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DYE TRACING IN THE BEACON HILL PERICLINE, EAST MENDIPS

by

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ABSTRACT

Repeat tracer tests using fluorescent dyes were made on four swallets in the Carboniferous Limestone Seven Springs catchment, East Mendip. Downhead Swallet feeds a predominantly vadose conduit, with a major distributary which underflows the Seven Springs but does not feed Holwell Spring. Dairyhouse Slocker is tributary to the conduit below this distributary, but the Bottlehead conduit is independent and feeds only the Main Spring. Dewatering at Torr Quarry has caused a change in the function of the phreatic conduit from Heale Swallet, which previously was tributary to the main Downhead conduit. The conduit has not been directly intersected by quarrying, but diffuse leakage induced by the steepened hydraulic gradient towards the quarry captures all the flow. The Bottlehead Slocker conduit is similarly affected, with leakage being large at low flow, but insignificant at high flow. The Downhead Swallet conduit is affected least by quarry dewatering, because of its vadose nature and greater distance from the quarry. Nevertheless movement of water from the conduit into the diffuse flow zone does occur, particularly during the periods of active swallet recharge.

INTRODUCTION

Dye tracing techniques have been widely used to trace the flow of sinking streams (also called swallets or slockers) to springs in the Mendip Hills. The main purpose of this work has been to establish sub-surface flow routes and catchment areas (Atkinson *et al.*, 1967; Drew *et al.*, 1968). However tracer results have also provided evidence of the interactions which can occur between conduit and diffuse flow in the aquifer. Atkinson *et al.* (1973) reported a double peak in a dye breakthough curve for a test undertaken on the rising limb of a flood hydrograph in the Stoke Lane Slocker to St Dunstan's Well conduit. The first peak contained the major part of the injected dye which travelled directly through the conduit, while a second smaller and more dispersed peak was explained as dye re-entering the conduit after temporary storage in the diffuse zone. However, the second peak could well have been due to a systematic discharge-related change in the background fluorescence, as has been subsequently observed at this site in later unpublished tests by ourselves. This possibility is supported by a calculated tracer recovery of 120% for the test if an estimate of abstraction during the second peak is included in the tracer budget.

In this paper we report the results of several traces which were undertaken in the Eastern Mendips to investigate the degree of interaction between the conduit and diffuse flow zones under differing recharge conditions, and under the influence of abstraction from a quarry sump drawing on the saturated diffuse flow zone.

STUDY AREA

The study area is the southern limb of the Beacon Hill pericline at the eastern end of the Mendip Hills (Figure 1). The core of the pericline comprises Silurian volcanics and Devonian Old Red Sandstone, the former only outcropping west of the major north-south Downhead Fault; (Duff *et al.*, 1985; Green and Welch, 1965). The Carboniferous Limestone dips at 30 to 40° to the south, and comprises massive, well-bedded, fine to coarse-grained limestones of low primary porosity. It is predominantly pure, but at its base contains a shaley unit, the Lower Limestone Shales, transitional to the clastic sediments of the Old Red Sandstone. To the east the Carboniferous Limestone is overlain unconformably by the Jurassic Inferior Oolite, a massive, fissured, coarse bioclastic and ooidal limestone some 15 m thick. This dips gently to the east, and is capped by impermeable clays of the Fullers Earth.

The Old Red Sandstone forms the highest land in the area, rising to 288 m AOD, but the relief in the east Mendips is much lower than in the west because the Mesozoic rocks have only been partially removed, giving a gently rolling topography. Water emerging from springs in the Old Red Sandstone forms streams which sink after flowing onto the Carboniferous Limestone across the Downhead Fault (Figure 1). The main stream sinks are at elevations between 181 and 223 m AOD and comprise Downhead Swallet, Dairyhouse Slocker, Bottlehead Slocker and Heale Slocker. Barrington and Stanton (1977) also record other smaller sinks which are not considered here. Water resurges from a number of points at Seven Springs in the Whatley Brook (128 m AOD), and also apparently in the Nunney Brook at Holwell Rising (113 m AOD), although only Dairyhouse Slocker has been proved to latter (Atkinson et al. 1973). Holwell Spring is perennial, but during the summer months although some of the swallets remain active, Seven Springs ceases to flow, and losses occur from the Whatley Brook at this point. The aquifer is also affected by pumping from Torr Quarry, a large (1.1 km^2) limestone quarry which has an annual production of 6 million tonnes. Prior to 1987 winter groundwater levels in the vicinity of the quarry were approximately 150 m AOD, but since 1987 planned dewatering by abstraction from the quarry sump and expansion of the lower working levels 50-60 m below original land surface, have affected groundwater conditions, which are monitored with a network of observation boreholes. During 1987 the sump pumping level was at 134 m AOD, but in 1991 was between 142 and 144 m AOD.

