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CHANGES IN STREAMS BETWEEN SWALLETS AND INLETS IN THE CAVE AT ST. CUTHBERT'S SWALLET, PRIDDY, SOMERSET

by

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ABSTRACT

At every site where water flows from a surface stream sink to an inlet in the cave, there are changes in calcium, magnesium and bicarbonate concentrations, in spite of the fact that in many cases, these distances are short. The changes are caused by limestone dissolving in the stream in the space between swallet and the open cave, and not by admixture with water percolating from a different source. When the size of a surface stream rises, concentrations of many solutes in the stream, including calcium and bicarbonate, fall. However, results show that at every near-surface inlet for which sufficient data is available, the rate of limestone solution increases when stream sizes rises. Once the stream is within the open cave, stream characteristics are remarkably stable and, in sampling trips in normal conditions, they only change when mixed with water from a different source. The present results demonstrate that the quantity of limestone passing into solution increases very considerably as a result of an increase of stream size. Although the total volume of the streams entering the cave is the same as it was in the past, after the largest stream entering the cave changed its route the hydrochemical characteristics of the Main Stream downstream of Plantation Junction have changed. The change is not limited to an increase in the hardness of the stream. Although the number of data points is small, it is clear that the response of the total hardness to stream size has undergone a major change. Regression equations describing temperature changes between the sinks and the inlets were statistically significant in the earlier period of study when more sensitive thermometers were used.

INTRODUCTION

The hydrology of St. Cuthbert's Swallet and its associated surface streams was studied by Stenner from 1965 to 1973. The surface streams had also been studied intensively by Atkinson in 1969 and 1970 (Atkinson, 1971, Smith and Drew, 1975). However, as described elsewhere (Stenner, 1997), the route taken by the largest tributary (the Mineries Pool Outflow Stream, previously known as Plantation Stream) changed at some time between 1985 and 1991, making it necessary to repeat most of the previous studies.

Because of the changes, the stream distribution in the cave and the fundamental hydrochemical characteristics of several streams entering the cave (those entering via the Old and New Routes, and via the September Series) had changed. Consequently, the patterns of limestone solution and calcite deposition by these streams had also changed. The size of the stream flowing through unstable boulders at the top of Arête Chamber had increased considerably and for safety reasons it was particularly important to assess changes of solution rates among these boulders.

Between 1994 and 1997, Sandford and Williams made eight comprehensive data and water sample collections from the cave, while Stenner made an intensive study of the characteristics of surface streams entering the cave, at three sites. Knights extended the range of chemical analyses by analysing the majority of samples for sulphate and nitrate by ion chromatography (IC) in the Chemistry Department of Bristol University. The stream size was measured at two surface sites many times by salt dilution (Stenner and Stenner, *in prep*).

The changes in the stream distribution in the cave have been described elsewhere (Stenner, 1997). Detailed descriptions of the hydrochemical characteristics of the surface streams are also available (Knights and Stenner, 2001; Heathwaite *et al*, 1999). The present paper presents a description of changes which have been measured in water flowing from various surface sinks to points of re-emergence in the cave. These changes are presented together with those measured by Stenner between 1966 and 1973, and the two data-sets are compared. The locations of the sites in relation to the survey of the cave (Irwin, 1991) are shown in Figure 1.

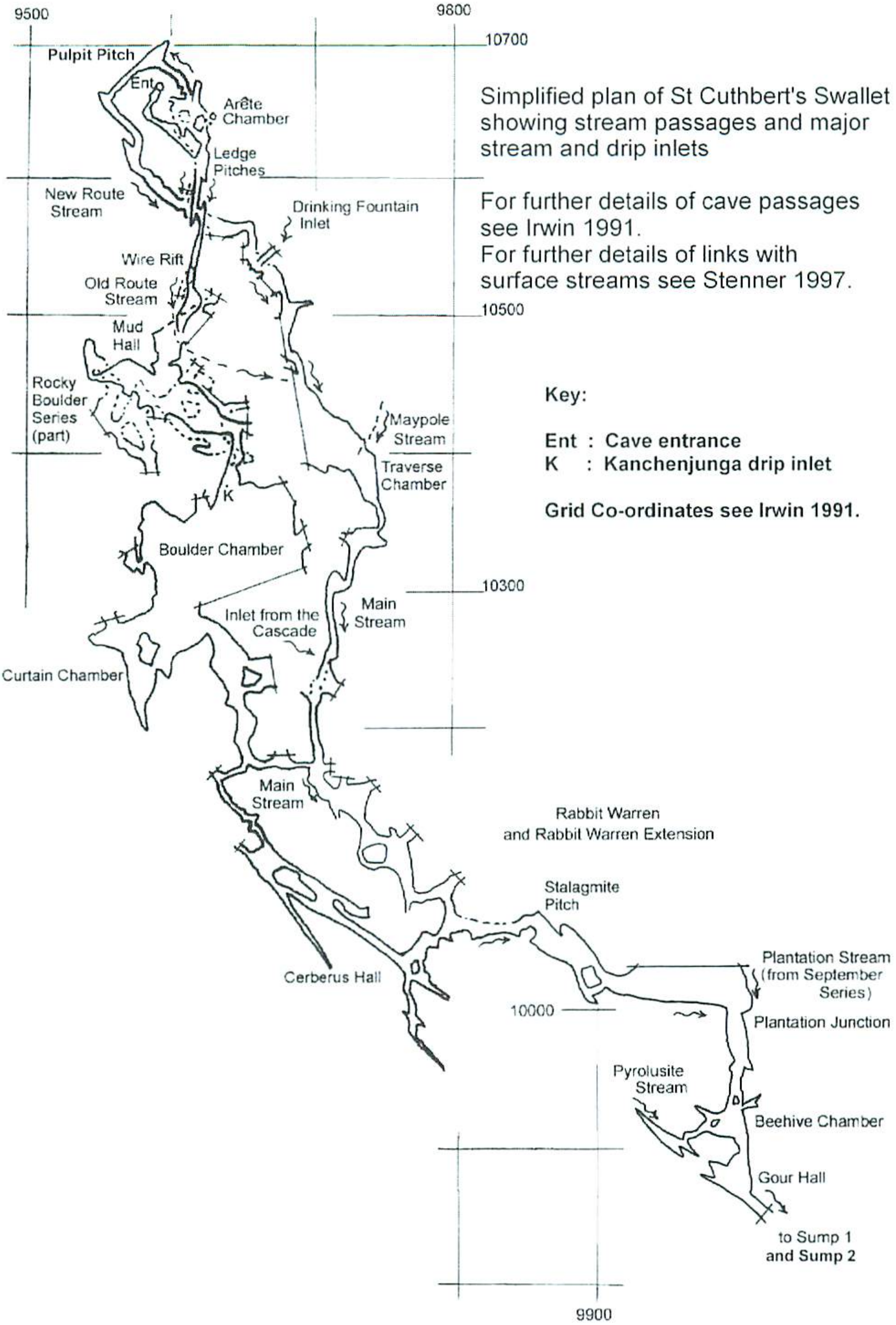
When a change in hydrochemical characteristics is observed in a stream which has flowed from one site to another, that change may have been caused by the dissolution or deposition of one of the solutes, or it may have been the result of admixture with water from a different source. An important example of this in the context of cave hydrochemistry, occurs when the calcium or total hardness changes between two sampling stations. If this happens in stable conditions, it can be important to find out whether this change signals calcium carbonate solution/deposition, or whether it signals admixture with water from another stream. This question was addressed directly when stream distribution in St. Cuthbert's Swallet was investigated in 1968. On 10/02/68, a weir at Plantation Swallet was used to measure the stream size. From a single direct measurement of the size of Pulpit Passage East Inlet, the stream size of the Plantation inlet stream at Plantation Junction was calculated by using stream ratio measurements through the cave. The result indicated that, within experimental limits, the stream at Plantation Junction was the same size as it was at the surface. Water from other sources was negligible, and any changes between the two stations had taken place within the water of the stream (Stenner, 1997).

