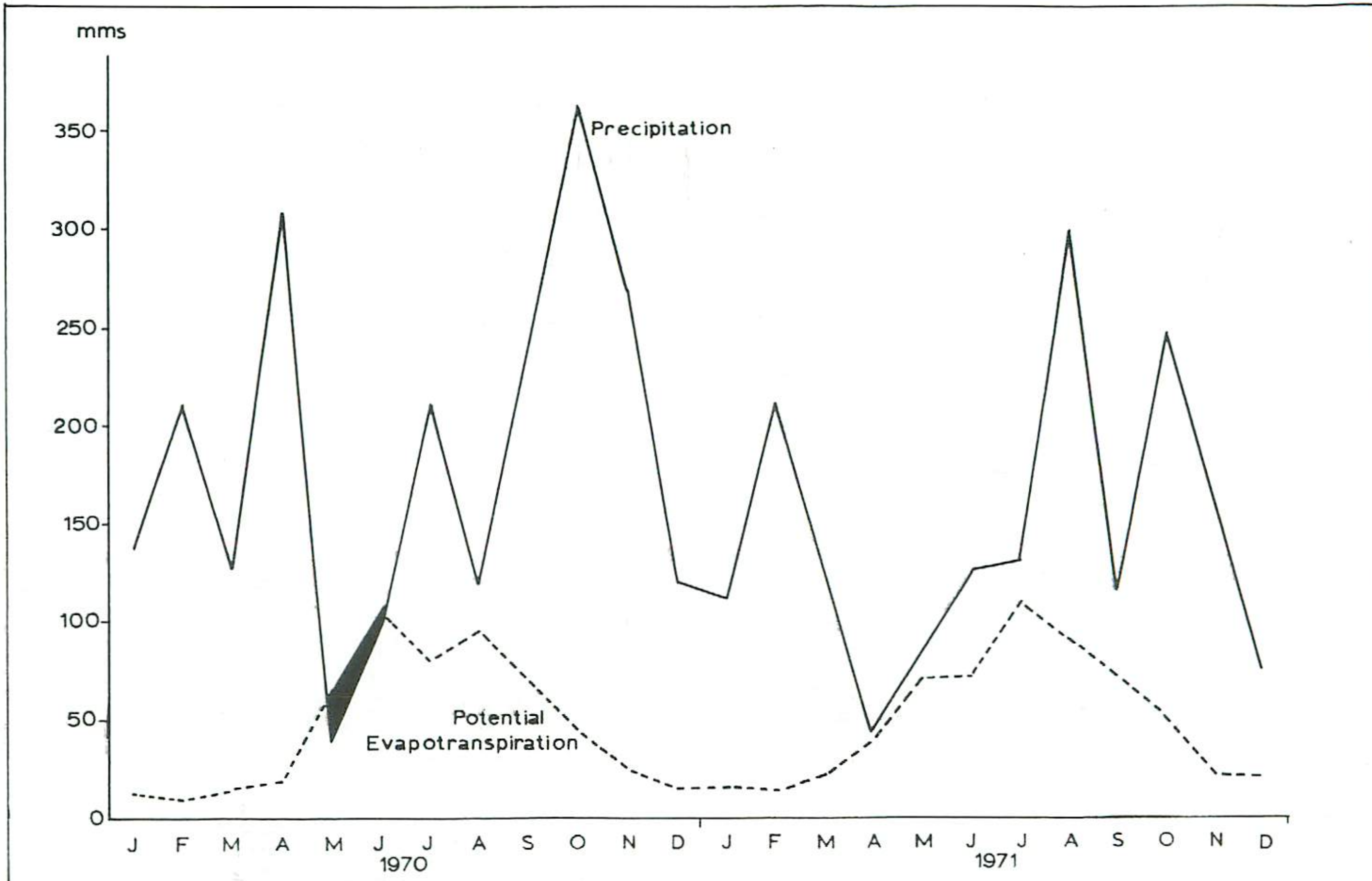

Fig. 40: Precipitation and Potential Evapotranspiration at Ribblehead during 1970 and 1971

were too small to be measured by standard titration methods. Stevenson (1968) suggests that in the Ingleborough area the median calcium content of precipitation (expressed as calcium carbonate) may be between 4 and 5ppm. whilst Sweeting (1966) obtained values of 6 to 7ppm. calcium carbonate, both negligible amounts compared to that in the rivers flowing from the area.

The Soil and Vegetation Cover and its influence

The Three Peaks region includes large areas of bare limestone but where a soil cover does exist it is one of two main types each reflecting the presence or absence of a boulder clay cover over the limestone. Where a boulder clay cover exists a peaty gley soil is usually found which exhibits poor drainage, often being waterlogged for much of the year. Biological activity in the soil is restricted and the soil is usually highly acidic. The typical vegetation cover is *Nardus spp., Molinia caerulea* and *Eriophorum vaginatum* with various species of *Juncus* in the wetter areas. This soil type, the Wilcocks Association of Hall and Folland (1970), is common over much of West Kingsdale and some parts of Ingleborough.

The second major soil type is a mesotrophic brown earth which mainly occurs where the limestone bedrock is 20 to 50cm. below the surface and there is no boulder clay overlying the limestone. These well-drained soils are only slightly acidic and have a high level of biological activity. The typical vegetation cover is *Festuca ovina* and *Agrostis tenuis*. This soil type is common over much of the plateau areas of the Three Peaks.

In order to investigate the effects of the peaty gley soil on water flow into the limestone mass an experiment was conducted in West Kingsdale. Survey details were obtained for Swinsto Hole and Simpsons Pot and the surveys were marked out on the surface. Soil samples were then collected from directly above the caves and up to 8m. each side of the cave using a rammer and core tube (Reynolds, 1970). Two sets of samples were obtained, one after a relatively wet spell and one after a relatively dry spell. The samples were then dried and the percentage soil moisture content calculated (Gardner, 1965). Statistical analysis (chi-square) of the results of this sampling failed to reveal any evidence of enhanced drainage by the underlying caves, even when the cave roof was only 2m. below the surface (Halliwell, 1977).

