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REPEATED DYE TRACES OF UNDERGROUND STREAMS IN THE MENDIP HILLS, SOMERSET

by

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ABSTRACT

Three underground streams were dye traced as many as twenty-four times, at various flows between the extremes of flood and drought. This systematic study, the first of its kind to our knowledge, has shown that:

1. Travel time (the time between input of dye at the swallet and its first arrival at the resurgence) is inversely proportional (1:1) to mean resurgence output over the same period. This is characteristic of simple phreatic streams, which should be distinguishable using graphic analysis from vadose and complex phreatic streams.
2. Rhodamine WT dye, the most stable of the common fluorescent dyes, is progressively lost, to a significant and unpredictable extent, in transit from swallet to resurgence. Successful tracing therefore requires more dye at low flows than at high flows.

BACKGROUND

Water tracing in the Mendip caves has a long and distinguished history (Barrington and Stanton 1977, 209–213). The early experimenters, beginning at Wookey Hole Cave (ST 532.480) in 1860, used chaff, dyes or coloured powders, hoping for results visible to the naked eye.

The modern phase of water tracing began in 1965 using the spores of a moss, *Lycopodium clavatum,* which were flushed down the swallets and caught at the resurgences in plankton nets. For the first time the tracing agent could not be detected by the unaided senses, and some attempt at quantitative analysis of results could be made (Atkinson, Drew and High 1967; Drew, Newson and Smith 1968).

Spore tracing suffered from certain practical disadvantages and by 1970 it gave way to dye tracing. Fluorescent dyes were put into the swallet streams and detected, using a fluorometer, in water samples taken from the resurgences. Dye concentrations could be measured accurately, and dilution, percentage recovery, etc., could be calculated. The tracing potential and acceptability of many dyes were evaluated (Smart and Laidlaw 1977) and the most generally useful one proved to be the red dye Rhodamine WT.

By 1980 about 90 Mendip swallet streams had been proved to feed one or more of the resurgences. There had been cases, however, where the dye had failed to show up at a resurgence, even when the connection had previously been proved, and dye tracing sometimes failed to confirm, or actually contradicted, connections that had apparently been proved by spore tracing.

It was realised that the time interval between the input of dye at the swallet and its first appearance at the resurgence (travel time) was