Such cases, where direct proof of the nature of change have been established, are rare and alternative evidence concerning the causes of change needs to be discussed. The following hypothesis can be made for cases where changes of total hardness are measured between two stations. If there was a significant change in non-alkaline hardness between the two stations, it is probable that water from a separate source had mixed with the stream. Conversely, if no change of non-alkaline hardness took place between the two points, then the changes were likely to have been caused by the solution of limestone or by the deposition of calcite, rather than by admixture with water from a different stream (Stenner and Stenner, *in prep*). If the same conclusion is reached when examining data from several sets of samples, the likelihood of this hypothesis being true is considerably increased.

EXPERIMENTAL DETAILS, ACCURACY AND PRECISION

Water samples were collected from sites shown in Figure 1. Duplicate samples for aggressiveness determinations were saturated with AnalaR $CaCO_3$ at the site. Whenever sediment was visible in the stream, the sample was filtered through an 11 cm diameter Whatman 541 paper at the time of collection. Samples were kept cool and in the dark until analysed.

Water temperatures were measured for most of the study period, using a calibrated electronic thermometer graduated to 0.1° C. The stream size (Q, in litres/minute) of St. Cuthbert's Stream (close to the stream sink) was measured by salt dilution, using a simple constant flow apparatus and standard KCl solutions (Stenner and Stenner, *in prep*). A standard KCl solution was added from a constant head bottle and water samples were collected from



Simplified plan of St Cuthbert's Swallet showing stream passages and major stream and drip inlets

For further details of cave passages see Irwin 1991.
For further details of links with surface streams see Stenner 1997.

Key:

Ent : Cave entrance
K : Kanchenjunga drip inlet

Grid Co-ordinates see Irwin 1991.

Figure 1. *Simplified survey of St Cuthbert's Swallet showing stream routes and sampling sites.* After Irwin, 1991.

a suitable downstream site until potassium in the samples reached a stable plateau. From the data the stream size was calculated by the Method of Mixtures. In many of the regressions involving stream size (Q) that were investigated, a discharge function $Q^{-0.4}$ was used. This power function is related to the time taken for a stream to flow between two given points and using this function has been shown to be more likely to yield a significant correlation than other functions (such as square root, or inverse) with related factors. More detailed descriptions of laboratory methods are available elsewhere (Knights and Stenner, 1999).

Ion balances were calculated to examine the reliability of experimental data. The requirements of the ion balance examination determined the choice of chemical species selected for analysis. All concentrations were expressed as 10^5 × Molarity. The following standard errors were calculated (as 10 × 10^{-5} Molar, ~ ppm as $CaCO_3$): Total hardness (by titrating a 25 ml aliquot with standard EDTA solution), 0.8; calcium (by subtracting magnesium from total hardness), 0.8; aggressiveness to $CaCO_3$ (by the Stenner procedure (Stenner, 1969)), 0.8; alkaline hardness (by titrating with standard HCl), 3.0; non-alkaline hardness (by subtracting alkalinity from total hardness), 3.8; magnesium (by atomic absorption spectrophotometry), 0.17; sodium, 0.13; potassium (both by flame emission spectrophotometry), 0.05; chloride (by silver nitrate titration, potassium chromate indicator), 2.6; sulphate, 0.3; and nitrate (by ion chromatography), 0.23.

LIMESTONE SOLUTION BETWEEN SURFACE STREAMS AND INLET STREAMS

In studies of Tyning's Stream (G.B. Cave, Charterhouse-on-Mendip), changes between the surface and Stream Passage in G.B. Cave were examined, and on 13 occasions it was possible to calculate the Ca:Mg Molar ratio of the increase of Ca and Mg between the two stations (Stenner, 1973). The mean ratio was 20:1, with a Standard Deviation 6.0. The mean difference between total and alkaline hardness was 0. The Ca:Mg ratio of a rock sample from the basal bed of the Black Rock Limestone in the Gorge near Mud Passage, in G.B. Cave, was 30:1, and the ratio of samples of the same bed at the surface was reported to be close to 15:1. The mean increase measured in the water samples therefore lies between these two extreme ratios. It was concluded that the increments of Ca and Mg were caused by the dissolution of limestone, which reacted with carbon dioxide dissolved in the stream to give a mixture of calcium and magnesium bicarbonate (Stenner, 1973, section 5 paragraph 1, p.209).

The intensity of sampling has not been high enough to allow such detailed investigations to be made in St. Cuthbert's Swallet. However, calculations have been made for the changes between

(i) Plantation Swallet and Plantation Junction between 1966 and 1973,

(iii) the Soak-away Sink and Pulpit Passage between 1994 and 1996.

Using the raw data, the increments of Ca and Mg from the surface sink to the inlet in the cave were calculated for each separate set of data. The increments of total and alkaline hardness were calculated by the same method as had been used at G.B. Cave, taking alkaline hardness as the bicarbonate of a bivalent metal. The results are presented in Table 1.

Site	Plant.Swallet to Plant.Jn '66-73	Soakaway Sink to Pulpit Pass. '66-73	Soakaway Sink to Pulpit Pass. '94-96
Mean Δ tot. hard ppm as $CaCO_3$	11.5	19.3	20.4
Mean alk.:mean Δt.hard Molar ratio	1.0	1.1	0.9
Mean Δ non-alk.hard ppm as $CaCO_3$	All N.D.	0.5	1.4
Mean Ca:Mg Molar Ratio	20.0	15.7	14.1

Table 1. *Mean increments of some stream characteristics between surface sinks and inlets in the cave.*

Figures for changes of non-alkaline hardness support the suggestion that changes between the surface and the cave were caused by changes within the streams, rather than by admixture with water from another source. This was proved for the stream from Plantation Swallet to Plantation Junction by direct measurement on one occasion on 10/02/68, as described above. Molar ratio of the increments of total and alkaline hardness was in each case close to 1.0:1. This showed that the increments of calcium and magnesium took place as bicarbonates. The mean Ca:Mg ratios are a measure of the Ca:Mg ratio in the basal beds of the Black Rock Limestone which has dissolved. The results have shown that the increments of calcium and magnesium took place as bicarbonates.

The results also show that in all three cases there was no significant change in mean non-alkaline hardness, as would have been the case if there had been a significant admixture with water from a different stream. The validity of this claim is strengthened by the high number of sample sets for each site.

In other words, the sets of ratios from all three sites demonstrate that limestone solution by the stream between the surface sinks and the cave inlets was taking place.

In the case of the Plantation Stream, the set of measurements collected on 10/02/68, mentioned above, provide the first proof that no water from another source joined the stream between the surface and Plantation Junction; this has been confirmed by the present study.

FACTORS ASSOCIATED WITH THE HARDNESS OF STREAMS ENTERING ST. CUTHBERT'S SWALLET

Some regression equations between solute concentrations and stream size were calculated. In the results given below, $\rho(n)$ is the correlation coefficient for n pairs of data. Values which are significant at the p=5% level are presented in bold text.