DYE TRACING METHODS

A series of tests were made from the four stream sinks in November and December 1987 (Tests 1-4) and March 1991 (Test 5) under differing hydrological conditions using the fluorescent dyes Rhodamine WT, Fluorescein and Tinopal CBS-X (Table 1). Tests 1 and 5 were made under rainy conditions with high swallet and spring flows, Tests 2 and 3 during a period of recession without storm recharge to the swallets, and Test 4 under baseflow, but again with high swallet flows.

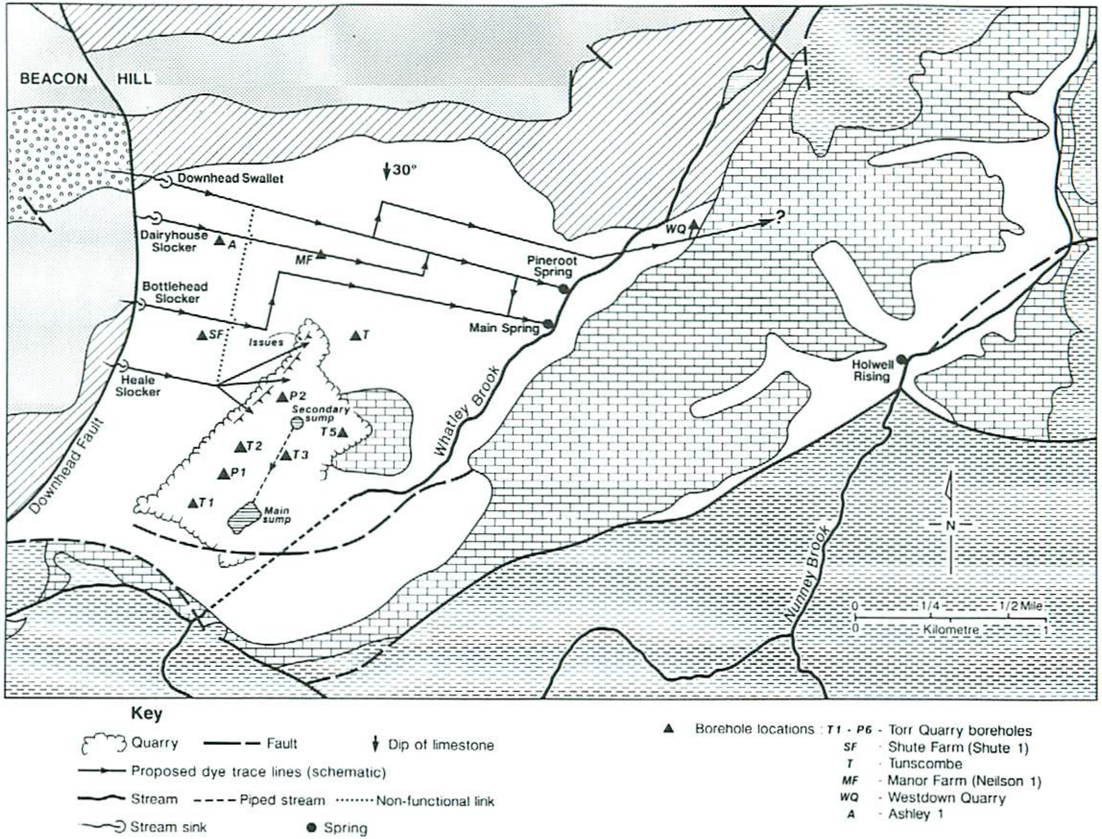

Figure 1a) *Geology and hydrology of the study area (see generalised vertical geological section (next page) for key).*