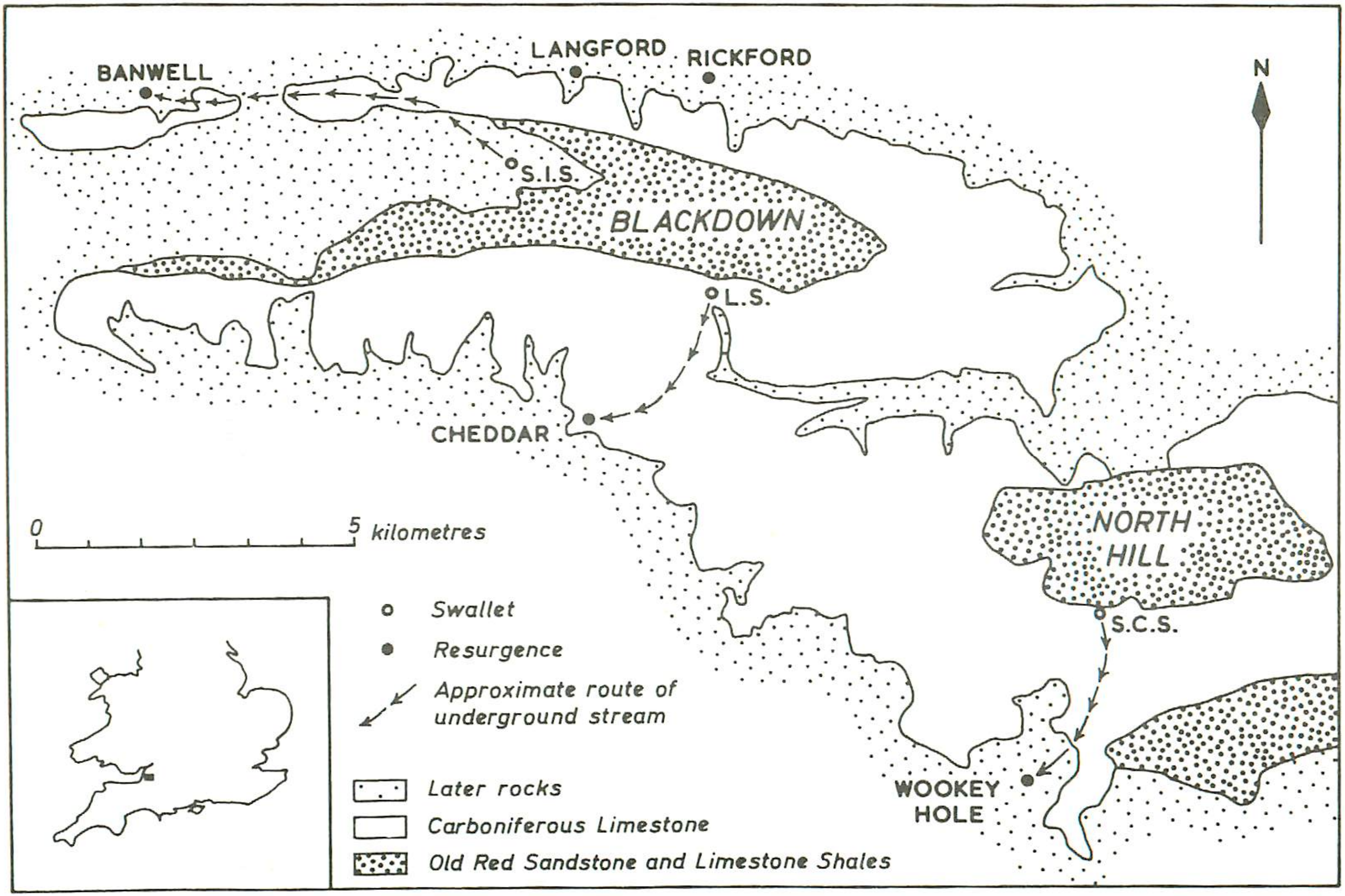

Fig. 10: Simplified geological map of the central Mendips, showing the three tracing sites. S.I.S. = Swan Inn Swallet, L.S. = Longwood Swallet, S.C.S. = St. Cuthbert's Swallet.

influenced by, among other factors, the state of the underground stream: short travel times normally occurred in floods, and long ones in dry weather.

The present studies were undertaken following a comment by Barrington and Stanton (1977, 213): "Repeat traces on a single swallet-spring connection, to show the size of the time variable, have yet to be undertaken. It is possible that academic study could establish factors relating travel times to a scale of standard flows at a Mendip spring with a permanent flow-gauging station . . .".

THE DYE TRACES

Three underground streams, each known to feed a resurgence at which flows were measured at least once daily, were chosen for the 1977–79 experiments (Fig. 10). The connection between St. Cuthbert's Swallet (ST 543.505) and Wookey Hole Cave, first proved in 1860, was traced 15 times (W.I.S.): Longwood Swallet (ST 486.557), spore-traced to Cheddar Springs in 1967, was traced 24 times (P.L.S.): and Swan Inn Swallet (ST 486.579), dye-traced to Banwell Spring in 1977, was traced 4 times (W.I.S.).

In all traces the dye used was Rhodamine WT. A known weight of dye in the form of 20% aqueous solution was poured slowly into the swallet stream. At the resurgence an automatic sampler took water samples at 2-hour intervals. These were analysed in a Turner fluorometer using filters that only permit light at the Rhodamine WT wavelength to pass.

The Cuthbert's to Wookey Hole traces

In 12 out of the 15 traces, input was 100ml. of 20% dye solution (23.8g. of dye). The other inputs were 150ml. (twice) and 200ml. Water samples were taken at Wookey Hole Paper Mill (ST 532.478), 200m. downstream of the resurgence. Resurgence output was continuously monitored at the Bristol Waterworks Company's flow measuring station on the River Axe at Henley (ST 527.458). Although this is 2km. downstream of the resurgence, the only significant addition to flow in the Axe between the two, except in the wettest weather, is about 2 Ml/d. (megalitres per day; 1 Ml. is 1000 cubic metres) from Glencot Spring (ST 532.470). Much of the flow from this spring is known to derive from leaks in the bed of the Axe inside Wookey Hole Cave (Stanton 1974), so the flow at Henley is almost a replica of true resurgence output.