The soil cover over much of West Kingsdale is penetrated to bed-rock by a number of small depressions with no obvious surface water flow feeding them. Soil samples were also collected in a radial pattern around a small number of these depressions and these provided strong evidence, in the form of lower soil moisture values nearer the shake-holes, of horizontal flow through the soil towards the depressions. Thus it is apparent that the small depressions act as soil water drains concentrating water flow into the limestone in the same way as major stream sinks act. The concentration of acidic soil waters at this limited number of entry points to the limestone suggests that the depressions act as focal points for limestone solution and may be self accelerating.

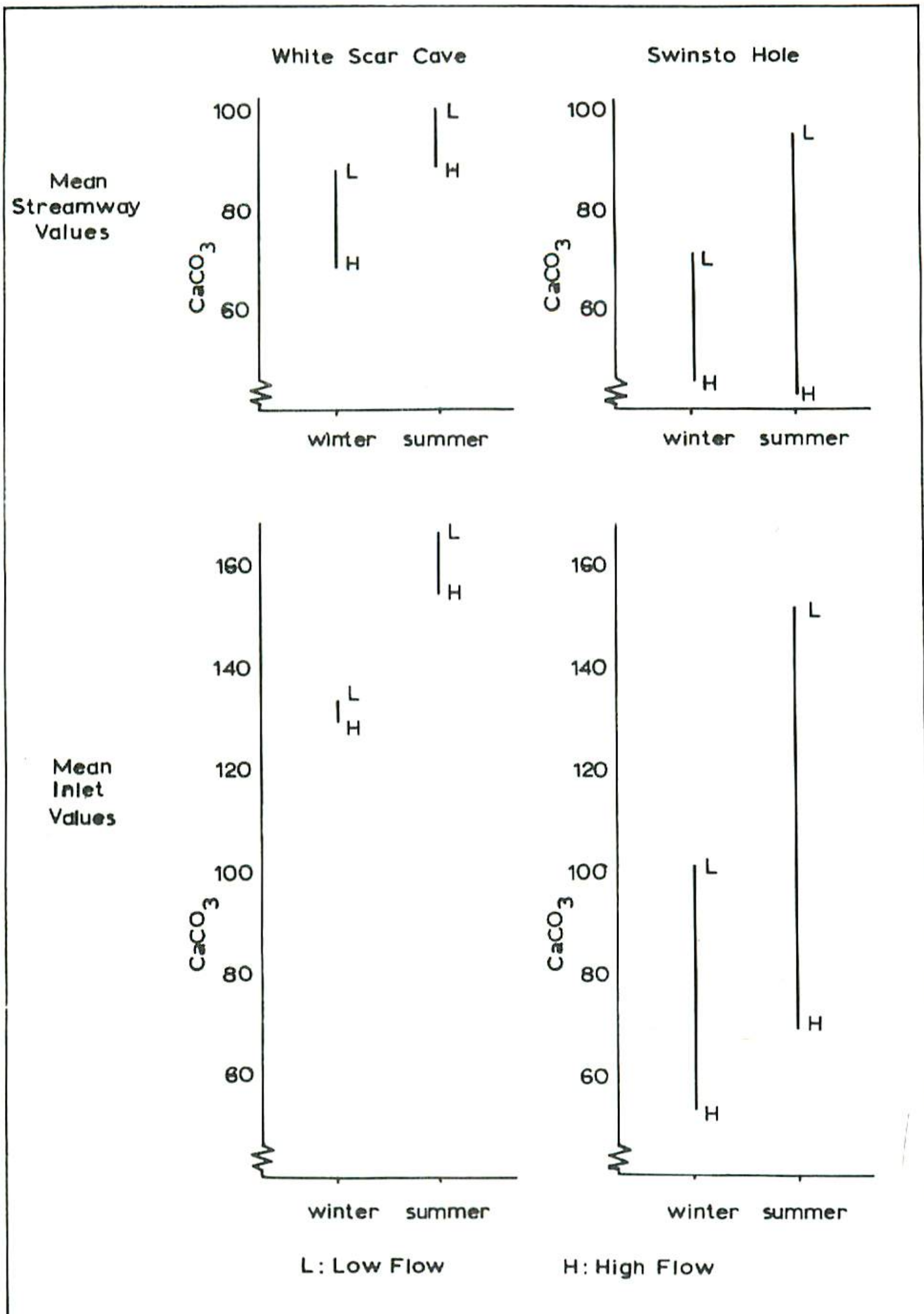

Fig. 41: Ranges of calcium hardnesses (ppm.) recorded in Swinsto Hole and White Scar Cave.