In this paper, regression equations which are not significant at the p=5% level will be given only when it is important to demonstrate the contrast with similar graphs at other stations, or when it seems likely that further work might yield a significant correlation. In several instances, it is suspected that relatively minor co-relationships may turn out to be extremely significant in a multi-variant system. At this stage no multi-variant analyses have been carried out.

Plantation Stream at Plantation Swallet, 1966 - 1973

At Plantation Swallet, Atkinson's data and that from Stenner yielded different regression equations correlating total hardness with stream size at the site. The equations themselves gave no clue as to the reasons for the differences. The authors decided to examine regression equations graphically. After plotting the two sets of data on the same graph, Figure 2, the reason for the difference became obvious: One data-point in Stenner's data ($Q^{-0.4} = 0.525$, total hardness = 116) is a serious misfit. On this occasion, water was probably leaking undetected around the weir and the value recorded for the stream size was thus too low. Disregarding this datum, the remaining data for the site were indistinguishable from those of Atkinson. The regression equation for Atkinson's data was:

$$\text{Total hardness} = 549.5 \times Q^{-0.4} + 41.1 \qquad \rho(14) = \mathbf{0.923}$$

That for Stenner's data, including the bad data-point, was:

$$\text{Total hardness} = 86.9 \times Q^{-0.4} + 89.3 \qquad \rho(10) = 0.594$$

That for Stenner's data, excluding the bad data-point, was:

$$\text{Total hardness} = 272.5 \times Q^{-0.4} + 68.7 \qquad \rho(9) = \mathbf{0.898}$$

Finally, that for Atkinson's and Stenner's data, combined, and excluding the bad data-point, was:

$$\text{Total hardness} = 346.3 \times \text{Q-0.4} + 61.3 \qquad \rho(23) = \mathbf{0.788}$$

The apparent difference between the two sets of data had been caused by the distorting effect of a single bad measurement, the decision to represent the regression equation graphically led to this being discovered. Another similar example, at St. Cuthbert's Stream, will be discussed below. In spite of the one bad data-point in Stenner's data set, the combined results show that at Plantation Swallet there was a highly significant relationship between total hardness and stream size in Plantation Stream.

St. Cuthbert's Stream, 1966 - 1973

St. Cuthbert's Stream sank at two points close to one another near the Entrance Shaft, except for the small variable proportion overflowing into Maypole Sink. Between 1969 and 1973, Stenner did not measure the stream size of St. Cuthbert's Stream. In 1969 and 1970, Atkinson measured the stream size of St. Cuthbert's Stream, using a portable V-notch weir.

Water entering the Culvert flowed to the Entrance Pitch, into Arête Chamber as a heavy drip, and from here into the Old Route. In normal flow conditions, or whenever the culvert was dammed, the whole stream used the second (soak-away) sink, close to the bank of the depression. From the soak-away sink, the water flowed to up to six inlets in Arête chamber and Pulpit Passage depending on the size of the stream. The distribution of the water between the surface and the various inlets changed from time to time, probably as a result of movement of boulders in the ruckle between the surface and Pulpit Passage (Stenner, 1997, Tables 1 and 2).

Using Atkinson's data, a highly significant correlation was obtained between the stream size at St. Cuthbert's Stream and that at Plantation Swallet. The regression equation is shown in Figure 3. Figure 4 shows the relationship between total hardness and Discharge Function ($Q^{-0.4}$) in St. Cuthbert's stream. As in Figure 2, Stenner's data for the same relationship, using stream ratio data throughout the cave to estimate the stream size of St. Cuthbert's Stream, are shown together with Atkinson's data. As at Plantation Swallet, most of Stenner's data-points are indistinguishable from those of Atkinson, apart from two data-points which suggest that on those two occasions, the method used by Stenner led to an underestimate of St. Cuthbert's Stream size of approximately 50%.

The distribution of data-points in Figure 4 suggests that there might be a better representation of the total hardness/stream size relationship than the linear regression equation. The dotted line suggests a linear relationship until the total hardness reached a maximum value of approximately 150 ppm as calcite. In summer months, when Atkinson did not measure stream size, total hardness rose further to 180 ppm as calcite, possibly as a result of enhanced biological activity adding extra carbon dioxide to the stream.

We do not consider that the high correlation coefficient shown in Figure 3 is an indication that the two streams shared a common origin. More detailed chemical analysis of samples in 1995 proved conclusively that the former St. Cuthbert's Stream did not pass through the Mineries Pool (Stenner and Stenner, *in prep*). It is likely that the high correlation is a consequence of the proximity and similarity of the two catchment areas.

St. Cuthbert's Stream, 1994 - 1996

Following the diversion of the Mineries Pool Outflow stream into St. Cuthbert's depression, St. Cuthbert's stream is now approximately three times as large as it was before 1985. Figure 5 shows the regression equation between alkaline hardness and Discharge Function ($Q^{-0.4}$) and Figure 6 shows the relationship between alkaline hardness and stream size as a time series between 1994 and 1997. The choice of alkaline hardness may seem curious, because although alkaline hardness, total hardness and calcium obviously share common relationships with many variables, the measurement of alkaline hardness is well known to be more susceptible to errors than total hardness or calcium. The reason for the choice is that between September 1995 and January 1996 there was an unprecedented surge of calcium sulphate in the Pool Outflow stream. The relationship between calcium and stream size and that between total hardness and stream size were less significant than that between alkaline harness and stream size. This is because the calcium sulphate surge had distorted the first two relationships, but had had no effect on the alkaline hardness/stream size relationship. In normal circumstances, the Ca/stream size and the total hardness/stream size regressions would be similar to the alkaline hardness/stream size regression, but with slightly higher correlation coefficients because of the better accuracy and precision of the measurements.

The quantity of data used to assemble the regression equations shown in Figures 2 and 4 is much smaller than that used to examine regression equations presented above, for St. Cuthbert's Stream between 1994 and 1996. However, the proof that no additional water joined Plantation Stream on its journey from Plantation Swallet to Plantation Junction is directly relevant, as are the comments concerning the seasonal nature of stream sizes. Figures 2 and 4 share so many features with Figure 5, it is reasonable to conclude that at Plantation Swallet, and in St. Cuthbert's Stream before 1985, the situation was similatr to that described above; the predominant factor influencing hardness was stream size. Seasonal influences were restricted to an indirect link with stream size.

THE HARDNESS OF INLET STREAMS IN ST. CUTHBERT'S SWALLET AND INFLUENCES ON THE HARDNESS

Hardness and stream size

Measuring the size of inlet streams has proved to be difficult and has been feasible only by extensive application of the Method of Mixtures, using it at each successive stream junction. Most sites are unsuitable for attempting a direct measurement of stream size. This view is confirmed above when comparing Stenner's data with those from Atkinson showed that on two occasions, Stenner's long-winded method led to him underestimating the stream size of St.Cuthbert's Stream at the surface by 50%

This imprecision in the values obtained for the size of inlet streams has certainly reduced the significance of regression equations including the size of inlet streams. Possibly of greater significance, switching of routes between sinks and inlets, from natural causes and by human interference, have caused very great changes in the relative size of inlets. For example, there have been times when the size of the East Inlet in Pulpit Passage has been much smaller than its normal size, although the size of St. Cuthbert's Stream had been unusually high. The consequences of the switches are certain to have had an effect on the hydrochemical characteristics of the inlets involved.

Despite these limitations, we have related changes in hardness to the size of each inlet in the cave, rather than to the size of the parent stream on the surface. The single apparent exception to this rule was at Plantation Junction, which was assumed, backed by the single set of direct measurements, to be a simple, single sink-to-inlet system, where the size of the Plantation Junction inlet was the same as that at Plantation Swallet.

