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COMPARISON OF THE RESULTS OF QUANTITATIVE AND NON-QUANTITATIVE TRACER TESTS FOR DETERMINATION OF KARST CONDUIT NETWORKS: AN EXAMPLE FROM THE TRALIGILL BASIN, SCOTLAND

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ABSTRACT

The relative advantages of fluorescent dyes and *Lycopodium* spores as tracers are discussed. The major advantage of fluorescent dyes is that they may be detected quantitatively. Thus, in combination with discharge measurements, a dye mass balance can be prepared for tracer tests in karst conduits, which permits elucidation of the underground network. The advantages of this procedure are illustrated by comparison of the networks derived from non-quantitative (*Lycopodium* and dye) and quantitative (fluorescent dye) tracer methods in the Traligill Basin, Scotland. These tests also suggest that *Lycopodium* does not give a true indication of travel time, due to sedimentation underground. This could also cause contamination problems in later tests. For non-quantitative tracer tests, sensitive methods are necessary if incorrect inferences on conduit networks are to be avoided. In general, however, quantitative tests give much less ambiguous results, and are therefore to be preferred.

KEY WORDS Lycopodium Dye tracers Karst conduits

INTRODUCTION

In karst areas, where much of the groundwater flow is concentrated into solutionally enlarged conduits, the definition of the underground network by water tracing techniques is necessary for adequate water resource management (Newson, 1972a). Thus calculation of the total available supply at a resurgence using a water budget approach (e.g. Atkinson, 1977) requires the definition of the catchment that is controlled by the spatial distribution of the conduit network. Detailed knowledge of underground connections in karst areas is also vital in many engineering works, such as dewatering during mining operations (Atkinson *et al.*, 1973; Molitvin,

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1967), and the design and construction of large dams (Pavlin, 1961; Altug, 1976). Information on conduit networks is also necessary for prediction of the effects of waste disposal and accidental spillage at stream sinks and other points (Aley, 1972; Atkinson and Smith, 1974; Quinlan and Rowe, 1977; Preka and Preka-Lipold, 1977; Thomas and Beckford, 1982). Finally, a proper understanding of the geomorphology and evolution of the underground drainage, which is often useful in explaining its present function, must be based on knowledge of the unexplored parts of the underground system derived from tracer experiments (Crabtree, 1979; Smart, 1981; Smart, 1982).

This paper demonstrates the advantages that can be gained from quantitative tracing using fluorescent dyes, compared with the non-quantitative *Lycopodium* spore and dye methods.

LYCOPODIUM SPORES AND FLUORESCENT DYES AS TRACERS

Although radioisotopes (Burdon, 1963; Smith and Clark, 1963; White, 1977), inorganic salts (Zupan and Behrens, 1976; Müller and Käss, 1980), and microbiological substances (Batsche *et al.*, 1970; Fletcher and Myers, 1974; Keswick *et al.*, 1982) have all been successfully employed in tracing karst groundwaters, *Lycopodium* spores and fluorescent dyes are probably the most commonly used tracers (Atkinson and Smart, 1981). The relative advantages and disadvantages of these two tracers have been summarized by Drew and Smith (1969), Brown and Ford (1971), Aley and Fletcher (1976), Gospodaric and Habic (1976), Smart and Smith (1976), Gardner and Gray (1976), and in several other publications.

The *Lycopodium* tracing technique involves injection of spores of the clubmoss *Lycopodium*, coloured using biological stains, into sinking streams and trapping them at resurgences with plankton nets (Drew and Smith, 1969; Aley and Fletcher, 1976; Gardner and Gray, 1976). Different colour spores can be separated on analysis, allowing simultaneous tracing of up to five inputs, but the analysis and preparation techniques require skilled personnel and considerable care. The spores whilst chemically and mechanically resistant have a density greater than water, and tend to settle in non-turbulent flow. They cannot therefore be considered conservative tracers. Furthermore, the spore recoveries are non-quantitative because neither the catch efficiency of the sampling net is known, nor is the recovery of the laboratory analysis procedure determined. *Lycopodium* cannot therefore be employed in quantitative tests, where tracer mass budgets are computed.

In contrast, dyes are quantitatively detectable in water at concentrations as low as $0{\cdot}05\ \mu g\,l^{-1}$, although generally only three simultaneous injections are possible due to spectral overlap (Smart and Laidlaw, 1977). The best dye tracers may be considered conservative under the conditions and duration of many tests in karst conduits, particularly as the errors in the discharge measurements (used to calculate dye recoveries) are often of the order of 10 per cent. Smart (1981) quotes an average recovery of 103 per cent with a standard deviation of 10·7 per cent for twenty-two tests in the same sink to rising system using Rhodamine WT, but further analysis indicates losses of the order of 2·4 per cent per day of residence in the underground system (Stanton and Smart, 1981). Similar figures are quoted by various workers for other dyes in a large number of experiments (see Drogue, 1971; Atkinson *et al.*, 1973; Gospodaric and Habic, 1976; Calmels *et al.*, 1977; Smart, 1976, and Crabtree, 1979, for example). Furthermore, as suggested by Drogue (1971), Smart (1976) and Stanton and Smart (1981), low dye recoveries may well be due to failure to detect very low concentrations in the 'tail' of dye pulses. This proposal is supported by the results of activated carbon monitoring by Bauer and Perlega (1980), and by the flushing of stored dye described by Bidovec (1968). Dyes are therefore suitable tracers for quantitative experiments in karst areas.