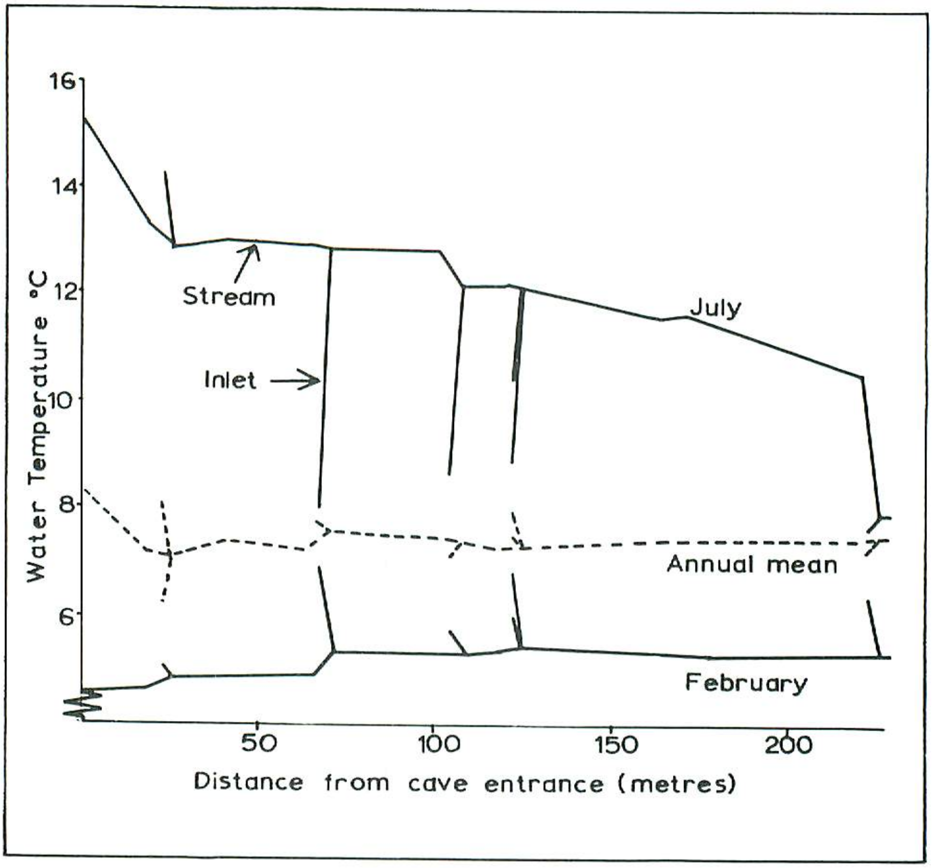

Fig. 42: Water temperature (°C) recorded in Swinsto Hole.

RESULTS OF UNDERGROUND WATER SAMPLING

Introduction

The initial investigation involved collecting water samples from the Long Crawl of Swinsto Hole (SD694775), a major swallet in West Kingsdale. Later, when access was granted for scientific work, a further programme of sampling was undertaken in White Scar Cave (SD712745), a major resurgence in Chapel-le-Dale.

Water hardnesses

The first, and expected, result of the underground sampling was to prove that the inlets joining the cave streamways had a considerably higher calcium content than the streamway. This was found to be true for both caves even though their mean hardnesses were different. In Swinsto Hole under low flow conditions the inlets had a mean calcium carbonate hardness, based on samples collected on different dates from several sites, of 101ppm. in winter and 151ppm. in summer, whilst in White Scar the same range was 133 to 164ppm. The main streamways of the two caves also differed with the Swinsto streamway under low flow conditions having a mean hardness, again based on repeated sampling of a group of sites on different dates, of 70ppm. in winter and 95ppm. in summer, in White Scar Cave the same range was 87 to 99ppm. A possible explanation for the wider range of Swinsto hardness values is their greater discharge dependency illustrated in Figure 41. This Figure shows the seasonal variation in calcium carbonate in each cave and how this changes in response to high and low water flows. Thus the longer lines in the diagram referring to Swinsto stress how the water hardnesses in Swinsto are affected to a greater degree by discharge variation. Indeed in Swinsto the discharge related variations over-ride the seasonal variations and the two lines for the different seasons overlap in contrast to the lines for White Scar. It is suggested that the lower response rate in White Scar reflects the higher volume of water present in the limestone and which must be expelled by floodwater before the actual floodwater can reach the cave. The volume of this fissure water is large because although a few inlets dried up in the drought of 1976 the majority continued to flow but at reduced discharge levels. This contrasts with Swinsto where under very dry conditions some of the smaller inlets totally dried up. This difference reflects the differing volumes of limestone drained by the two caves at the point of sampling.

Both caves also demonstrate the well known feature of increasing hardness along the length of the cave streamway. In White Scar the water issuing from Sump 1 was found to have a mean hardness, based on samples collected at intervals throughout the year, of 88ppm. whilst it emerged from the cave with a mean of 105ppm. In Swinsto Hole the water sinking into the entrance was found to have a mean hardness of 68ppm. whilst towards the end of the Long Crawl the mean was 75ppm., this distance is only about 15% of that traversed along the White Scar streamway. Sampling in Swinsto, especially under flood conditions supported the conclusions of Stenner (1970) based on his work on Mendip that the increases in hardness were almost entirely due to inlets joining the streamway and did not reflect streambed erosion. The results from White Scar also supported this conclusion.

Water temperatures

In addition to collecting water samples for later analysis, water temperatures were measured at each of the sampling sites within the caves. Unlike the water hardnesses the results showed the two cave streamways to have similar mean water temperatures, 7.5°C in the case of Swinsto and 7.6°C in the case of White Scar. The mean annual air temperature recorded at Malham Tarn between 1921 and 1951 was 7.0°C (Manley, 1956). However, the two streamways differed considerably in their variablility of water temperatures. The mean annual range of streamway temperatures in Swinsto was found to be 9.6°C whilst in White Scar it was only 1.3°C. Within the mean range for Swinsto is hidden the fact that near the entrance the range was 14.4°C whilst towards the end of the crawl it was down to 7.3°C (Figure 42). This illustrates how rapidly cave waters can exchange heat with the cave atmosphere and walls. However in White Scar individual extreme events such as drought or snowmelt have been revealed by continuous recording equipment to give an extreme range of about 6°C. This shows how extreme conditions such as large snowmelt pulses may overwhelm the ability of a cave to moderate water temperatures. Under low flow conditions the lake sections of the White Scar streamway appear to have some moderating effect on water temperatures.

The inlet temperatures of the two caves were found to be significantly different. From Swinsto Hole the inlets were found to have a mean temperature of 7.3°C, a mean coefficient of variation of 20.5% and a mean temperature range of 5.2°C; similar figures for White Scar inlets were 8.1°C, 3.3% and 1.1°C. These differences in variability again reflect the rapid direct response to precipitation of the Swinsto inlets compared to the White Scar inlets where the discharge influences are moderated by 'push-through' effects, that is the expulsion of water already in the vadose trickle system by water newly entering the system.

RESULTS OF SURFACE WATER SAMPLING

As part of the assessment of limestone erosion in the Three Peaks region all the risings in Chapel-le-Dale, some of those in Kingsdale, and some along the Craven Fault to Austwick were all sampled every two weeks over a period of 16 months (Hem, 1959; Rainwater & Thatcher, 1960). Samples were also collected from a number of surface streams at points before they sank into the limestone. The results from the analyses of the samples enabled the sites to be split into five groups according to different characteristics of calcium carbonate hardness (Fig. 43) and other variables.