Regression equations between total hardness and Discharge Function ($Q^{-0.4}$) at a number of inlets are shown in Figure 7. At the inlets in the Arête Chamber to Pulpit Passage area from 1994 to 1997 and from Plantation Inlet from 1966 to 1973, the general pattern of the regression equations was similar to that found at G.B. Main Stream (Stenner, 1973), between Tyning's Swallet and Stream Passage. The pattern was also similar to that found in the surface streams, as discussed in the previous section. In every case, the hardness was inversely proportional to the Discharge Function ($Q^{-0.4}$) of the inlet. This is a significant discovery. However, among the data from the Arête Chamber to Pulpit Passage area from 1966 to 1973, the regression equations between total hardness and stream size were all non-significant, with very low correlation coefficients. Why this set of figures failed to give significant data in this period of the study (and only when comparing hardness with stream size, other comparisons yielded positive statistics) is a mystery. Perhaps the proven relative poor precision of the stream size of the inlets is responsible, although it is possible that switching of flow between the possible routes to the Arête Chamber to Pulpit Passage area was responsible for the poor regression statistics from 1966 to 1973.

The hardness of an inlet and the hardness of the surface stream

The relationship between total hardness of inlet streams and that of the surface stream is shown in Figure 8. In these graphs, the 1:1 relationship is shown as a dashed line. Comparison between the regression lines and the dashed line gives a direct indication of the parts of the relationships in which limestone solution was most prominent. Many of the correlation coefficients were high, but more importantly, the result is not what might have been anticipated. The greatest increase in concentrations of dissolved limestone took place when the hardness of the surface stream was low. That is (see Figures 2, 4, 5,7 and 8), when the stream size was high. When the hardness at the surface is low, the potential limestone solution is a maximum, but the time available for this solution to take place is a minimum, because the time of the stream's flow through the zone where solution takes place is a minimum. Figure 8 therefore shows, unexpectedly yet with great certainty, that the size of the potential for limestone solution is a more important factor than the time available for the solution to take place.

This conclusion is very important. High discharge values, when concentrations are translated into quantities, play a magnified part in limestone solution in that part of the cave between the stream sink and the open cave. In fact, the overall role of streams in spate in the transport of limestone is certainly even greater than indicated in the present paper. Newson conclusively showed that in a cave stream in spate, significant quantities of calcium carbonate are transported by the stream as suspended calcite crystals, as a result of the mechanical erosive effects of the stream in spate (Newson, 1971, Smith and Newson, 1974). Suspended calcite crystals were not analysed in the present study. Whenever suspended material was noticed in a sample, it was removed by filtering the water at the time of collection, in the field. In the real situation, the unmeasured quantities of suspended limestone fragments must be added to the estimates for limestone in solution to obtain an estimate of the total limestone load transported by the streams.

HARDNESS CHANGES IN STREAMS IN ST. CUTHBERT'S SWALLET BETWEEN THE SURFACE AND THE INLETS

A different way of examining limestone solution was attempted, so as to avoid weaknesses caused by relatively less reliable stream size data from the cave. The limestone solution between the surface stream and the inlet (ΔTot. hard) was calculated directly. The study of the relationship between limestone solution (ΔTot. hard) between Plantation Swallet and Plantation Junction and Discharge Function ($Q^{-0.4}$) was inconclusive. There were not enough measurements to provide a comparison with a similar conclusive study in G.B. Cave (Stenner, 1973). In G.B., a more intensive study had been made of changes between the surface and the point of the stream's re-emergence in the cave. The results very strongly supported the concept that there was a maximum value towards which the hardness approached, with an enhancement whenever stream temperatures exceeded 12°C. The more limited data from the present study suggested that whenever the total hardness at Plantation Swallet was approximately 150 ppm as calcite, no significant change in total hardness took place between the swallet and Plantation Junction.

The failure to yield positive correlation coefficients between ΔTot. hard and Discharge Function, which was found at the Plantation Inlet, was repeated at the inlets in the Arête Chamber to Pulpit Passage area of the cave.

A different approach was attempted. At several stream inlet sites, regression equations for the relationships between ΔTot. hard and the total hardness of the surface stream were calculated and plotted. The results are shown in Figure 9, and now most of the relationships were significant; or encouraging when the number of data-points was too small to yield a positive conclusion. Regression equations from the Arête Chamber to Pulpit Passage area from 1966 to 1973 were significant, in addition to those from Plantation Inlet and the recent data from the Arête Chamber to Pulpit Passage area. Many of the correlation coefficients were high. Bearing in mind the link that has been established between total hardness and Discharge Function in the surface streams, the new relationships confirmed the fact that increase in dissolved limestone was highest when stream sizes were high.

To amplify this point, from the figures for increase of total hardness at two sites and stream size data, the quantity of limestone passing into solution between the surface and the inlet was calculated, in grams per day. The regression equation between this quantity and the stream size was calculated at the two sites. The results are shown in Figure 10, and are statistically significant. The results quantify the warning published elsewhere (Stenner, 1997), concerning the danger to the continued access to the cave posed by the diversion of Plantation Stream into St. Cuthbert's Stream.

This part of the study has quantified the fact that between the surface and the cave, when stream size goes up, so does the increase of hardness. The change in concentration of limestone in solution goes up when the stream size increases. This means that as the stream size goes up, so does the weight of limestone going into solution in the ruckle and quite dramatically so. It is obviously not a good idea to allow increasing quantities of water to go through strategically important boulder ruckles. This is not hearsay, not simple "common sense" or words of wisdom handed down on tablets of stone by elders. Just plain, measured fact.

HYDROCHEMICAL CHANGES IN THE MAIN STREAM DOWNSTREAM OF PLANTATION JUNCTION

Since 1991, it has been impossible to measure differences between a surface stream and the Plantation Inlet Stream at Plantation Junction. By comparing the data for the present Plantation Inlet stream with those for the former stream, the magnitude of the consequent changes at this site can be assessed. Data summaries for the Main Stream at Beehive Chamber have confirmed a significant change at this site (Stenner, 1997; Table 3, p.15). The relationships between total hardness and Discharge Function ($Q^{-0.4}$) at the combined stream at Beehive Chamber before and after the stream change are shown in Figure 11. This figure shows the change in hardness profile at the site, as well as the fact that the recent sampling trips included several in very high water conditions! More data points (from less extreme stream levels) will clarify the present relationship between total hardness and stream size downstream of Plantation Junction. But furthermore, Figure 11 shows that the relationship between total hardness and Discharge Function at the site has undergone a fundamental change. This is in spite of the fact that the present total stream size below Plantation Junction is the same as it would have been previously (the Plantation Stream change has only changed the route of the stream to the same point). This consequence could not have been foreseen.

TEMPERATURE CHANGES IN STREAMS IN ST. CUTHBERT'S SWALLET BETWEEN THE SURFACE AND INLETS

When changes in temperature of a stream between the surface and the cave are being investigated, it is important to be able to determine whether the water temperature is tending to attain a constant temperature. If so, it is important to determine what this temperature is. Studies from G.B. Cavern, St.Cuthbert's Swallet, Wookey Hole Cavern and Swildon's Hole have all shown that inlets deep within the cave have a temperature, which varies from one inlet to another, towards which the inlet water trends and which does not vary from winter to summer. However, in the case of inlets fairly close to the surface which are derived from surface streams, the "stable" temperature may vary slightly.