THEORY OF FLOW NETWORKS

Brown and Ford (1971) recognized five types of fluid networks (Figure 1) which could be discriminated by virtue of their fluid and tracer mass balances. In Type 1 and Type 2 systems, all the dye injected at a stream sink is recovered at a single resurgence. The Type 2 system, however, has at least one underground tributary resulting in a greater discharge at the resurgence. Type 1 systems are relatively rare in extensive karst areas, but the Tupper Sink to Raspberry rising system in Rogers Pass, Canada, is of this type (Brown *et al.*, 1969). If partial dye recoveries occur, then the proportion of flow from injection site to sampled resurgence is the same as the

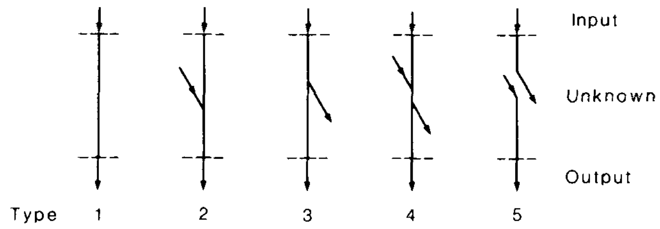

Figure 1. Types of fluid systems (after Brown *et al.*, 1969)

proportion of the injected dye recovered (Types 3 and 4). Most karst systems are of Type 2, having only tributaries, or of Type 4, having both tributaries and distributaries. Systems of Type 5 (no tracer recovery) cannot be defined purely from non-detection of tracer at the sampled resurgence, because excessive dilution may have reduced concentrations below the limit of detection. The complete recovery of the injected tracer at other springs would, however, suffice.

This theory provides a basis for the formal analysis of karst networks but requires the determination of a tracer mass balance. Hence, it cannot be employed with tracers such as *Lycopodium* for which this cannot be found. In simple networks without distributaries, non-quantitative point to point tracing may suffice, but in complex networks such non-quantitative tests may give rise to ambiguous results. In the remainder of this paper, we illustrate the advantages of quantitative methods for definition of karst conduit networks, by comparing the interpretation of results from non-quantitative tests with later quantitative tests in the same area, the Traligill Basin in Northwest Scotland.

THE STUDY AREA

The Traligill Basin, Sutherland, Scotland, has an area of 17 km^2, about half of which is underlain by carbonate rocks of the Cambro-Ordovician Durness Carbonates (Figure 2). These comprise a 155 m thick sequence of well-bedded but extensively recrystallized dolostones of low primary porosity (Swett, 1969). The carbonates are underlain conformably by thin shales and calcareous grits, which pass downward into massive impermeable orthoquartzites of the Eriboll Sandstone. The Cambro-Ordovician rocks are exposed due to a culmination in the north-south trending Moine Thrust (Peach and Horne, 1907), a major regional dislocation with movement probably in excess of 20 km. In this area displacement has occurred along at least three major planes (Christie, 1963) with the carbonate rocks most extensively exposed in the lowest nappe. Many minor thrusts and high angle reverse faults occur, giving an imbricate zone, but dips are generally to the east–southeast. The dislocations are a major control on groundwater movement, and many of the known sinks, caves and resurgences are developed along the thrust planes (Ford, 1959).

Topographically, the carbonates form an extensive undulating plateau between 280 and 300 m AOD, which is overlain in the south by fluvioglacial deposits and peat several metres thick. To both the north and east, steep slopes developed on the orthoquartzites rise in a series of crags to 975 m AOD, forming impressive topographic divides. The catchment boundary to the south underlies the plateau and is not known, while to the west the Traligill runs off the carbonates and debouches into Loch Assynt at Inchnadamph (NC 251219, 70 m AOD).

Surface streams from the orthoquartzites and peat sink at the contact with the carbonates, as, for example, the drainage of Gleann Dubh at Traligill Sink (NC 271209). Five other major sinks occur in the upper basin to the east of Cnoc nan Uamh (NC 279205) at Loch Mhaolach Coire (NC 277198), Cuil Dubh (NC 282195), Allt a Bhealaich Upper (NC 283198), Allt a Bhealaich Lower (NC 278202) and Pipe Sink (NC 288201). Along the northern margin of the carbonate rocks in the Lower Basin are three minor sinks, Enclosure Sink (NC 268211), Glenbain Hole (NC 265218) and Glenbain Sink (NC 262216). Water resurges at Traligill Rising (NC 267212, 137 m AOD), a major rising in the Lower Basin, and at the smaller risings on the northern bank further