The five hardness groups

Group 1

The first easily differentiated group of sites were the surface waters sampled before the water enters the Great Scar limestone, sites such as Kingsdale Beck (SD710796) and Winterscales Beck (SD753796). This group of 10 sites formed approximately 12% of all the surface sites sampled in the Ingleborough area. The mean calcium carbonate content based on fortnightly (usually 26) samples from each site range from 20ppm. to 68ppm. although individual samples at single sites reached 100ppm. calcium carbonate. These relatively high values are believed to result from water flow over and/or through the Yoredale limestones overlying the Great Scar limestone. These unusually high hardnesses were however balanced by the low minimum hardnesses with individual values as low as 8ppm. calcium carbonate resulting from strong dilution effects and thus all these sites demonstrate high coefficients of variation of calcium carbonate hardness. Values of the coefficient of variation of calcium carbonate at individual sites range from 35.5% to 54.1% with a

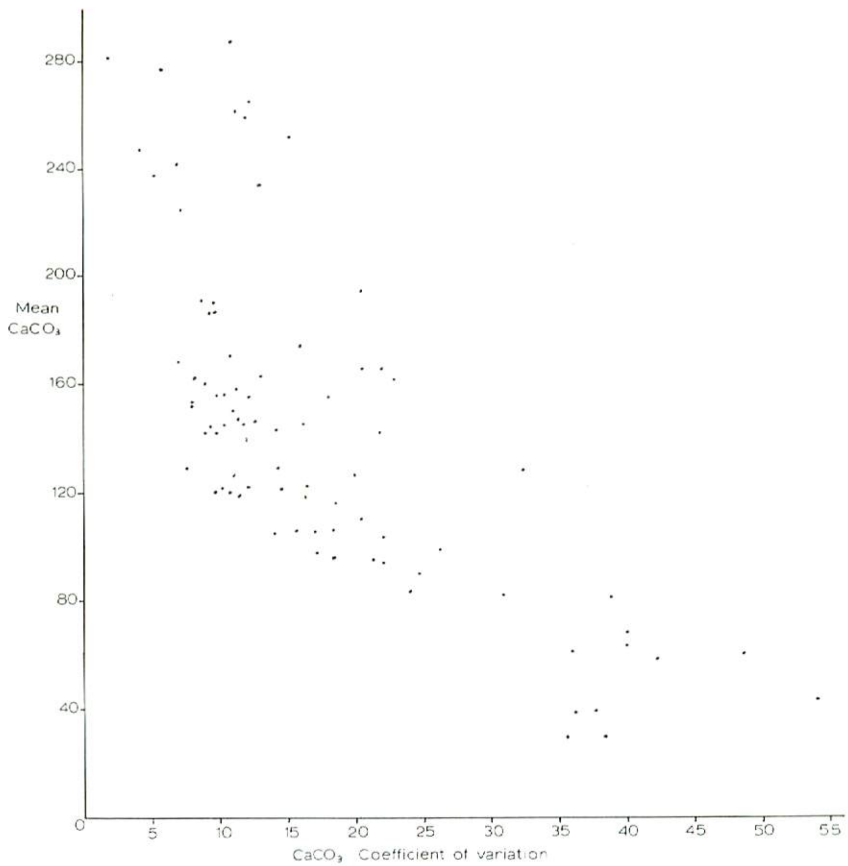

Fig. 43: Mean and coefficient of variation of calcium carbonate content of surface sampling points.

mean of 40.2%. These sites also quite naturally demonstrate the largest range and variation in water temperatures with extreme values of 0.0°C and 22.5°C at individual sites. The mean coefficient of variation of water temperatures over all the sites in the group is 50.8%.

Group 2

The second identifiable group consists of the larger risings, usually sink/resurgence systems such as Keld Head (SD696766) or God's Bridge (SD732763). There are nine sites in this group and as may be seen from Figure 43 they form a link between the surface sites and the third group, the smaller permanent flow sites. The mean calcium carbonate content at individual sites was found to range from 81ppm. to 99ppm. although under low flow conditions the maximum calcium carbonate content at individual sites rose to as high as 140ppm. Similarly