For example, at both the East and Main West inlets in Pulpit Passage, water emerges from the Soakaway Sink. From 1965 to 1974 there were 9 pairs of temperature measurements at each site describing temperature changes from the surface stream to the inlet. The mean temperatures of the inlet streams were 8.3 and 8.5 °C respectively (standard deviations were 0.82 and 0.64 °C respectively). At both sites, whenever the surface temperature was over 9°C, the water temperature fell on emerging at the inlet, and whenever the surface temperature was below 8 °C at the surface, the water temperature rose. However, when the surface temperature was between 8.0 and 8.2 °C, the water temperature sometimes rose and sometimes fell. This may be because a large flow of surface water locally changed the ambient temperature of the rocks through which the water flowed.

As a result, when attempts were made to find the ambient temperature of major stream inlets relatively close to the surface, using cumulative data from the site, anomalies were found, whatever temperature was chosen. The best that can be done is to estimate the temperature which leads to the smallest number of anomalies. This procedure was used in G.B. main stream (Stenner, 1973; p213), and in St. Cuthbert's Swallet, and is probably valid for use in temperature studies in all caves in locations where there are pronounced seasonal variations.

Estimates for the "stable ambient temperature" of the major inlets were chosen; Pulpit Passage East Inlet, 8 °C; Pulpit Passage Main West Inlet, 8 °C; Plantation Inlet (pre 1986), 10 °C. It was then possible to relate the observed temperature change (from surface to the inlet) to the estimated potential change. In the case of all six inlets studied in the period 1965 to 1973 for which sufficient data points were available there was a significant (at the 5% probability level) direct correlation between the observed change and the potential change. Some of the correlation coefficients were very high, suggesting very strongly that the concept of a potential temperature is a valid one. Strangely, data for the more recent studies gave only a single significant correlation between temperature change and potential temperature change (Figure 12). Possibly the unreliability of electronic thermometers is responsible, alternatively the unusually high range of stream size values, caused by the change of route of Plantation Stream, compounded by diversion of the stream from the Soak-away Sink may have been responsible.

Next, the observed change was calculated as a percentage of the potential change. This quantity, which has obvious usefulness in cave studies, had been investigated in G.B. Cave, where 10 sets of data were available. Two regression equations were found, using the estimate of 7.5°C for the ambient temperature (where |Ti - Ts| represents the numerical difference between temperature of inlet and temperature at surface).

$$\frac{|Ti - Ts|}{|Ti - 7.5|} \times 100 = -0.035Q + 9.3 \qquad \gamma(10) = -0.61$$

$$= -8.0\,|Ti - 7.5| \qquad \gamma(10) = \mathbf{-0.75}$$

At all inlets where there were sufficient data, regression equations between the increase as a percentage of the potential ΔT and stream size were calculated. The relationship was encouraging at the Plantation Inlet.

Finally, regression equations between the temperature increase as a percentage of the potential ΔT and the potential ΔT was calculated. The relationship in the Plantation Inlet at Plantation junction was encouraging. That at pulpit pitch, 1994-97 is shown in Figure 13. No multi-variant analyses have been attempted.

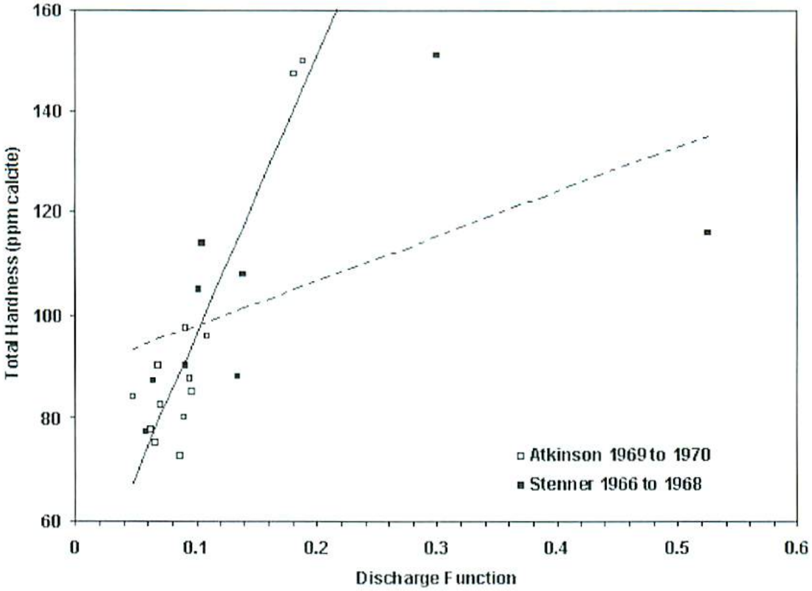


Figure 2. *Total Hardness and Discharge Function ($Q^{-0.4}$) at Plantation Swallet (a) 1969 and 1970 (Atkinson) and (b) 1966 to 1968 (Stenner).*

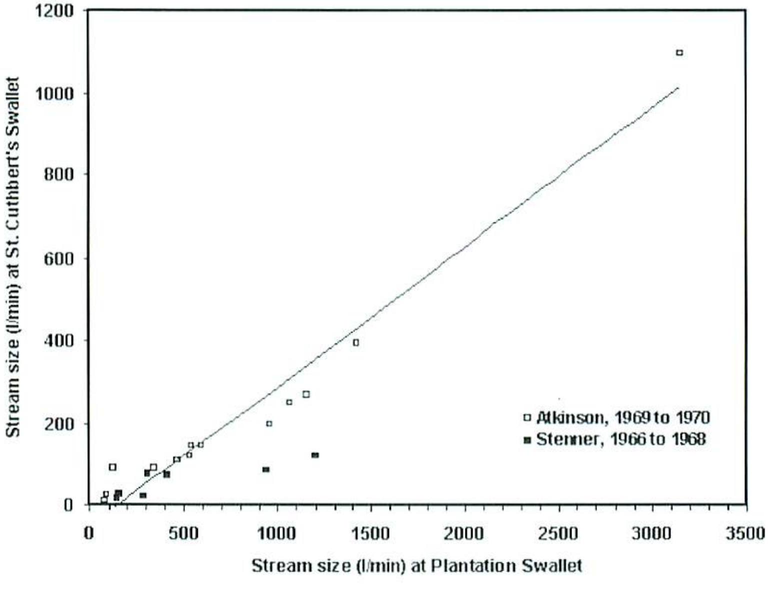


Figure 3. *Stream size at St. Cuthbert's Swallet and stream size at Plantation Swallet (a) 1969 and 1970 (Atkinson) and (b) 1966 to 1968 (Stenner).*