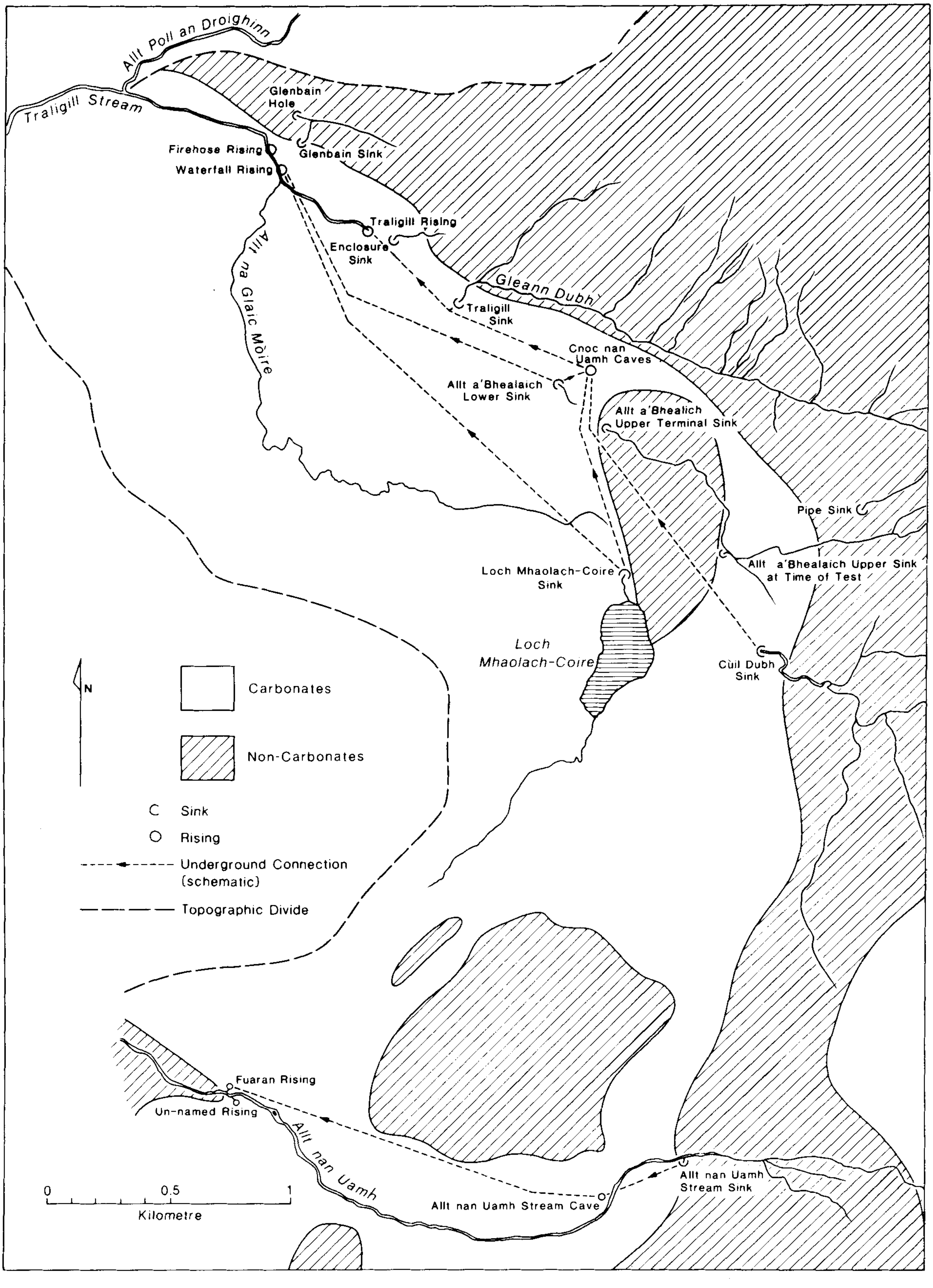

Figure 2. Geology and drainage of the Traligill Basin and the Allt nan Uamh based on non-quantitative tracer test results

downstream, Waterfall Rising (NC 264215) and Firehose Rising (NC 264216). The latter is associated with a short stream cave draining westward. All three risings are developed on prominent thrust faults. A stream cave may also be entered 0·5 km northeast of Traligill Sink at Cnoc nan Uamh. The water emerges from a deep sump at 225 m AOD, and can be followed westward for 180 m before plunging down a thrust plane into a second sump at 166 m AOD. It is probable that most water in the carbonates is transmitted through such conduits. To the south, risings are also found in the Allt nan Uamh valley, at Fuaran Rising (NC 261177) on the north bank, and an unnamed site directly opposite on the south bank. Another stream cave is also known, the Allt nan Uamh Stream Cave, which is associated with a sink in the main Allt nan Uamh stream-bed (NC 278174).

NON-QUANTITATIVE TRACING WITH LYCOPODIUM SPORES AND DYES

Four spore injections were made into the Loch Mhaodach Coire, Allt a Bhealaich Upper and Lower and Allt nan Uamh stream sinks, using between 1·0 and 1·5 kg of spores (Table I). Nets were placed at the Traligill and Waterfall Risings, in the main stream below the Firehose Rising, and in two surface streams, the Allt na Glaice Moire (at NC 264214), and Allt Poll an Droighinn (at NC 259219). In the Allt nan Uamh valley, nets were placed on the two risings at Fuaran Rising, and in the upstream sump of the Allt nan Uamh Stream Cave. The spores were prepared and analysed using the methods described in Drew and Smith (1969). The nets were initially sampled daily, then every two days, although some nets were lost during a flood event one day after injection. The results are presented in Table I, together with those from a non-quantitative Rhodamine B/charcoal detector test (Drew and Smith, 1969) conducted at about the same time from Cuil Dubh Sink (Glenn, personal communication), and a visual dye test from the Cnoc non Uamh downstream sump. Similar rapid non-quantitative dye tests are often conducted in karst areas and, as will be demonstrated below, their partial failure can result in substantial errors in the inferred conduit network.

None of the tracers from the Traligill basin sinks was discharged southward to the Allt nan Uamh valley (Figure 3). The network here appeared quite simple, with the stream sink feeding the stream cave as expected, and resurging on the north bank at the Fuaran Rise. No spores were, however, recovered from the Allt a Bhealaich Upper, where the water sinks through gravel at points progressively downstream in the stream channel, depending on flow. The route is probably rather immature and, combined with the low velocities as the water percolates through the gravel, sedimentation of the spores may have occurred.

Spores from both Allt a Bhealaich Lower and Loch Mhaolach Coire showed the same pattern, giving positive results at all of the sampling sites in the Traligill Basin. The spore traces indicate at least one distributary in the system, but without quantitative information it is not possible to determine its position in

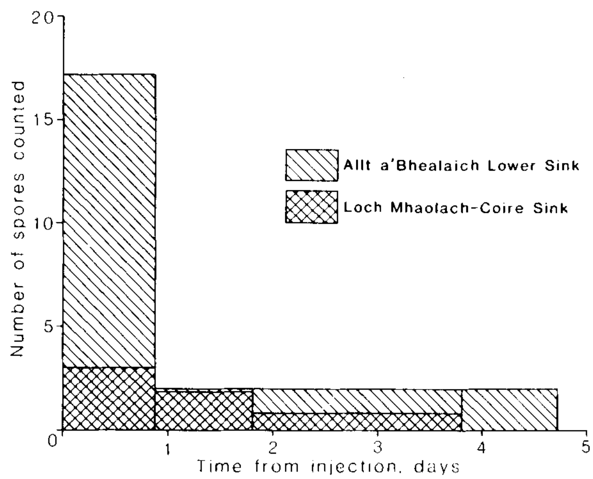

Figure 3. Spore recovery/time histogram for Loch Mhaolach Coire and Allt a Bhealaich Lower sinks at Traligill Rising

Table I. Results of non-quantitative tracing using dyes and *Lycopodium*

Injection site	Tracers injected (kg)		Sites where tracers recovered: Cnoc nan Uamh caves	Traligill Rising	Waterfall Rising	Below Forehose Rising	Allt nan Uamh streamcave	Fuaran Rising
Lycopodium spores								
Loch Mhaolach Coire	1·5	Bismark Brown	+	+	+	+	–	–
Allt a Bhealaich Upper	1·5	Methyl Violet	–	–	–	–	–	–
Allt a Bhealaich Lower	1·0	Undyed	+	+	+	+	–	–
Allt nan Uamh Stream Sink	1·5	Malachite Green	–	–	–	–	+	+
Dyes								
Cuil Dubh	0·6	Rhodamine B	+	+	–	–	–	–
Cnoc nan Uamh Caves		?		+	?	?		