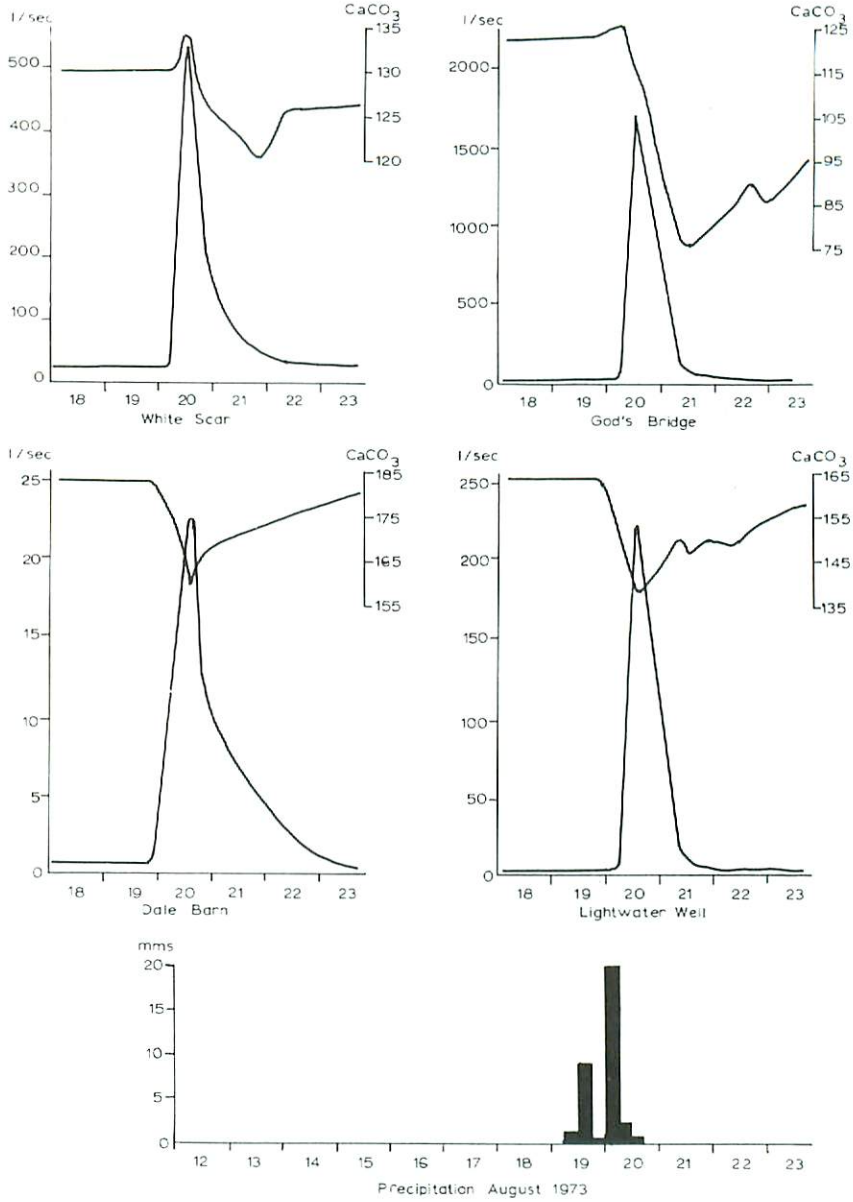

Fig. 44: **Discharge (litres per sec.) and calcium carbonate hardness (ppm.) at conduit fed and diffuse flow fed sites during a single storm event, 20 to 22 August 1973.**

single sample minimum calcium carbonate hardnesses at individual sites ranged from 19ppm. to 70ppm. reflecting the different percentages of diffuse flow water feeding the sites. As a consequence of being major resurgences the sites experienced major dilution pulses and this is reflected in their moderately high coefficients of variation for calcium carbonate hardness. The coefficient values for individual sites range from 17.3% to 38.8% with a mean value of 24.8%. Water temperatures were also found to be very variable at these sites although less variable than at the surface sites. Individual temperatures recorded at the sites range from 3.3°C to 12.6°C and although the mean temperatures at all the sites were within the range 7.1°C to 8.3°C, the coefficient of variation of water temperatures for the sites range from 5.4% to 28.2%. Continuous recording equipment installed within White Scar Cave has revealed distinct snowmelt pulses passing through the cave at 4°C with the speed of their passage obviously having restricted the process of heat exchange with the cave walls and atmosphere.

Group 3

The next group of sites is the permanent flow smaller risings which form the major group (56%) of sample sites. All these sites had mean calcium carbonate hardnesses of between 100 and 200ppm. with an overall group mean of 143ppm. These sites also demonstrate quite consistent calcium carbonate hardnesses with the coefficient of variation of calcium carbonate for individual sites ranging from 7.0% to 32.3% with a mean of 13.7%. The group can be sub-divided to a certain extent by the magnitude of the coefficient of variation of calcium carbonate hardness. A few sites such as Skirwith Cave (SD709738) and Batty Wife Cave (SD766793) have unusually high coefficients of variation for the group, that is values in excess of 20%, and these sites appear to be used as flood overflows by nearby cave systems. The truth of this concept has been proved by dye tests in the case of Skirwith Cave (Waltham, 1977). In contrast many of the risings around the edge of Scales Moor have coefficients of variation of calcium carbonate hardness of less than 10%. The majority of risings within this group are presumed to be diffuse-flow fed risings because no known sink has been dyetested to them. However, much of the water issuing from the risings originates as precipitation on the bare limestone pavements of Scales Moor and White Scar Moss and is transmitted underground almost as rapidly as it would be with a sink feeder. Figure 44 shows the discharge and calcium carbonate responses to a single storm event for true resurgences and typical limestone pavement catchment sites. Thus although certain of these sites experience some discharge variation they may still be argued to be diffuse-flow fed sites with their relatively low mean hardnesses reflecting the lack of soil cover over the limestone of their catchment.

Group 4

The fourth group of sites are those risings with mean calcium carbonate hardnesses in excess of 200ppm. and coefficients of variation in excess of 10%. All but one of these six sites are located within the Craven Fault zone and all are in depressions in fields with no exposed