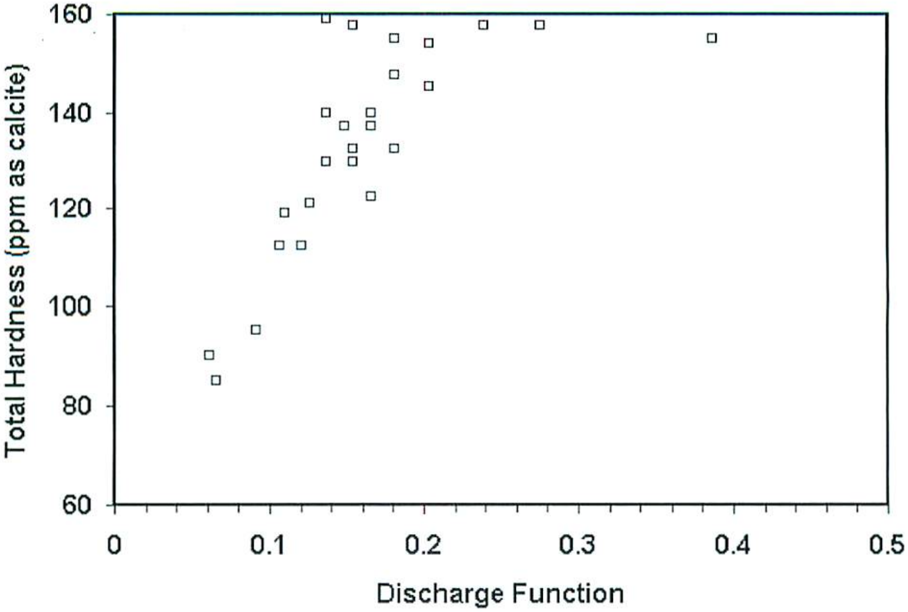


Figure 4. *Total Hardness and Discharge Function ($Q^{-0.4}$) at St. Cuthbert's Swallet (from Atkinson, 1971).*

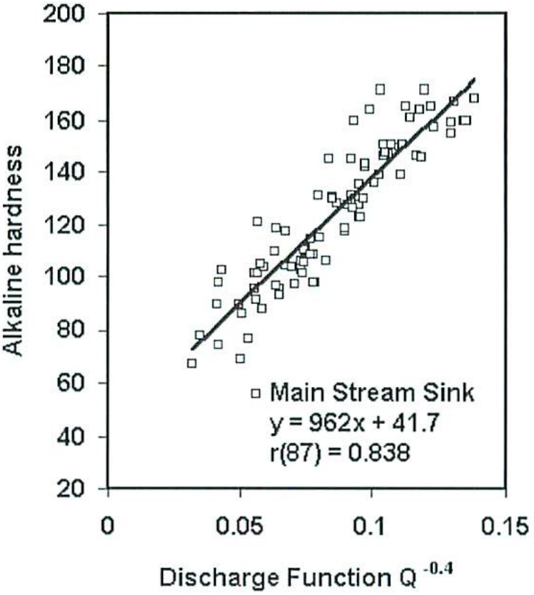


Figure 5. *The relationship between alkaline hardness (ppm as calcite) and Discharge Function ($Q^{-0.4}$) at the Main Stream Sink, 1994-97.*

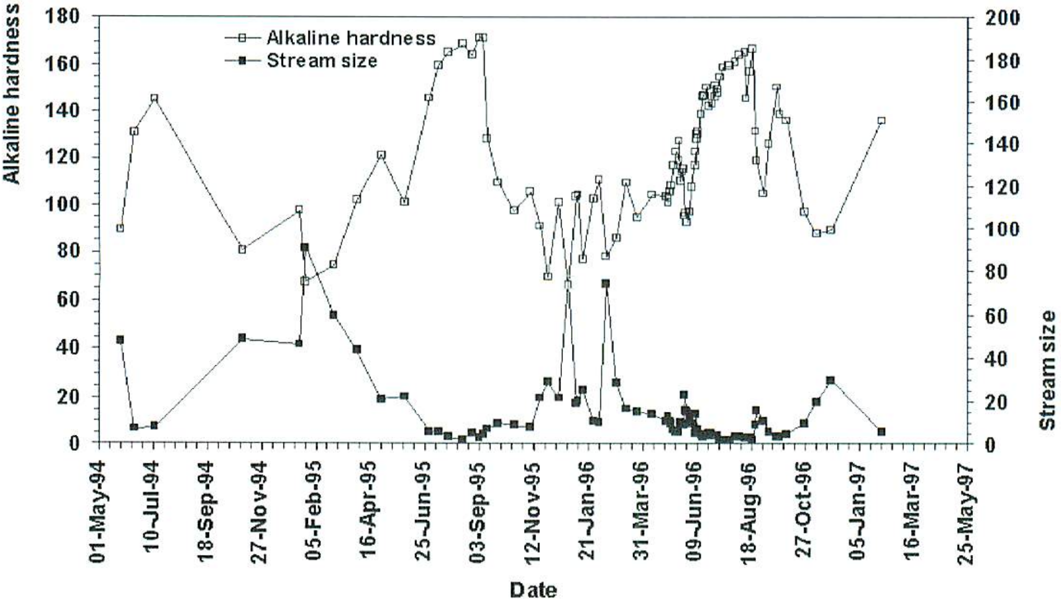


Figure 6. *Alkaline hardness (ppm as calcite) and stream size (litres per minute) at St. Cuthbert's Stream, Main Stream Sink, May 1994 to February 1997. The data-point marked in grey is an estimate, the salt dilution having failed.*

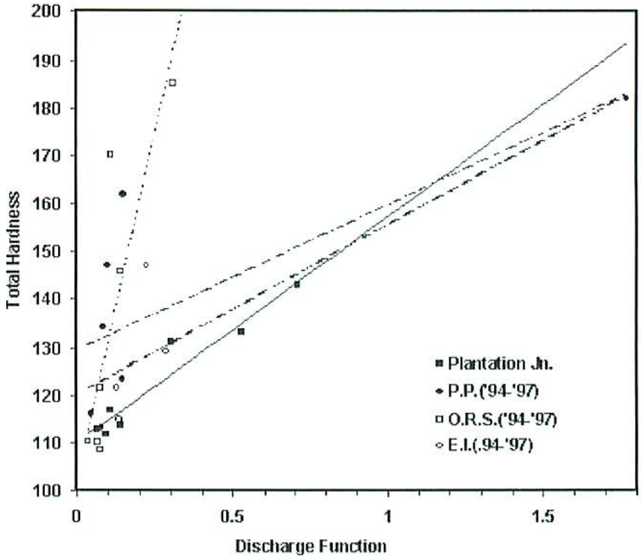


Figure 7. *Total Hardness of inlets and Discharge Function ($Q^{-0.4}$) at (a) Plantation Inlet ('66 - '71), (b) Pulpit Pitch ('94 - '97), (c) Old Route Stream ('94 - '97), and (d) Pulpit Passage East Inlet ('94 - '97).*

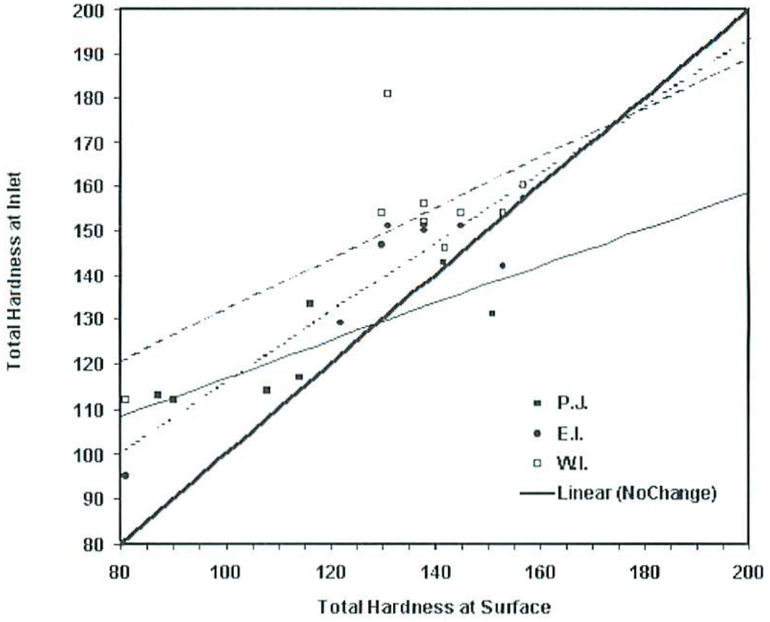


Figure 8(a)-(c). *Total Hardness of Inlet and Surface Stream (ppm as calcite) at (a) Plantation Inlet, Pulpit Passage - (b) East Inlet and (c) West Inlet (all 1966 - 1973).*