Fig. 11A shows conclusively that, in this particular underground system, travel time is inversely proportional to resurgence output. Over the whole range of flows from flood to drought, doubling the output almost exactly halves the travel time. The curve is unique to this underground connection, and is discussed more fully in a later section.

Fig. 11B gives details of 13 of the 15 traces (one, not shown, was incomplete due to sampler breakdown, and the other was omitted for the

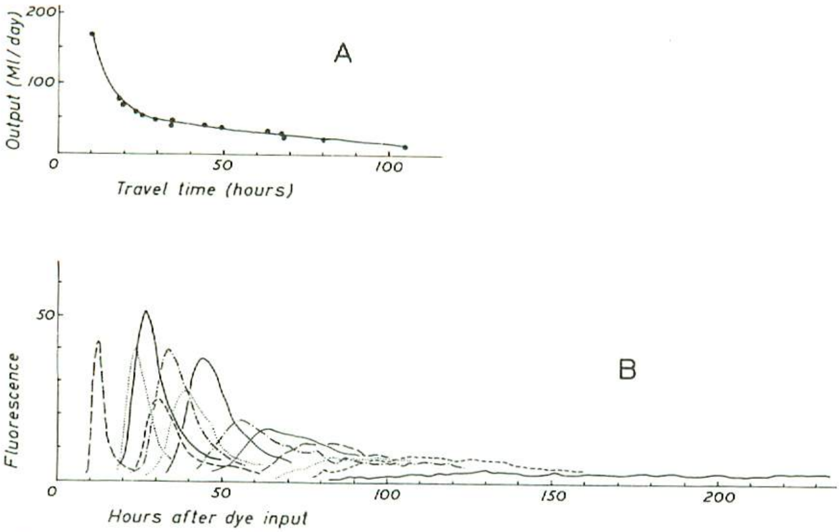

Fig. 11: The Cuthbert's to Wookey Hole traces. A: Resurgence output plotted against travel time. B: Fluorescence at the resurgence (converted to equivalent of 100ml. dye input in each case).

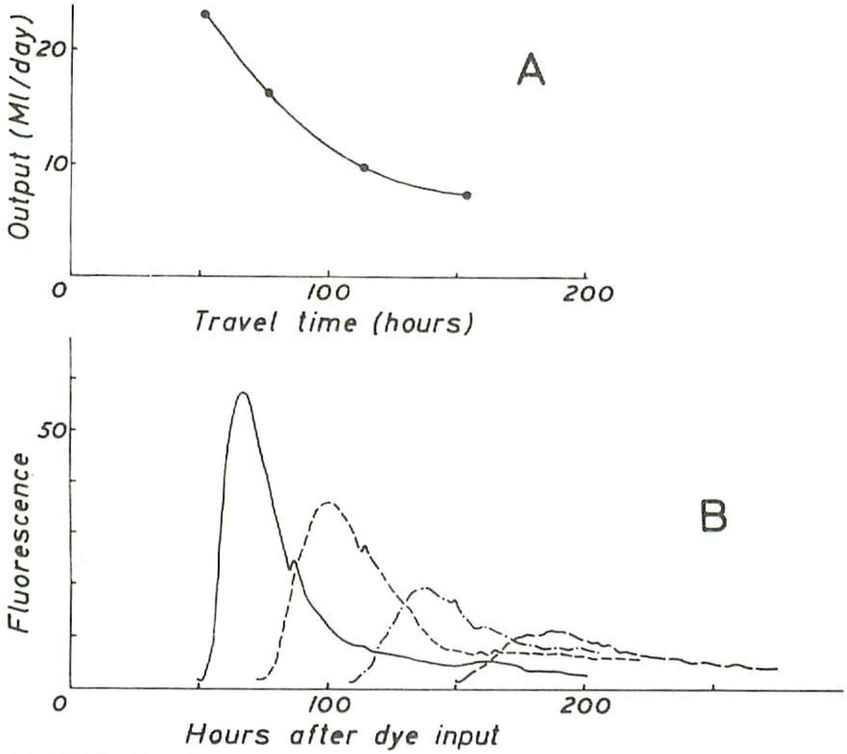

Fig. 12: The Swan Inn to Banwell traces. A: Resurgence output plotted against travel time. B: Fluorescence at the resurgence (converted to equivalent of 250ml. dye input in each case).