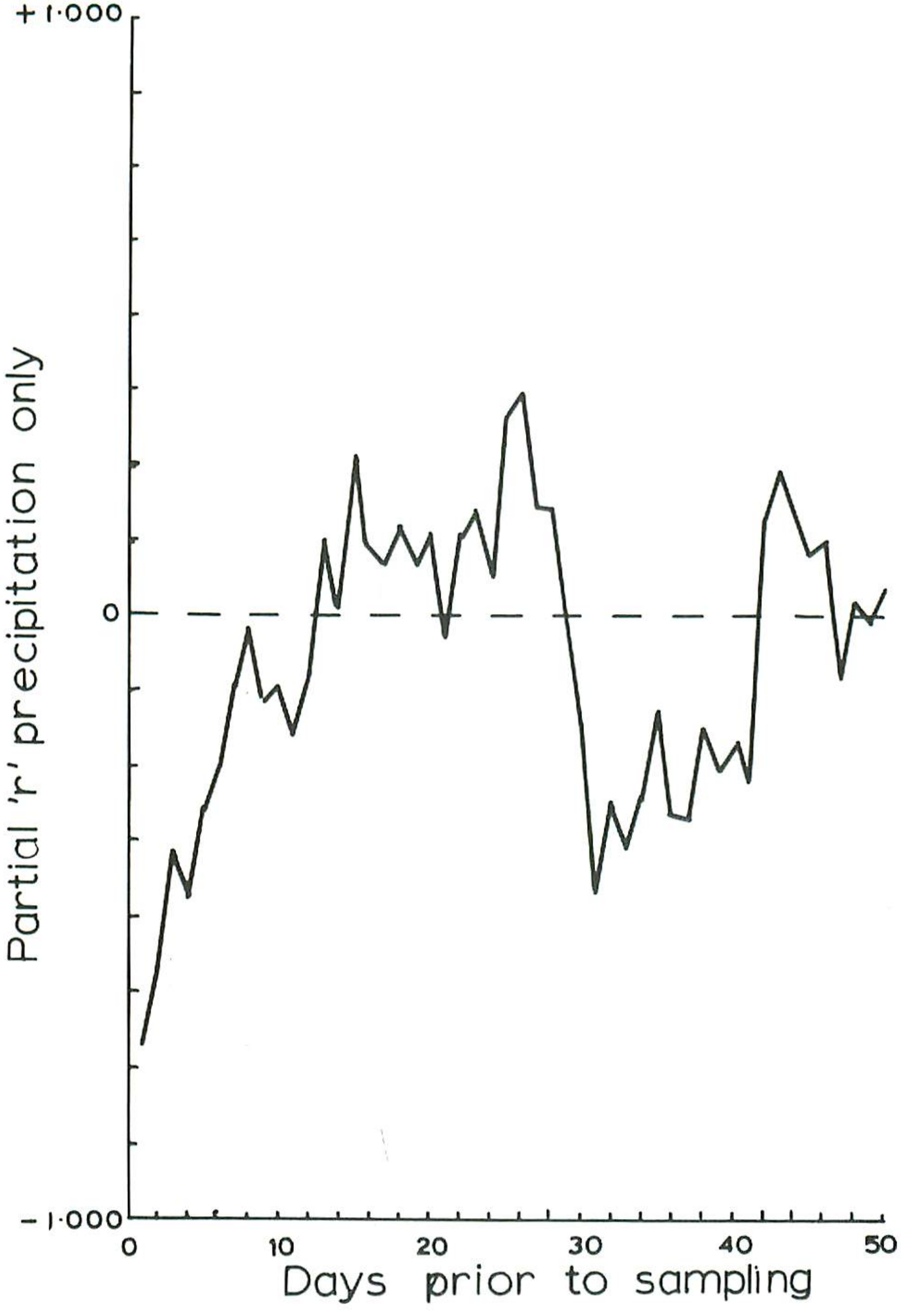

Fig. 45: Graph of partial correlation coefficients relating calcium carbonate content to precipitation at the White Scar resurgence for delay factors of 1 to 50 days.

bedrock. It is thought that they are fed at least partially by local soil drainage and this could explain the variations in hardness and to a certain extent discharge at the sites. The site areas are generally higher grade agricultural land than at most other sites and thus there is a higher level of soil biological activity and hence soil carbon dioxide concentration. The majority of the sites also had above average magnesium content for the region with the bicarbonate hardness often exceeding the calcium carbonate hardness implying the presence of magnesium in solution. It may be argued that this is good indirect evidence of the dolomitization of the Craven Faults in areas other than those where dolomite may be found at the surface (Garwood & Goodyear, 1924).

Group 5

The final group of sites are similar to the previous group with mean calcium carbonate hardnesses in excess of 200ppm. and in being situated mainly along the Craven Fault zone. However the two groups may be differentiated because the latter group of six sites have coefficients of variability of calcium hardness of less than 8% and in one case (Yarlsber Farm) the coefficient is only 1.8%. Thus these sites are assumed to be fed entirely by diffuse-flow water with little or no conduit-flow water reaching them.

In addition to the various groupings suggested by the analysis results the study also spotlighted unusual sites which would be worthy of further study, such as the way in which Skirwith Cave functions as a flood overflow route for water which does not normally emerge from the cave or the abnormally high magnesium content of the waters issuing from Site 34 (SD749782). Samples were also collected from a number of points on surface rivers draining off the limestones. These sites are scattered across Figure 43 reflecting the variations in site type feeding the surface river. The data on the risings was also used to estimate flow-through times on a statistical basis.

FLOWTHROUGH TIMES

Water samples were collected from over eighty surface sites of which the majority were risings at the base of the limestone. The fluctuations in water hardness were then statistically analysed using a suite of computer programs based on parametric partial and multiple linear correlation and regression techniques to find the best fit with variations in meteorological conditions at different delay times prior to sampling. The methodology of this style of analysis was first described in detail by Pitty (1966, 1968) who outlined the theoretical background to the method. The problems involved in using the method, the interpretation of the results, and a detailed comparison of the results with those produced by other methods of estimating flowthrough times may be found in Halliwell (1977).

The statistical analysis gave fairly consistent results across the whole area with the differences reflecting the different catchment characteristics. All the sites which showed any evidence in the water hardness variations of experiencing dilution pulses had a strong negative correlation with precipitation one day prior to sampling, that is the heavier the rainfall the lower are the calcium carbonate hardnesses at the risings approximately one day later (Fig. 45). These strong correlations are taken to indicate that the majority of the dilution pulses travel through the limestone in about one day. However other highly correlated delay factors were also found at many other risings. The most consistently occurring secondary above-average correlations were for delay factors of 30 to 40 days with both a direct relationship with air temperatures and an inverse relationship with precipitation combining to produce high multiple correlation coefficients. The direct relationship with air temperatures is assumed to result from high air temperatures increasing soil biological activity and hence soil carbon dioxide concentrations. This delay span has been interpreted as the mean flowthrough time for diffuse-flow or vadose seepage water within the limestone mass originating from areas of thin soils or bare limestone pavements. At several sites it is also possible to distinguish a third set of above average correlation coefficients for a delay factor of 75 to 85 days. This delay period is much weaker than the 30 to 40 day period and results mainly from air temperature effects with little relationship to precipitation. It is more easily recognisable in summer only data subsets and is often submerged in winter by short term dilution effects. It is thought that this flowthrough may reflect the influences of non-limestone rock, peat and thick soil cover on the limestone mass delaying water entry into the limestone. Two lines of evidence suggest this idea, the first is the non-occurrence of this delay factor at sites at the extreme southern end of Scales Moor where the soil cover is thin or non-existent, whilst further north along the edge of Scales Moor the risings do exhibit this delay factor. The second is the occurrence of this delay factor in the results of this style of analysis on the inlet data for Swinsto Hole where the influence of the boulder clay cover has already been described.