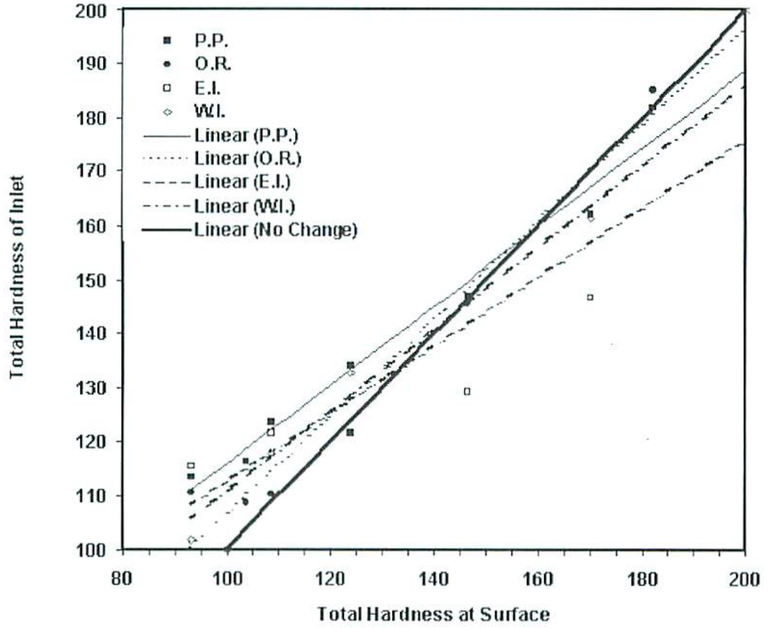


Figure 8 (d)-(g). *Total Hardness of Inlet and at Surface Stream (ppm as calcite), at (d) Pulpit Pitch, (e) Old Route Stream,, (f) Pulpit Passage East Inlet and (g) Pulpit Passage West Inlet, all 1994 - 1997.*

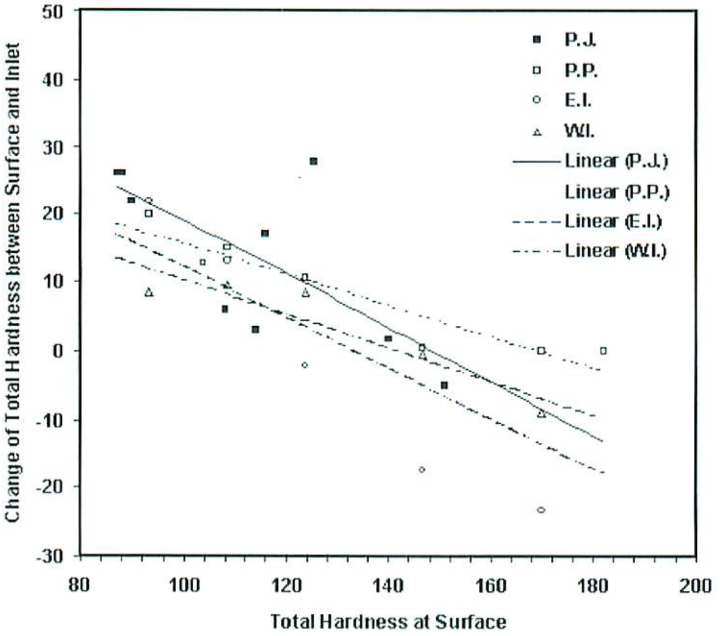


Figure 9. *Change of Total Hardness between Swallet and Inlet related to the Total Hardness of the surface stream, at (a) Plantation Inlet ('66 - '71), Pulpit Passage - (b) Pitch, (c) East Inlet and (d) West Inlet ('94 - '97).*

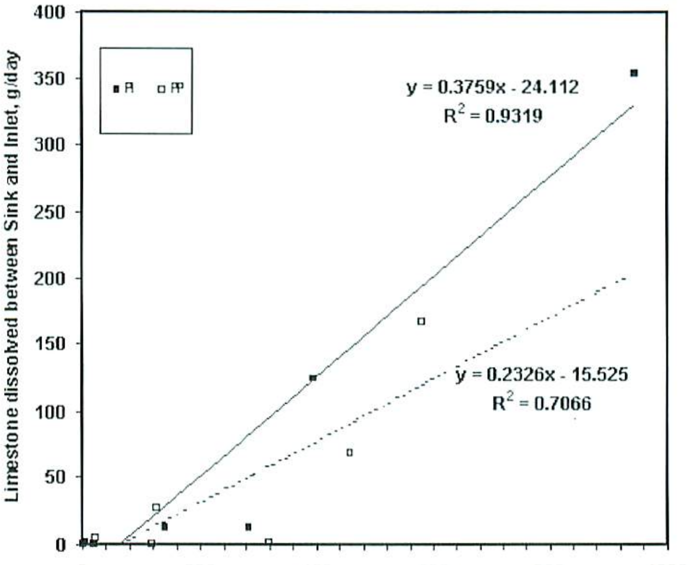


Figure 10. *Limestone dissolved (in grams per day) between swallet and inlet related to stream size (litres/min), at (a) Plantation Inlet ('66 - '71) and Pulpit Pitch ('94 - '97).*

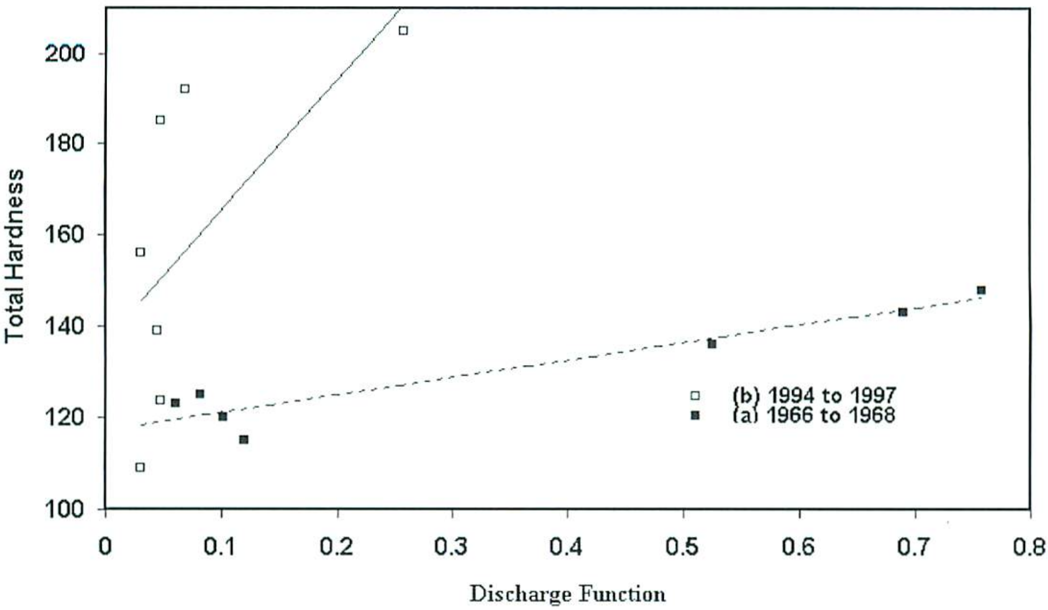


Figure 11. *Discharge Function ($Q^{-0.4}$) and Total Hardness of St. Cuthbert's Swallet Main Stream at Beehive Chamber in (a) 1966-1968 and (b) 1994-1997.*