sake of clarity in the diagram). There are some unexpected features. It had been supposed that dye concentrations would be lower at high flows, because of extra dilution, but the opposite is true. At very low resurgence outputs the dye can hardly be detected. Dye concentrations can also vary markedly between traces at the same resurgence output. These matters are discussed below.

The Swan Inn to Banwell traces

In the 4 traces, either 200ml. or 250ml. of dye solution (48g. or 60g. of dye) was used in individual tests. Input at the swallet was not straightforward because the stream is easily diverted from it; if re-diversion was necessary the input of dye was delayed for 24 hours to allow normal underground flow conditions to become established. The water sampler was installed in the Bristol Waterworks pumping station beside Banwell Spring (ST 399.592). Flow at the pumping station was measured once daily.

The results of these traces, plotted as Figs. 12A and 12B, are almost identical to those of the St. Cuthbert's to Wookey Hole traces. Similar deductions can be made, and are discussed below. A curiosity is the tiny peak on the falling limb of each of the fluorescence curves. If it really exists (and it depends on a single sample in each case) it could indicate the presence of a minor oxbow to the underground stream, causing delay in the arrival of a small part of the dye.

The Longwood to Cheddar traces

In the 24 traces, from 84ml. to 360ml. of dye solution (20g. to 80g. of dye) was used in individual tests. Dye input was to the stream just above the highest known sink, 50m. upstream of the cave entrance. The dyed water sank at several places between here and the wet-weather sink 80m. further down the valley. The combined flow from all the Cheddar springs was sampled immediately downstream of the roadside lake (ST 465.539). Resurgence output was continuously monitored at a specially constructed University of Bristol gauging station, accurate to ± 10%.

Fig. 13A shows that, as at Wookey Hole and Banwell, travel time is inversely proportional to resurgence output. However, although the fluorescence/time diagram, Fig. 13B, is also similar in that the highest fluorescence peaks occur at high resurgence outputs, it is greatly complicated by the presence of up to 3 peaks in any one trace. This indicates that several alternative conduits were available for the dyed water to follow on its way to the resurgence. For the sake of clarity, only 7 selected curves are presented in Fig. 13B. Further analysis of the multiple-peaked curves is currently being undertaken (P.L.S.)

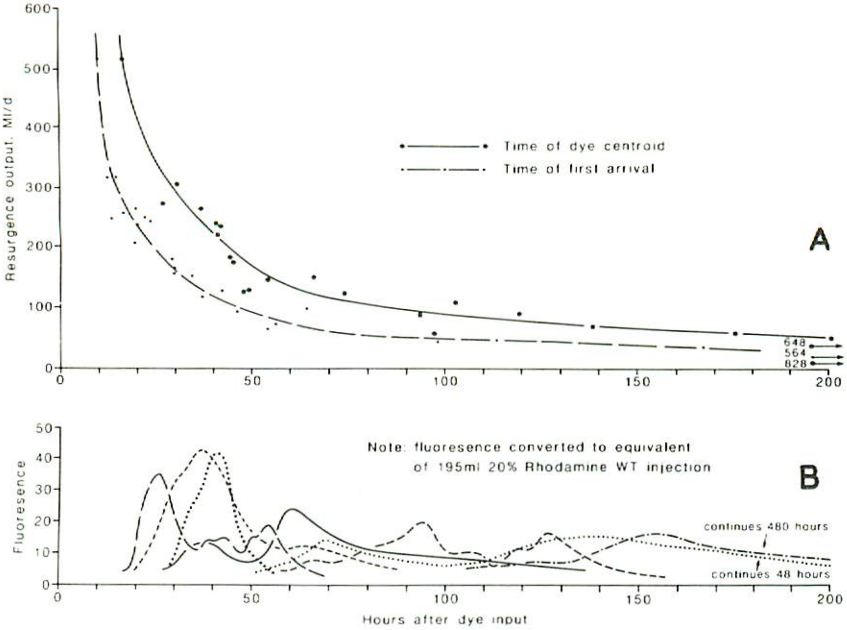

Fig. 13: The Longwood to Cheddar traces. A: Resurgence output plotted against travel time (first arrival) and against time to recovery of half the dye injected (dye centroid). B: Fluorescence at the resurgence.