Surface sites above the limestone mass (the Group One sites defined above) show only one day dilution influences in their water hardness fluctuations. The major resurgence sites of Group Two also show strong one day delay correlations with precipitation but most also show 30 to 40 day correlation effects. This would be expected because it is this longer flowthrough diffuse origin water which provides the background flow onto which the short term dilution pulses are superimposed. The Group Three sites detailed above tend to have stronger 30 to 40 day coefficients than 1 day coefficients because the bulk of their water is of diffuse flow origin. The Group Four sites tend to be similar in their responses to the Group Three sites although the relationship with antecedent conditions for any particular delay period is weaker. This weakening is taken even further in the Group Five sites where as a consequence of the small scale fluctuations in hardness this type of analysis fails to produce meaningful results. Surface stream sites below the limestones show patterns of correlation coefficients similar to those seen at the risings feeding the surface streams. Detailed sets of correlation values for individual sites are given in Halliwell (1977).

SUMMARY MODEL

Although the hydrological regime will vary radically as a consequence of short term storm events, it is possible to produce an outline model representing median conditions. Figure 46 is an attempt to do this based on the theoretical systems outlined by Smith et al (1976). Unfortunately some of the figures are only indirect estimates because little or no work has been done in the area which would enable their accurate quantification. The estimated swallet contribution of 20% is based on work on the Keld Head system where the sink input and rising output were measured on several occasions at different flow levels during 1973 and 1975 (Halliwell, 1977). Recent work by Towler (1980) on the Sell Gill (SD811743)—Newhouses (SD802739) system gives sink inputs of 10-15% under low flow conditions although this can rise to 45% in flood. The split of percolation input between the soil water and bare rock pathways is based on average catchment characteristics. The flow from storage in waterfilled fissures is based on the flow regime of White Scar Cave, both during the 1976 drought, and by approximate hydrograph analysis (Atkinson, 1977).

The precipitation input to the area averages 2000mm. per year with a standard deviation of 360mm. (Ribblehead data 1954-71). Average estimated evapotranspiration losses are around 600mm. per year thus leaving 1400mm. per year of effective rainfall. The White Scar rising has an estimated catchment based on surface features and known underground drainage routes of 3 square kilometres and an estimated median outflow of 50 l. per sec. based on approximately fortnightly sampling in 1976 and 1977. This only accounts for 38% of the effective rainfall and thus the remainder must pass through the cave system as flood pulses or overflow into other systems such as Skirwith Cave. Similar calculations on other estimated catchments in the area produce broadly comparable results.

The question then arises, how does the flood water enter the cave system? The 20% swallet input of median conditions has been seen to rise to 25% in the case of Keld Head and 45% in the case of New Houses rising. These increases are however accompanied by increased runoff from the bare limestone pavements with grikes such as those on Scales Moor acting as major sinks. Similarly the surface depressions rapidly funnel water into the limestone and large scale increases in vadose seepage water have been described qualitatively by a party who were trapped in White Scar by flooding, and on a more quantitative basis for Swinsto Hole (Halliwell, 1974). These large scale increases in flow lead to the overflow of catchment boundaries. This can occur both on the surface with the advance beyond normal sinks and along dry valleys of surface streams as seen in Crina Bottom and Winterscales Beck (Halliwell, 1977), or totally below ground as in the Calf Holes to Browgill system (Towler, 1980). Measurements on this apparently simple system revealed that in flood considerably more water entered the system than left it, thus indicating the presence of a sizeable but as yet untraced flood overflow.