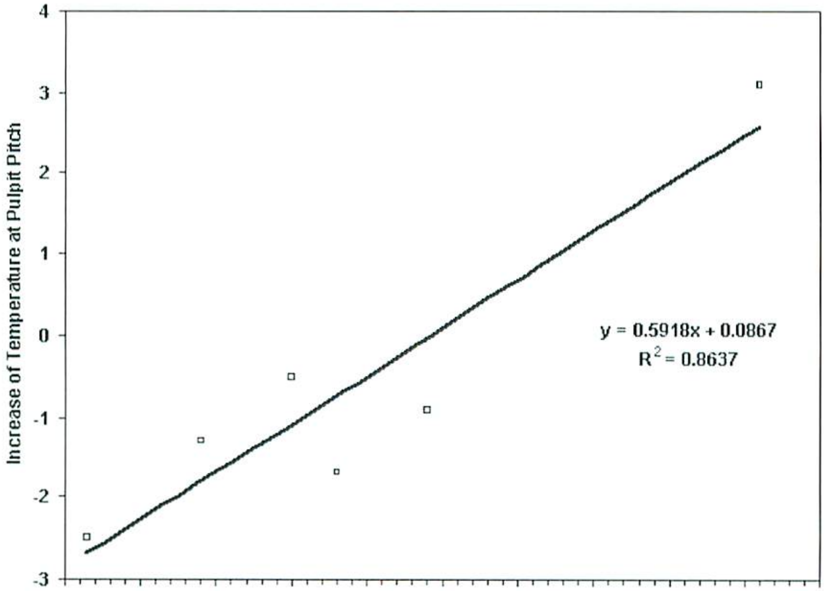


Figure 12. *Increase in temperature of New Route Stream at Pulpit Pitch, 1994 - 1997, related to the potential increase of temperature.*

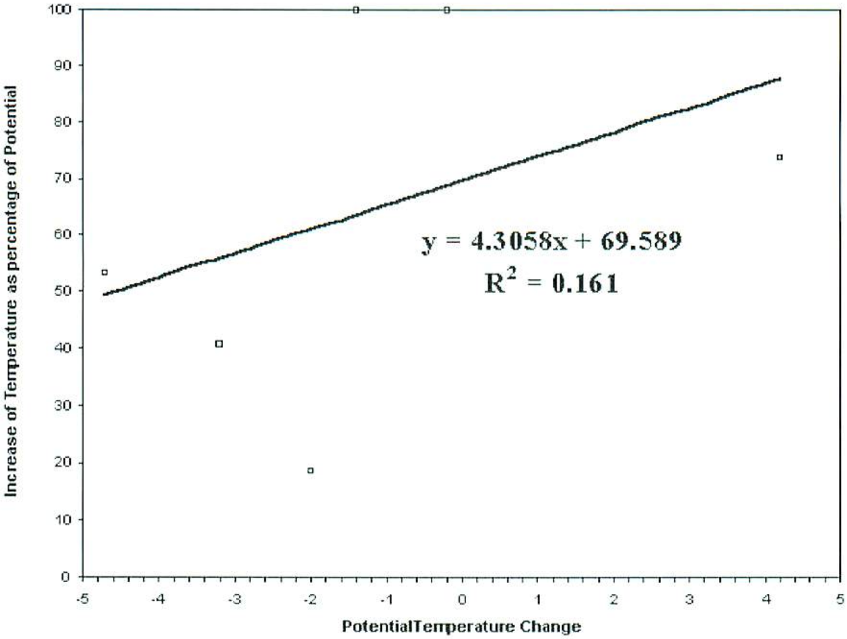


Figure 13. *Increase in temperature of New Route Stream at Pulpit Pitch, 1994 - 1997, as a percentage of the potential increase in relation to the potential increase.*

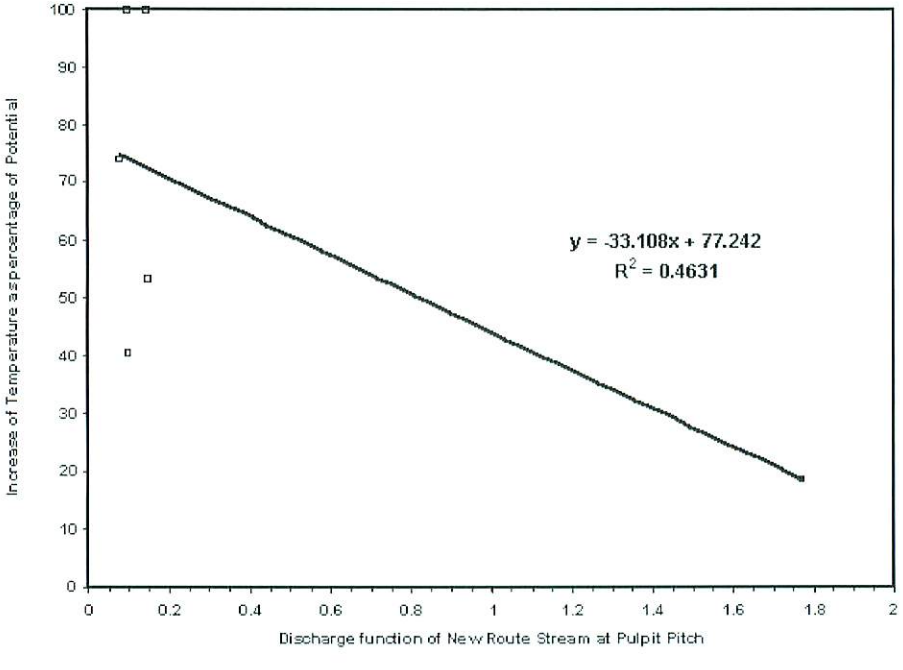


Figure 14. *Increase in temperature of New Route Stream at Pulpit Pitch, 1994 - 1997, as percentage of potential increase in relation to Discharge Function ($Q^{-0.4}$).*

CONCLUSIONS

1. At every site where water flowed from a surface stream sink to an inlet in the cave, there were changes in calcium, magnesium and bicarbonate. Rather than being caused by admixture with water percolating from a different source, these changes were caused by limestone dissolving in the stream in the space between swallet and the open cave.
2. When the size of a surface stream rises, concentrations of many solutes in the stream, including calcium and bicarbonate, fall. However, as water flows from swallet to open cave, at every site in St. Cuthbert's Swallet which has been examined, solution of limestone takes place, the increment in concentration of dissolved limestone increasing as stream size rises.
3. Although the total volume of the streams entering the cave is the same as it was previously, the hydrochemical characteristics of the Main Stream downstream of Plantation Junction has changed. The change is not limited to an increase in the hardness of the stream; although the number of data points is small, it is clear that the response of the total hardness to stream size has undergone a major change.
4. Regression equations relating temperature changes between surface sinks and inlets with many factors were investigated. Among recent data, no significant relationships were found in the recent data between temperature changes and potential temperature changes. This important failure may have been a consequence of the switch to electronic thermometers, or it may have been a consequence of the enormous variability of stream size at the various inlets, caused by switching of flow routes (including that of Plantation Stream).

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