DISCUSSION

A) Travel time relationships

It is not surprising that travel times are inversely proportional to resurgence output. A *phreatic* (water-filled) cave system is, in its simplest form, like a water pipe: its capacity is virtually constant, so if water is pushed in twice as fast at one end it flows through the system in half the time. Variations are introduced when phreatic streamways of different lengths, draining different areas, join; but for simple swallet-resurgence connections the rule is probably general—unless the catchment is so extensive that rainfall is not uniformly spread over it. In such a case travel times could depart from the norm, depending on the relative positions of the input site and the local rainstorm. (If, for example, heavy rain fell at a point between the resurgence and the input site, the swallet water could be ponded back and the travel time longer than expected.)

It may be argued that a phreatic cave system cannot be compared to a simple water pipe because it consists of a complex of branching conduits of different bore sizes. But just as in surface rivers the average bore size of a segment of phreatic tunnel, be it major waterway or minor tributary, is related to the volume of water that regularly flows through it, so that in either case a doubling of the throughput will halve the travel time. Proportionality is maintained all through the phreatic network.

Fig. 14 is a log-log plot of travel times against resurgence outputs, with best-fit straight lines calculated and drawn. The gradients of nearly unity express the inversely proportional relationship typical of water pipes and dominantly water-filled caves, and the closeness of the individual points to the straight line (i.e. the nearness of the correlation coefficient to 1) is a measure of the simplicity of the hydraulic connection.

It may be assumed that the output – travel time relationship of any simple underground hydraulic connection could be plotted as a best-fit straight line on Fig. 14, where each would have its unique position, gradient and length (the latter limited at one end by maximum flood capacity and at the other by the drying-up of the swallet stream). More complex systems would be represented by connected straight lines of various lengths and gradients.

In a *vadose* (largely air-filled) cave system there is an appreciable increase in the volume of contained water when levels rise in a flood. Thus, although travel times will normally shorten as resurgence output increases,