All other sites negative.
+ Tracer detected; – No tracer detected.

the conduit network. Because the visual dye trace from Cnoc nan Uamh was only positive at Traligill Rising, it is necessary to assume a distributary in the network from the two Upper Basin sinks prior to Cnoc nan Uamh caves. This interpretation is supported by the results of the Cuil Dubh dye trace, which was also only detected at Traligill Rising. Furthermore, as there is no evidence to indicate if the two flows from Loch Mhaolach Coire and Allt a Bhealaich Lower combine prior to the distributary (for instance, similar recoveries of the two tracers at the different resurgences), both distributaries must be marked as separate flow paths. This produces an apparently complex network (Figure 2), with both sinks having an individual distributary, a pattern which is often observed in the results of *Lycopodium* tracing studies (see, for instance, Maurin and Zötl, 1959; Newson, 1972b).

Neither of the dye traces was positive at the Firehose Rising. Furthermore, it was not possible to determine if any water from the sinks traced by *Lycopodium* spores was recovered at this site. Because access at the rising was difficult, it was impossible to place a *Lycopodium* net directly in the flow and, as is normal in such cases, the net was placed downstream of the rising in the main stream. However, because spores from the Waterfall and Traligill Risings were already present, it was impossible to establish if the Firehose Rising was in fact positive. No information, therefore, was obtained on the feeders for one of the three major network outlets.

In summary, five non-quantitative traces had indicated a moderately complex underground system in the Traligill basin. Two of the upper basin sinks had independent distributaries, which fed to the Waterfall Rising and Cnoc nan Uamh caves. The third fed only the latter, with water then resurging at the Traligill Rising. This interpretation relies heavily on the failure of the non-quantitative dye traces to establish links other than to Traligill Rising, compared to the spores which also demonstrated a link to the Waterfall Rising.

QUANTITATIVE TRACING WITH FLUORESCENT DYES

Further tests were then made in the basin employing quantitative fluorescent dye tracing techniques. Dye concentrations were measured in hand samples using a Turner III filter fluorometer and the methods of Smart and Laidlaw (1977). At each stream sink, the discharge was determined only at injection, while at the resurgence regular stage measurements were converted to discharge using a rating curve prepared from current meter measurements. Discharge figures are accurate to ± 10 per cent, whereas dye concentrations are generally better than $\pm 0{\cdot}1$ per cent. Dye recoveries (the amount M of injected tracer passing a sampling point) were calculated by integrating the product of tracer concentrations (c) and discharge (Q) over the duration of the tracer pulse ($T = 0, t$) thus:

$$M = \int_0^t c \cdot Q \cdot \mathrm{d}t$$

The large error in discharge estimates makes the values of dye recovery rather imprecise, and this limits the sensitivity of the budget method. Dye injections were made at Traligill Sink, Enclosure Sink and Glenbain Hole in the Lower Basin, sampling at Traligill Rising and either downstream of the Firehose Rising or directly at this site and the Waterfall Rising. These sites and the Cnoc nan Uamh cave stream were also used for tests from the Upper Basin at Pipe Sink, Allt a Bhealaich Upper, Cuil Dubh and Loch Mhaolach. The dye budget for the Traligill Sink test will be discussed in detail to illustrate the procedure.

A 10 g injection of Rhodamine WT as a 20 per cent solution was injected about 250 m above Traligill Sink. Mixing was complete by the sink and the dye was sampled in order to determine sink discharge by the dye dilution method (Brown *et al.*, 1969). The discharge was 159 $\mathrm{l\,s^{-1}}$ compared to 210 $\mathrm{l\,s^{-1}}$ determined at Traligill Rising by current meter, and 300 $\mathrm{l\,s^{-1}}$ in the main stream below the Firehose resurgence, including 10 $\mathrm{l\,s^{-1}}$ contributed from the Allt na Glaice Moire tributary. The time/concentration curves for the three sites are given in Figure 4a, and Figure 4b presents the dye and discharge budgets for the system. At Traligill Rising 7·8 g of dye were recovered, while 10·0 g passed the sampling station below Firehose Rising, indicating 2·2 g had been discharged through the Waterfall and Firehose Risings together. Thus 78 per cent of the Traligill Sink water discharges at Traligill Rising. However, at low flow it is possible to enter a small cave at Traligill Sink where water from Cnoc nan Uamh can be observed mixing with the water flowing into the sink. At the time of the test, the Cnoc nan Uamh stream was discharging 102 $\mathrm{l\,s^{-1}}$ and, assuming no further water enters, then 78