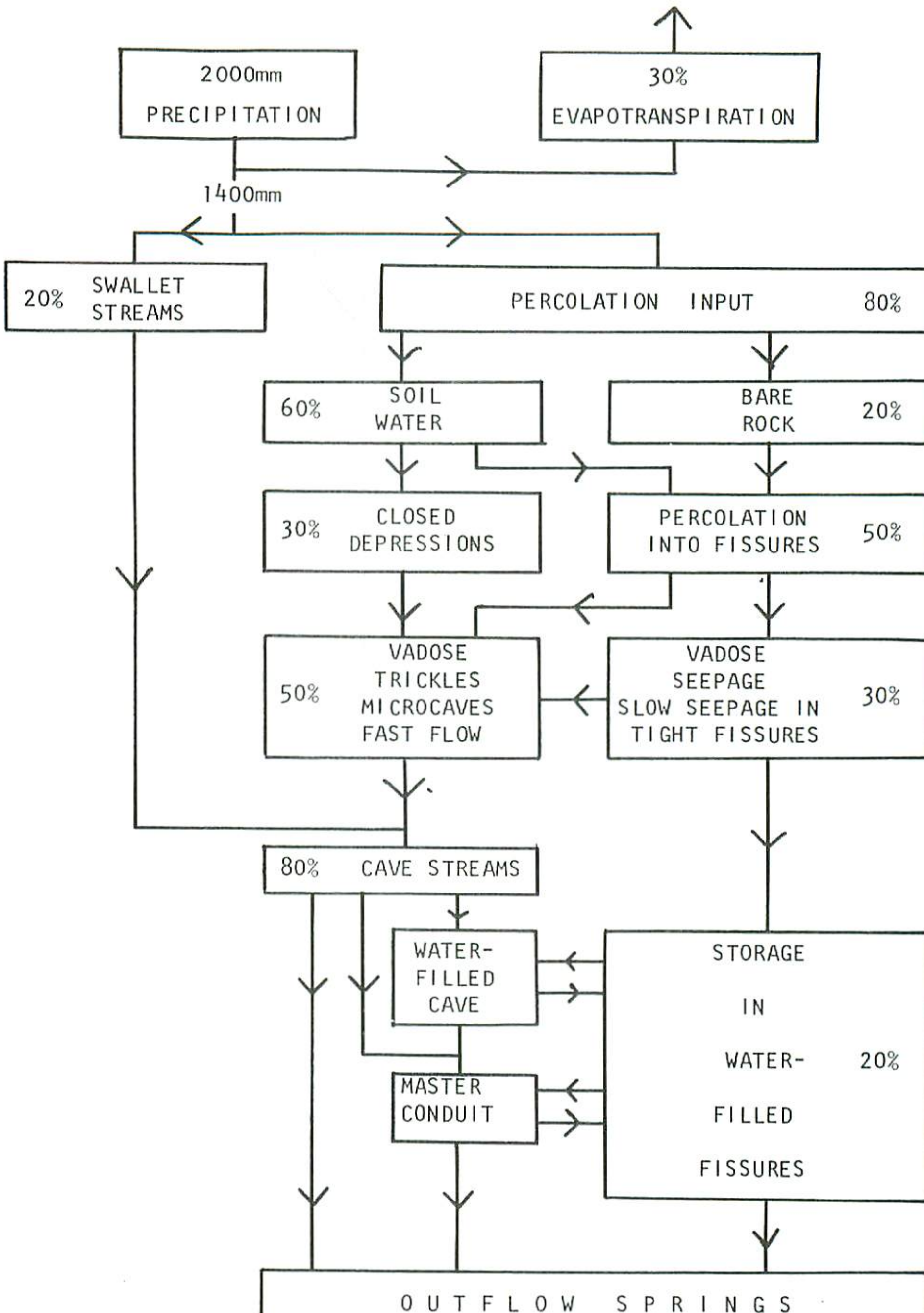

Fig. 46: Model of hydrological pathways in the limestones of the Ingleborough area under median conditions.

Once the flood pulses have entered the cave system they pass through it rapidly. This is shown by the results of dye-tests, the correlation analysis outlined above and by the short delay between peak discharge and minimum water hardness (Cavanagh, 1974).

Under low flow conditions the importance of the swallet flow and bare rock inputs decreases and vadose trickle and seepage waters become more important. Under extreme drought conditions, such as summer 1976, vadose seepage and trickle waters can be seen to be responsible for almost all the outflow from the risings because swallet flow ceases. This change is often accompanied by increases in water hardness values.

In any model consideration must be given to water hardness variations as well as to discharge variations. The hardnesses are more difficult to generalise because they are affected by discharge related dilution pulses and also vary seasonally. Thus any model values must of necessity be expressed in terms of ranges of values which may well be exceeded by individual events.

The streams flowing onto the Great Scar limestone already have calcium carbonate hardnesses of 50 to 70ppm. but these values are very variable. The major cave streamways usually have calcium carbonate contents of 70 to 100ppm. with any increase in hardness along the length of the streamway usually resulting from an inlet, these stepwise increases are especially noticeable under abnormally high or low flow conditions. The majority of the vadose trickle and seepage inlets have calcium carbonate hardnesses within the range 100 to 160ppm. but some exceed 200ppm. The latter sites tend to be those with the most stable hardnesses and discharges although in some cases such sites are used as flood overflows by faster discharge response systems producing an abnormally high hardness variability. The range of calcium carbonate hardnesses at the major risings in topographic lows in the basement rocks is usually within the range 80 to 110ppm. and includes both Group 2 and 3 sites as defined above. However the smallest diffuse flow, Group 3, risings situated at relatively high points on the basement may have hardnesses in the range 150 to 200ppm. (Halliwell, 1975).

The generalised discharge and hardness figures can be combined to produce an even more approximate model of the distribution of erosion throughout the system. Based on work undertaken in Kingsdale it appears likely that approximately 10% of the calcium carbonate load emerging at a resurgence entered the system already dissolved in the swallet waters. The samples of inlet seepage waters collected from Swinsto Long Crawl at a depth of about 15m. and those from White Scar at depths of around 150m. were found to be not statistically significantly different in their mean calcium carbonate values although their coefficients of variability of calcium carbonate were significantly different (Mann-Whitney U test, 95% level). However the inlets nearer the public section in White Scar had noticeably higher calcium carbonate hardnesses than those at greater depth farther into the cave where the overlying surface soil cover is much poorer. Furthermore the springs near

Twistleton Hall (SD701748) which because of their situation near the base of the limestone can only flow at shallow depth within the limestone, but are beneath relatively rich agricultural land which can be expected to have a high soil carbon dioxide concentration, had mean hardness in excess of 200ppm. Similar comments may be made for all the Group 5 sites, that is those with calcium carbonate contents in excess of 200ppm. Therefore it can be argued that the majority of limestone erosion occurs at shallow depth close to the soil-bedrock interface and reflects the soil carbon dioxide concentration in the catchment area.

CONCLUSIONS

This paper attempts to draw together much of the work which has been undertaken on the limestone hydrology of the Ingleborough region. However few people have worked on the region and a major difficulty arises where the work has been undertaken as undergraduate dissertations which have a very limited circulation and thus much of this work is easily lost. This is especially so when, as is commonly the case, the workers are based on an institution some considerable distance from the study area. This situation contrasts strongly with that of the Mendip area where research students from the nearby University of Bristol Department of Geography have been able to build on each other's work and move towards a reasonable understanding of the karst hydrology of Mendip. This situation is exemplified by the fact that by 1973 approximately 80% of all papers reporting systematic underground sampling were based on research in the Mendips with 50% of the papers being based on G.B. Cave.

In Yorkshire by contrast little or no subsurface sampling has been undertaken beyond that outlined above. What recent work has been undertaken, such as that of Casson (1979), Carter (1979) or Towler (1980), has often revealed more problems than it has solved by suggesting that current simple drainage and related chemical variation concepts may need re-examining. Dye-testing work by ULSA (Brook & Crabtree, 1969) and others has sometimes revealed results which differ from the classic work of the Yorkshire Geological Society, for example at Meregill Skit (Carter & Dwerryhouse, 1905). J. Farrer first tried estimating rates of speleothem growth as long ago as 1839 (Phillips, 1855; Dawkins, 1874) but little work has been done in this field since. Richardson (1965) outlined the need for work on cave meteorology but little work other than some by Bracewell (1977) has come to light. The list of work to be done is almost endless, many of the theoretical concepts have been formulated and tested in other limestone regions, especially the Mendips. So far few attempts have been made to apply them to the untouched areas of Yorkshire and to discover whether or not they still apply in the different conditions.

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