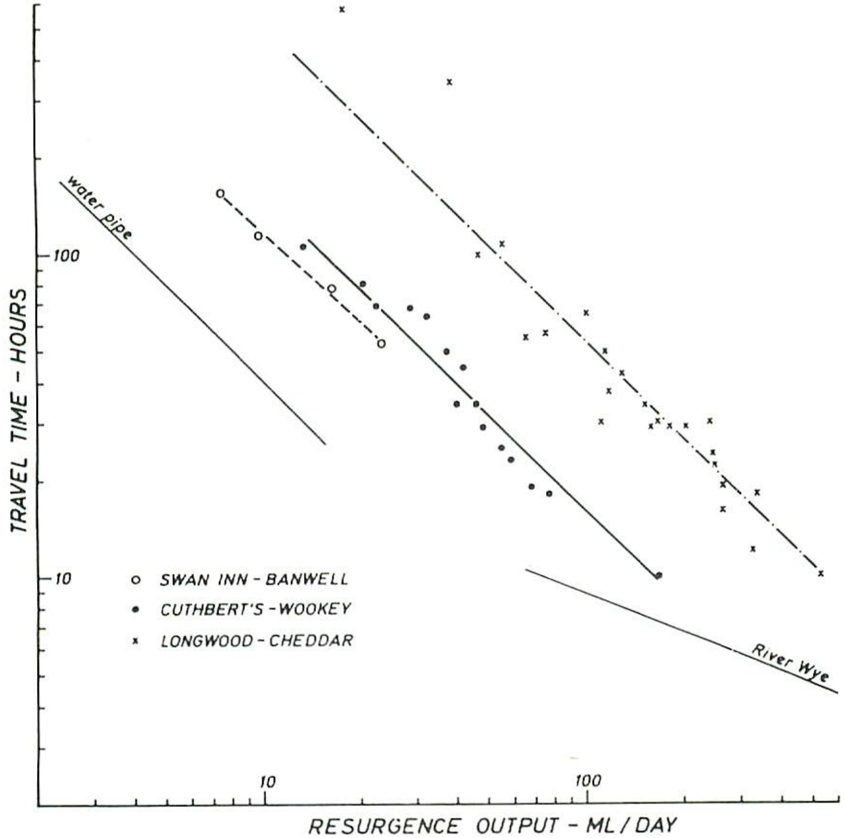

Fig. 14: Travel time relationships of the traced streams compared to a water-filled pipe and a surface river.

the change will be less pronounced than in phreatic caves. In extreme cases travel times could actually lengthen, as might happen if, for example, a doubling of resurgence output more than doubled the volume of contained water by flooding large chambers.

The characteristic feature of a vadose hydraulic connection, plotted on Fig. 14, should be a gradient significantly gentler than unity. This is in fact typical of surface rivers (such as the River Wye, Fig. 14, based on Fig. 2.5 of N.E.R.C. 1975), which, except in floods, are like vadose caves. (In floods, rivers overflow their banks causing travel times to lengthen, so that the gradient as plotted levels out and then reverses. Totally flooded caves, however, are effectively phreatic, with steeper gradients.)

These theoretical differences between vadose and phreatic travel times were used to predict that simple phreatic caves dominate in the unexplored regions between St. Cuthbert's Swallet and Wookey Hole Cave (Stanton 1978). The same is evidently true of the Swan Inn to Banwell and Longwood to Cheddar systems. Smart and Hodge (1979) showed by a pulse-wave experiment that at low flow only 9% of the Longwood to Cheddar conduit is vadose. Mendip streamways seem, indeed, to be mostly phreatic, unlike those of some other British cave regions.

Stanton (1981) used the straightforward relationship between resurgence output and travel time to calculate *standard travel times* (travel times at mean resurgence output) for St. Cuthbert's Swallet and other swallets of the Wookey Hole system, on the assumption that this is a simple phreatic system. Comparison of standard travel times and velocities gives a truer picture of the relative behaviours of different underground streams than has hitherto been available, and the standard travel time can be used to predict actual travel time, swallet to resurgence, for any resurgence output.

In contrast to the Wookey Hole, Banwell and Cheddar systems, the underground drainage system that discharges at both the Langford and Rickford resurgences (Fig. 10) has been shown to be highly complex (Drew, Newson and Smith 1968, Newson 1972, Crabtree 1977). Crabtree traced 5 hydraulic connections twice, and found that in 3 of them the travel time was longer at the higher resurgence output. General considerations suggest that these results, if borne out by more detailed work, will be diagnostic of an exceptional phreatic system rather than a vadose one.

B) Dye Losses

The outstanding feature of the fluorescence curves, Figs. 11B, 12B and 13B, is the way that the fluorescence (i.e. dye concentration) peaks weaken as travel times lengthen and resurgence output falls. More dye is therefore needed to produce satisfactory results at low flows than at high flows. The question must be asked: is there a progressive real loss of dye, through absorption or adsorption, with time; or is the loss only apparent, because the dye has time to mix with greater volumes of water, thus becoming more dilute?

There is no doubt that, although Rhodamine WT is less vulnerable than most other dyes, it can be permanently lost during underground transit. In a recent experiment (Stanton 1981) 4300ml. of this dye (1025g.) was injected into a stream in Singing River Mine (ST 445.574) at Shipham, West Mendip, under high flow conditions. In spite of intensive sampling of all local resurgences, likely and unlikely, for 80 days after input, no vestige of this exceptionally large quantity of dye was detected.

Stanton (1981) describes other cases where Rhodamine WT dye failed to reappear, even in swallet-resurgence connections that had previously been proved by spore tracing.

On the other hand, percentage dye recoveries were calculated for each of the Longwood to Cheddar traces, and the real loss of dye was found to be small, about 5% per 50 hours after input (Fig. 15). At low flows the fluorescence peaks were found to have very long tails which contained significant quantities of dye. The lowest calculated recovery was 77%, at extremely low flow when the dye pulse took 600 hours to clear the resurgence.