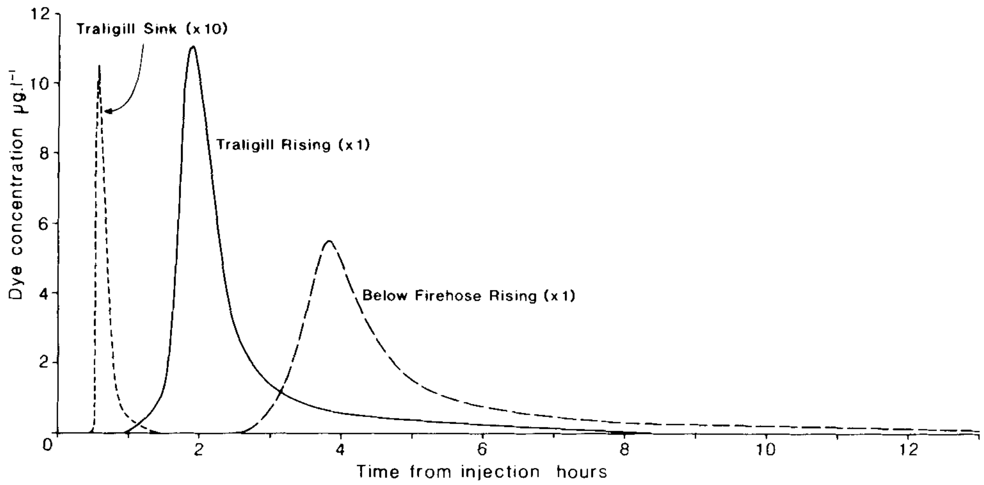

Figure 4a. Time/concentration curves for Traligill Sink test

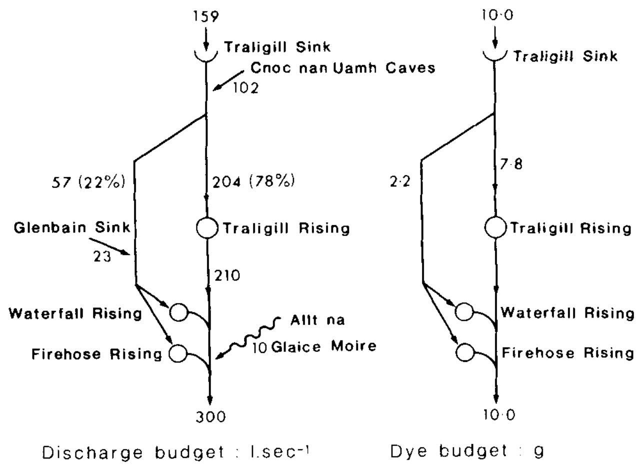

Figure 4b. Dye and discharge budgets for Traligill Sink test

per cent of this combined flow discharges at Traligill Rising (204 l. s^{-1}), while 57 l. s^{-1} passes towards the Waterfall and Firehose Risings. An additional input of 23 l. s^{-1} must be present in this system to account for the 80 l. s^{-1} discharged from these two risings, although it must be remembered that this amount is substantially less than the combined gauging errors. The underground network below Traligill Sink is therefore of Type 4, having both tributaries and distributaries.

In the Upper Basin, the tests were all successful, including that from Allt a Bhealaich Upper which had failed using *Lycopodium* spores in the previous trace. The tracing results are summarized in Table II, which shows dye recoveries calculated for the sampling sites. The tests were not synchronous and the results derived from Pyranine should be treated with some caution despite the calibration curve being prepared using river water, in view of the sensitivity of this dye to pH changes (Smart and Laidlaw, 1977). The Loch Mhaolach Coire test was affected by a flood at the lower springs, and either changes in background fluorescence (Smart *et al.*, 1976) or, more probably, an increase in pH due to carbonate percolation waters being expelled into the stream caused an excessively high recovery. It is more appropriate to express the results as per cent total recovery in this case.

Table II. Results of quantitative tracing using fluorescent dyes

Injection site	Dye and amount (g)	Dye recovery at sampling station: Cnoc nan Uamh caves	Traligill Rising	Waterfall and Firehose Rising	Total Lower Springs
Loch Mhaolach Coire*	200 Pyranine	106	(63)	(37)	188
Allt a Bhealaich Upper	30 Rhodamine WT	99	62	33	95
Cuil Dubh	90 Rhodamine WT	103	74	29	103
	40 Rhodamine WT	+	+	+	93
Pipe Sink	100 Pyranine	+	+	+	107
Traligill Sink	10 Rhodamine WT	–	78	22	100
Glenbain Hole	1 Rhodamine WT	–	–	0 98	98
Enclosure Sink*	10 Fluorescein	–	(70)	(30)	380

Notes + Dye detected but not quantified.
* Figures in parentheses per cent of dye recovered at lower springs as total recovery in excess of 100 per cent due to incorrect calibration curve.

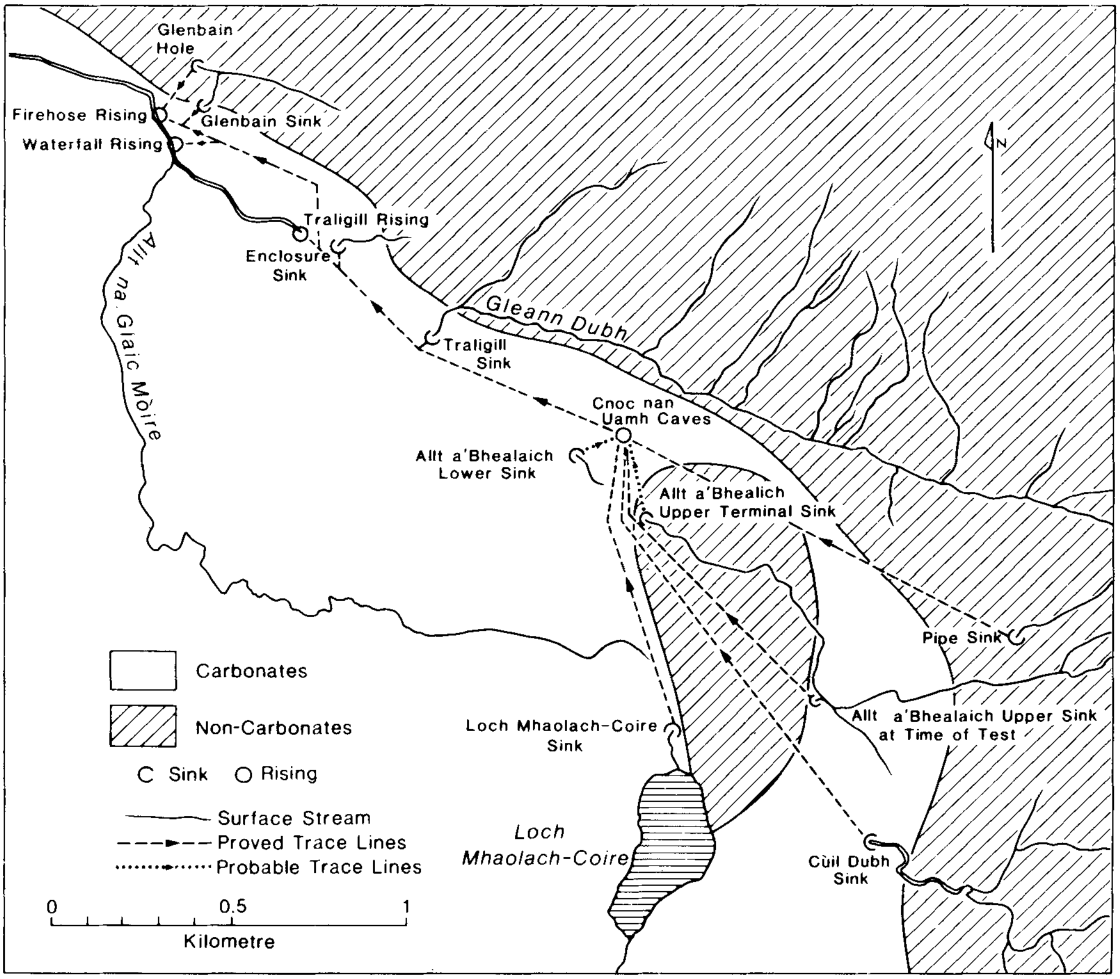

Figure 5. Underground drainage of the Traligill Basin based on quantitative fluorescent dye tracer test results