Few of the St. Cuthbert's to Wookey Hole traces were sampled to the absolute end of the dye pulse, but in 6 cases it is possible to extrapolate the curves with some confidence. They indicate (Table 4) dye losses on a more serious scale.

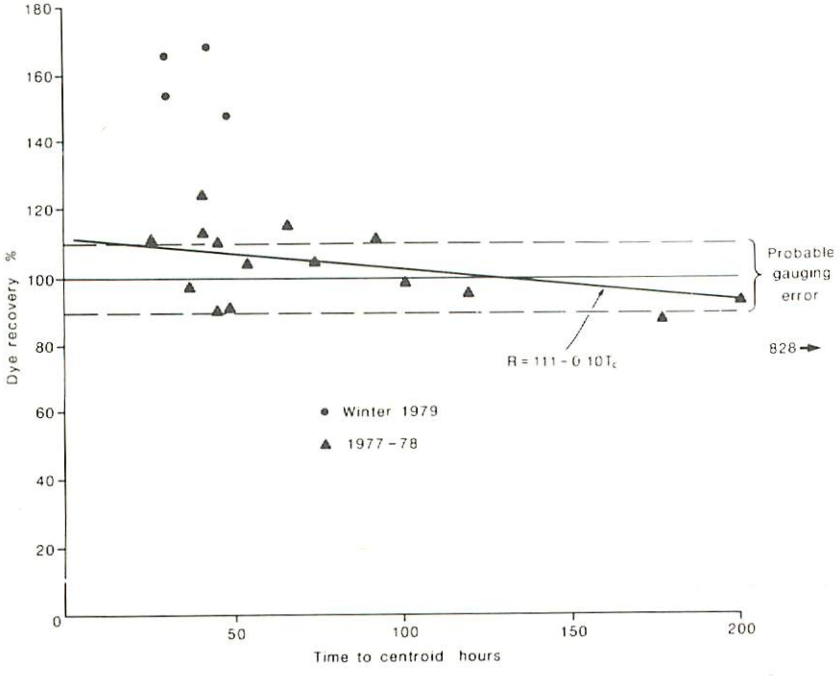

Fig. 15: Dye recovery in the Longwood to Cheddar traces.

TABLE 4

Trace	1	2	3	4	5	6
Travel time (hours)	10	23	25	29	67	105
(days)	0.42	0.96	1.04	1.2	2.8	4.4
Mean resurgence output during trace (Ml/day)	168	56	52.2	45.6	29.1	13.7
Duration of dye pulse (days)	0.58	2.5	2.6	2.4	5.5	9.2
Mean fluorescence during dye pulse	11.9	5.1	8.7	6.9	3.2	1.1
Dye recovery (%)	100	62	102	66	44	12
Total resurgence output between dye input and end of pulse (Ml)	168	196	188	164	242	186

A seventh trace at a considerably lower resurgence output would have been possible but was not, unfortunately, attempted because it was assumed that the dye would all be lost.

Even at quite high flows there may be unpredictable variations in dye recovery. In Fig. 11 B the fluorescence peaks with travel times of 23 and 25 hours (traces 2 and 3 in Table 4) are of notably different sizes, although resurgence outputs were nearly the same. The higher peak marks the passage of 164% more dye than the smaller one.

A possible reason for the percentage dye losses being greater at Wookey than at Cheddar is that dye inputs at the former were smaller, so that the loss of an absolute quantity of dye per day would have a proportionately greater effect.

The hypothesis that dye would be more extensively dispersed within the conduit at low flows was roughly tested by injecting dye into an imitation swallet-resurgence system set up in the domestic bath (W.I.S.). In 6 visual 'traces' at progressively reduced flows (the greatest flow being 23 times the least) it was seen that:

a) dye penetration into dead ends was more effective at higher, more turbulent, flows.

b) dye clearance from wide lakes was relatively slower at low, less turbulent, flows. Long tails were produced.

c) Dye streaming was more marked at low flows, resulting in a more concentrated peak arrival of dye at the outlet than at high flows (an effect not seen in real traces).

d) after dye input, the volume of water required to clear dye from the system was about the same whatever the flow (a feature of the Cuthbert's to Wookey traces, Table 4, last line).