Clearly Pyranine is not a satisfactory quantitative tracer dye unless efforts are made to buffer the samples prior to analysis.

For Loch Mhaolach Coire, Allt a Bhealaich Upper and Cuil Dubh, all the injected dye passed through the Cnoc nan Uamh sampling site within the precision permitted by gauging errors. It is probable that this would also be the case for the two other Upper Basin sinks which have been proved to this site. The quantitative tracing results (Figure 5), therefore, show that the Upper Basin network is of Type 2 with tributaries only, the Cnoc nan Uamh cave stream forming the only major drainage route. In fact, between 80 and 90 per cent of the discharge of this conduit can be accounted for by flows from the Upper Basin sinks. In the Lower Basin, time/concentration curves for both the Firehose and Waterfall Risings were nearly identical, indicating they are fed by the same conduit. The discharge of Glenbain Hole, which feeds Firehose Rising only, is too small to cause significant dilution. These risings can therefore be treated as a single unit. Both the Upper Basin tests and those from Traligill Sink and Enclosure Sink in the Lower Basin show the same split in dye recoveries between Traligill Rising and the Waterfall/Firehose Risings, with 70 per cent on average discharging from Traligill Rise. This ratio may well vary with discharge, although the range of observed values is within the gauging error. The flow network in the Lower Basin is therefore of Type 4, having both tributaries and distributaries.

The underground system of the Traligill Basin, based on the 7 quantitative test results, therefore comprises a simple Type 2 tributary network in the upper basin, with sinks feeding a major trunk conduit through Cnoc nan Uamh caves to Traligill Rising. This conduit also collects water from Traligill Sink. A distributary very close to Traligill Rising guides water from this main route to two minor resurgences, which are fed by a single passage. The Firehose Rising also provides the only outlet for water from Glenbain Sink and Hole.

DISCUSSION

The additional network information obtainable by the application of quantitative tracer techniques is clearly shown by the Traligill Basin study discussed above. In particular, the quantitative results indicate that all the Upper Basin sinks are confluent prior to the distributary parts of the network. Even if a sampling site on this conduit had not been available, the fact that all these sinks show approximately the same proportion of flow in each distributary link, would enable this inference to be made. Furthermore, as the Lower Basin sinks show a similar dye distribution, the distributary can be located precisely between Traligill Rising and the Enclosure Sink tributary. None of this precise network information could be obtained from the non-quantitative tests.

A second clear advantage of the quantitative traces was illustrated at the Firehose Rising, where *Lycopodium* nets could not be placed, necessitating sampling downstream in the surface river. Because of the presence of tracer in nets placed upstream, it was not possible to determine if tracer had been discharged from the rising. However, for the quantitative dye traces, the additional tracer input from this site could clearly be determined from the tracer mass budget in the main river. This is frequently a problem with non-quantitative tests, particularly when discrete points of resurgence are not known, as can be seen from the experimental results of Day (1976) and Gardner and Gray (1976). In fact, it was possible to sample the Firehose Rising directly during the quantitative tests, because only a small sample bottle was required for determination of dye concentrations. Comparison of the resulting time/concentration curve with that at the Waterfall Rising, which was almost identical, allowed the conclusion to be made that both risings were fed from the same conduit. Detailed examinations of the time/concentration curves necessary for quantitative tracing can often allow such inferences on the nature of the underground system to be made, for instance, the presence of multiple conduits (Smart, 1981).

However, the shortcomings of the conduit network proposed following the non-quantitative traces are not wholly due to lack of tracer budget information. They are also caused by failure to determine links later proven to exist, due to non-detection of the tracer because of limited sampling or poor minimum detectability. This was primarily a problem with the dye tests using visual and charcoal detection methods, both much less sensitive than the fluorometric measurement used in the later quantitative traces. Had the Cnoc nan Uamh caves trace been positive at the Waterfall Rising, it would have been apparent that a lower basin distributary could equally well explain the distribution of tracer from the upper basin sinks, without the necessity for separate upper basin branches. This would have been supported by the Cuil Dubh trace had it also been detected at the Waterfall Rising. Nevertheless, these results would have merely permitted more correct inferences to be made, while the quantitative traces proved the nature of the underground system unequivocally.

The failure of the *Lycopodium* test from Allt a Bhealaich Upper, which was later successful using fluorescent dyes, was probably due to filtration and settlement of the spores in non-turbulent flow. This could either be due to the immaturity of the sinks, which where visible are small solutionally enlarged fissures rather than conduits. More probably it resulted from intergranular percolation through the quartzite gravels which mantle the stream-bed at the active sink point. Even with the injections at discrete stream sinks with known cave conduits, such as Cuil Dubh, there is evidence of sedimentation and resuspension of the spores in the underground channels. The time/concentration curves for the fluorescent dye traces are typically only hours long (Figure 4a); in contrast, the *Lycopodium* histograms continue for at least five days until sampling stopped (Figure 3). In tests in the Mendip Hills, spores were still present in the water from some swallets over one year from injection, despite a time of first arrival of less than one day. This prolonged storage and release of spores can preclude further tracing work in the area and is a particular problem with *Lycopodium*.

It is also important to remember that the spore recovery in some samples is so low that contamination from previous traces or during sampling handling, is a major hazard, particularly when insufficient samples are collected to give an adequate definition of the breakthrough curve. For Loch Mhaolach Coire, the positive result at Traligill Rising depends on the identification of only six spores from a total of approximately $1{\cdot}5 \times 10^{11}$ spores injected. This poor recovery is partially due to actual losses underground and to the relatively limited cross-section of flow filtered by the sampling nets. However, little is known about the hydraulic performance of the nets, and it is probable only a tiny proportion of the spores in flow filaments intercepted by the net are actually retained. This becomes a particular problem where clogging by suspended sediment occurs, or the nets are damaged during floods. Thus, while the analysis is inherently more sensitive for point to point connections (one spore in $1{\cdot}5 \times 10^{11}$ for the Loch Mhaolach Coire test) than equivalent traces run using fluorescent dyes (4×10^9 dilution for the same test), in practice larger injections of spores are required to achieve positive results (1·5 compared to 0·2 kg), due to the inefficiency of the spore retrieval system.

In contrast, both the minimum detectable dye concentration and the dye recovery were affected by fluorescence background, and its changes with time. Spectrofluorometers can be used to overcome this problem to some extent, by measuring peak heights at the maximum dye emission wavelength from the interpolated background level in the sample, rather than some arbitrary datum, normally that for distilled water. Such instruments whilst now more generally available are expensive and cannot be operated in the field. Attempts to eliminate background by physicochemical methods have been successful at the orange waveband (rhodamine dyes), where the problem is associated with *in vivo* emission from pigments in phytoplankton (Pritchard, 1979). At the green and blue wavebands, however, where background fluorescence is due to dissolved organic matter (Smart *et al.*, 1976), the problem remains unresolved.

CONCLUSIONS

Non-quantitative tracer tests using dyes and to a lesser extent *Lycopodium* are increasingly common in engineering and water resource applications. Many studies carried out by consulting organizations are never published. The example of the Traligill Basin, discussed in detail above, clearly illustrates the shortcomings of non-quantitative tests compared with full network definitions by means of quantitative dye mass balance. Non-quantitative tests may not:

1. Pinpoint the locations of tributary and distributary links in the system.
2. Indicate whether distributaries are independent or common to several sinks.
3. Show that springs share a common feeder.
4. Permit downstream additions of dye to be detected in systems with multiple or unknown springs.

The experiments also demonstrated the importance of using a sensitive tracer detection method, in order that all possible network connections are traced, not merely the major links. Both *Lycopodium* and fluorometrically determined fluorescent dyes were satisfactory in this respect but charcoal detector and visible dye tests proved fallible. *Lycopodium*, however, suffers from sedimentation underground, which gives delayed and very low recoveries, and possible problems of contamination during further tests. Thus fluorescent dyes determined fluorometrically are both the most reliable and most informative of the tracing methods used in this study.

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REFERENCES

Aley, T. 1972. 'Groundwater contamination from sinkhole dumps', *Caves and Karst*, **14**, 17–23.

Aley, T. and Fletcher, M. W. 1976. 'The water tracers cookbook', *Missouri Speleology*, **16** (6), 1–32.

Altug, S. 1976. 'Leakage study of the west side of the Oymapinar reservoir, Turkey', *Bulletin of the International Association of Engineering Geology*, **14**, 147–152.

Atkinson, T. C., Bradshaw, R. and Smith, D. I. 1973. *Quarrying in Somerset; Supplement 1: Hydrology and Rock Stability—Mendip Hills*, Taunton, Somerset County Council.

Atkinson, T. C. 1977. 'Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain)', *Journal of Hydrology*, **35**, 93–110.

Atkinson, T. C. and Smart, P. L. 1981. 'Artificial tracers in hydrogeology', in *A Survey of British Hydrogeology*, 1980, London, Royal Society, 173–190.

Atkinson, T. C. and Smith, D. I. 1974. 'Rapid groundwater flow in fissures in the chalk: an example from South Hampshire', *Quarterly Journal of Engineering Geology*, **7**, 197–205.

Batsche, H., Bauer, F., Behrens, H., Buchtela, K., Dombrowski, H. J., Geisler, R., Geyh, M. A., Hötzl, H., Hribar, F., Koss, W., Mairhofer, J., Maurin, V., Moser, H., Neumaier, F., Schmitz, J., Schnitzler, W. A., Schreiner, A., Vogg, H. and Zötl, J. 1970. Kombinierte karstwasseruntersuchungen im Gebiet der Donauversickering (Baden-Württenberg) in den Jahren 1967–1969', *Steirische Beiträge zur Hydrogeologie*, **55**, 5–165.

Bauer, F. and Perlega, W. 1980. 'Ergebnisse des Fluoreszenztracer nachweises mittels Akivkohle', *Steirische Beiträge zur Hydrologie*, **32**, 70–74.

Bidovec, F. 1968. 'The investigations of the karst underground water systems and hydrology', *Proceedings of the 4th International Speleological Congress III*, 279–285.

Brown, M. C. and Ford, D. C. 1971. 'Quantitative tracer methods for investigation of karst hydrology systems, with reference to the Maligne Basin area, Canada', *Transactions of the Cave Research Group of Great Britain*, **13**, 37–51.

Brown, M. C., Wigley, T. L. and Ford, D. C. 1969. 'Water budget studies in karst aquifers', *Journal of Hydrology*, **9**, 113–116.

Burdon, D. J. 1963. 'The use of tritium in tracing karst groundwater in Greece', *International Association of Scientific Hydrology Symposium*, March 1963, 309–320.

Calmels, A., Charriere, R., Fourneaux, J. C., Molinari, J., Sarrot Reynauld, J. and Talour, B. 1977. 'Multitracages dans les massifs karstiques du Vercors et de la Chartreuse (France)', in Gospodaric, P. and Habic, P. (Eds), *Underground Water Tracing*, Ljubljana: Institute of Karst Research, 239–254.

Christie, J. M. 1963. 'The Moine thrust zone in the Assynt region, N. W. Scotland', *University of California Publications in Geological Sciences*, **40**, 335–340.

Crabtree, R. W. 1979. 'Quantitative fluorometric dye tracing. Rickford and Langford resurgences, northern Mendip', *Proceedings of the University of Bristol Speleological Society*, **15**, 129–141.