It is tentatively concluded that the main reason for the weaker fluorescence peaks at low flows is that dye is progressively lost with time. The loss may be less obvious when large amounts of dye are used. Losses can be small in one hydraulic system, and great or total in another. In systems with small dye losses there is significant dispersion into the tail at low flows, and this may result from the trapping of dye in semi-static ponded zones. The great lengths of the tails at low flows simply reflects the time necessary for the low resurgence output to clear the dispersed dye pulse from the system.

The causes of dye loss are debatable, and probably multiple, but as shown by Smart and Laidlaw (1977) Rhodamine WT can be absorbed on contact with cave materials such as rock, mud and organic substances. The last mentioned are particularly potent dye scavengers.* All swallet streams carry organic material at times, some more than others. It is therefore not surprising that dye loss increases as the time available for absorption to take place lengthens, and that percentage loss may vary unpredictably.

The present series of tests were not designed to investigate dye losses, and firm conclusions must await more detailed studies.

CONCLUSIONS

1. Travel times in the swallet-resurgence connections tested are shown to be inversely proportional (1:1) to resurgence output throughout the range of normal flows. It follows that the underground drainage systems are basically simple phreatic ones.
2. By comparing log-log plots of travel time against resurgence output for different swallet-resurgence connections it should be possible to distinguish between phreatic and vadose, simple and complex hydraulic systems.
3. Rhodamine WT dye is progressively lost, to a significant and unpredictable extent, in transit from swallet to resurgence. The failure of many traces in the past may be ascribed to complete loss of dye in transit.

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* In experiments by one of the authors (W.I.S.) the domestic hot water system was coloured pale pink with Rhodamine WT dye. About 0.0025 g. of dye passed daily to the septic tank of 1.5 cubic metres capacity, and was entirely lost for the first 4 days. Then, apparently, the contents of the tank became saturated, for a strong solution of dye began to reach the sampling point in the tail drains.

REFERENCES

ATKINSON, T. C., DREW, D. P. and HIGH, C. J. 1967 Mendip Karst Hydrology Research Project, Phases One and Two, *Occ. Pub. Wessex Cave Club,* **2** (1), 38 pp.

BARRINGTON, N. R. and STANTON, W. I. 1977 *Mendip, the Complete Caves and a View of the Hills,* Cheddar Valley Press, 236 pp.

CRABTREE, R. W. 1979 Quantitative Fluorimetric Dye Tracing, Rickford and Langford Resurgences, Northern Mendip, *Proc. Univ. Bristol Spelaeol. Soc.* **15** (2), 129–141.

DREW, D. P., NEWSON, M. D. and SMITH, D. I. 1968 Mendip Karst Hydrology Research Project, Phase Three, *Occ. Pub. Wessex Cave Club,* **2** (2), 28 pp.

N.E.R.C. (NATIONAL ENVIRONMENTAL RESEARCH COUNCIL) 1975 Flood Routing Studies, *Flood Studies Report,* **3**, 76 pp.

NEWSON, M. D. 1972 Rickford and Langford Resurgences, Mendip Hills, Somerset, a problem in Limestone Hydrology, *Proc. Univ. Bristol Spelaeol. Soc.,* **13**, (1), 105–112.

SMART, P. L. and HODGE, P. G. 1979 A Pulse-wave Test at Charterhouse, *Jour. Wessex Cave Club,* **15** (176), 132–136.

SMART, P. L. and LAIDLAW, I. M. S. 1977 An Evaluation of some Fluorescent Dyes for Water Tracing, *Water Resources Research,* **13** (1), 15–33.

STANTON, W. I. 1974 Balch was right!, *Jour. Wessex Cave Club,* **13** (155), 102–103.

STANTON, W. I. 1978 Dye Tracing at Wookey Hole, 1976–77, *Cave Diving Gp. Newsletter,* No. 46, 1–2.

STANTON, W. I. 1981 Some Mendip Water Traces, 1976–1980, *Jour. Wessex Cave Club,* **16** (185), 120–127.