Day, M. 1976. 'The morphology and hydrology of some Jamaican karst depressions', *Earth Surface Processes*, **1**, 111–129.

Drew, D. P. and Smith, D. I. 1969. 'Techniques for the tracing of subterranean drainage', *British Geomorphological Research Group Technical Bulletin*, **2**, 36 pp.

Drogue, C. 1971. 'Réflexions sur les possibilités offertes par les traceurs pour la mesure de la vitesse d'écoulement dans les roches calcaires fissurés', *Bulletin B.R.G.M.*, **(2)** III, 4, 21–31.

Fletcher, M. W. and Myers, R. L. 1974. 'Groundwater tracing in karst terrain using phage T-4', *American Society of Microbiology, Abstracts of the Annual Meeting*, **52**.

Ford, T. D. 1959. 'The Sutherland Caves', *Transactions of the Cave Research Group of Great Britain*, **5**, 141–187.

Gardner, G. D. and Gray, R. E. 1976. 'Tracing subsurface flow in karst regions using artificially coloured spores', *Bulletin of the Association of Engineering Geology*, **13**, 177–197.

Gospodaric, R. and Habic, P. 1976. *Underground Water Tracing—Investigations in Slovenia* 1972–1975, Postojna, Institute of Karst Research.

Keswick, B. H., De-Shin Wong, and Gerba, C. P. 1982. 'The use of micro-organisms as groundwater tracers: a review', *Groundwater*, **20**, 142–149.

Maurin, V. J. and Zötl, J. 1959. 'Die untersuchung der Zusammenhäge unterirdischer Wässer mit besender Berücksichtigung der karstverhältmisse', *Steirische Beiträge zur Hydrogeologie*, **10/11**, 5–184.

Molitvin, P. V. 1967. 'Study of the relationship between surface and sub-surface fissure-karst waters in the Ay River basin', *Papers in Hydrology of the State Hydrology Institute*, **7**, 14–27.

Müller, I. and Käss, W. 1980. 'Resultat des Markierversuches mit Salzen', *Steirische Beiträge zur Hydrologie*, **32,** 77–81.

Newson, M. D. 1972a. 'Merits of a hydrological bias to karst erosion studies', *Transactions of the Cave Research Group of Great Britain*, **14,** 118–124.

Newson, M. D. 1972b. 'Rickford and Langford resurgences Mendip Hills, Somerset. A problem in limestone hydrology', *Proceedings of the University of Bristol Speleological Society*, **13,** 105–112.

Pavlin, B. 1961. 'Réalisation du bassin d'accumulation de Peruca dans le karst Dinarique', *Proceedings of the 7th Congress on Large Dams, Rome*, **R85,** 1–28.

Peach, B. M. and Horne, J. 1907. *Geological structure of the north-west highlands of Scotland*, Edinburgh, Geological Survey.

Preka, N. and Preka-Lipold, N. 1977. 'A contribution to study of self-purification capability of karst undergroundwater courses', in Tolson, J. S. and Doyle, F. L. (Eds), *Karst Hydrology*, Huntsville, Alabama. U. A. H. Press, 32–1 to 32–11.

Pritchard, D. Q. 1979. 'Background problems in fluorometric dye measurement in natural waters', *Proceedings of Oceans* 79 (*Fifth Annual Conference*), 572–582.

Quinlan, J. F. and Rowe, D. R. 1977. 'Hydrology and water quality in the Central Kentucky karst: Phase 1', *University of Kentucky Water Resources Research Institute Research Report*, **101,** 1–93.

Smart, C. C. 1982. 'Quantitative dye tracing in a glacierised alpine karst', *Beiträge zur Geologie der Schweiz—Hydrologie*, **28,** 191–200.

Smart, P. L. 1976. 'Catchment delimitation in karst areas by the use of quantitative tracer methods', *Proceedings of the 3rd International Symposium of Underground Water Tracing, Bled, Jugoslavia*, 291–298.

Smart, P. L. 1981. 'Variation of conduit flow velocities with discharge in the Longwood to Cheddar Rising systems, Mendip Hills', *Proceedings of the 8th International Congress of Speleology*, **1,** 333–337.

Smart, P. L., Finlayson, B. L., Rylands, W. D. and Ball, C. M. 1976. 'Relation of fluorescence to dissolved organic carbon in surface waters', *Water Research*, **10,** 805–811.

Smart, P. L. and Hodge, P. 1980. 'Determination of the character of the Longwood sinks to Cheddar resurgence conduit using an artificial pulse wave', *Transactions of the British Cave Research Association*, 208–211.

Smart, P. L. and Laidlaw, I. M. S. 1977. 'An evaluation of some fluorescent dyes for water tracing', *Water Resources Research*, **13,** 15–33.

Smart, P. L. and Smith, D. I. 1976. 'Water tracing in tropical regions, the use of fluorometric techniques in Jamaica', *Journal of Hydrology*, **30,** 179–195.

Smith, D. B. and Clark, W. E. 1963. 'An investigation of the hydraulics of an underground pool with Iodine–131', *Radioisotopes in Hydrology. Proceedings of the Tokyo Symposium*, Vienna, International Association of Atomic Energy, 77–88.

Stanton, W. I. and Smart, P. L. 1981. 'Repeated dye traces of underground streams in the Mendip Hills, Somerset', *Proceedings of the University of Bristol Speleological Society*, **16,** 47–58.

Swett, K. 1969. 'Interpretation of depositional and diagenetic history of Cambrian–Ordovician succession of Northwest Scotland', *American Association of Petroleum Geologists Memoir*, **12,** 630–646.

Thomas, C. P. and Beckford, S. 1982. 'Tracing well water pollution in a limestone aquifer', *Journal of the American Waterworks Association*, April 1982, 182–187.

White, K. E. 1977. 'Tracer method for the determination of groundwater residence–time distributions', *Proceedings of the Reading Conference on Groundwater Quality—Measurement, Prediction and Protection*, Medmenham, Water Research Centre, 246–273.

Zupan, M. and Behrens, H. 1976. 'Tracing with lithium chloride', in Gospodaric, P. and Habic, P. (Eds), *Underground Water Tracing*, Ljubljana: Institute of Karst Research, 187–191.