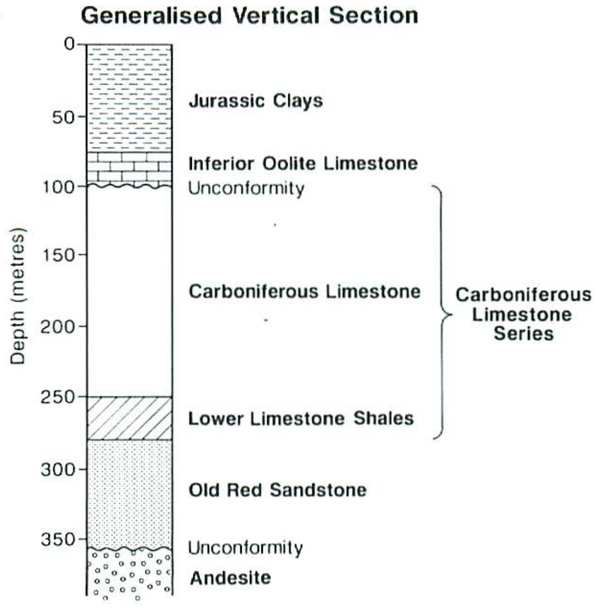

Figure 1b. *Generalised vertical geological section of the study area.*

Water samples were taken for analysis from Seven Springs and Holwell Rising either by hand or using Rock and Taylor 48 Interval samplers, from the sump pools and seepages in Torr Quarry by hand, and from the boreholes shown on Figure 1 using downhole samplers. The Westdown Quarry borehole to which two of the swallets were traced by Atkinson *et al.* (1973) was not sampled as it is no longer accessible. Unfortunately cold weather during Test 3 caused freezing of the samplers, and no samples were recovered. All water samples in 1987 were analysed directly using a Turner Model 111 filter fluorometer fitted with the filters recommended by Smart and Laidlaw (1977) and in 1991 using a Turner Designs Filter fluorometer fitted with the manufacturers filters. Dye concentrations are temperature corrected.

At Seven Springs water rises at a number of points, but in 1987 these could not be monitored by a single sampler installed downstream in the Whatley Brook because large variations in flow occurred when water was discharged from Torr Quarry. Separate samplers were therefore installed at the two largest springs, Main Spring and Pineroot Spring (Barrington and Stanton 1977), whose flows were periodically measured by current meter. However, the Torr Quarry discharges caused backing up at the Main Spring, a water level rise of 0.3 to 0.4 m in the Whatley Brook causing a reduction in spring flow from 80 to 20 L/s. These factors caused problems in estimation of dye recoveries, which may have uncertainties of as much as ± 20 %. In 1991 recoveries could be estimated downstream of the springs using gauging stations installed by Foster Yeoman Ltd, the operators of Torr Quarry.

Table 1. *Details of Dye Traces in Beacon Hill study*

Test No.	Injection Site	Dye + Quantity (g)	Conditions		Recovery (%)	
			Recharge	Water Level	Seven Springs	Torr Quarry
1	Downhead	RWT-47.6	+	f	40	D
	Dairyhouse	FL-200			109	ND
2	Bottlehead	RWT-47.6	O	f	37	ND
	Heale	CBS-200			D	ND
3	Downhead	RWT-47.6	+	f	F	D
	Dairyhouse	FL-200			F	ND
4	Downhead	RWT-47.6	O	f	50	—
	Dairyhouse	FL-200			106	—
5	Downhead	CBS-1000	+	r	30	2
	Bottlehead	FL-600			86	4
	Heale	RWT-120			0	45

Key

ND : not detected
D : detected
\+ : swallet recharge
O : swallet recession
f : falling
r : rising
F : samplers frozen
— : not sampled

RWT : Rhodamine WT
FL : Fluorescein
CBS : Tinopal CBS-X

RESULTS

The Swallet/Seven Springs Conduit System

Tracer dye injected at Downhead, Dairyhouse and Bottlehead swallets was detected at Seven Springs in all tests. The dye breakthrough curves show a rapid increase in concentration to the peak, with an exponential decline at a much slower rate on the falling limb (Figure 2). The minor peaks are related to backflooding and release of water from the conduit caused by intermittent pumped released of water from the Torr Quarry sump, as discussed previously. The general form of the curves is indicative of flow in dissolutional conduits. This is confirmed by the high straight line velocities calculated from time to peak concentration and time of first arrival, the latter values being comparable to those reported by Atkinson *et al.* (1973) from the results of the *Lycopodium* tracing (Table 2).

At high flow, dye concentrations at the Main Spring outlet are lower than for the Pineroot Spring (c 50%) but are essentially in phase. At lower flows (Trace 2 and 4), when Pineroot Spring comprises less than 10% of the combined spring discharge (compared to nearly 50% at higher flows), the two outlets show very

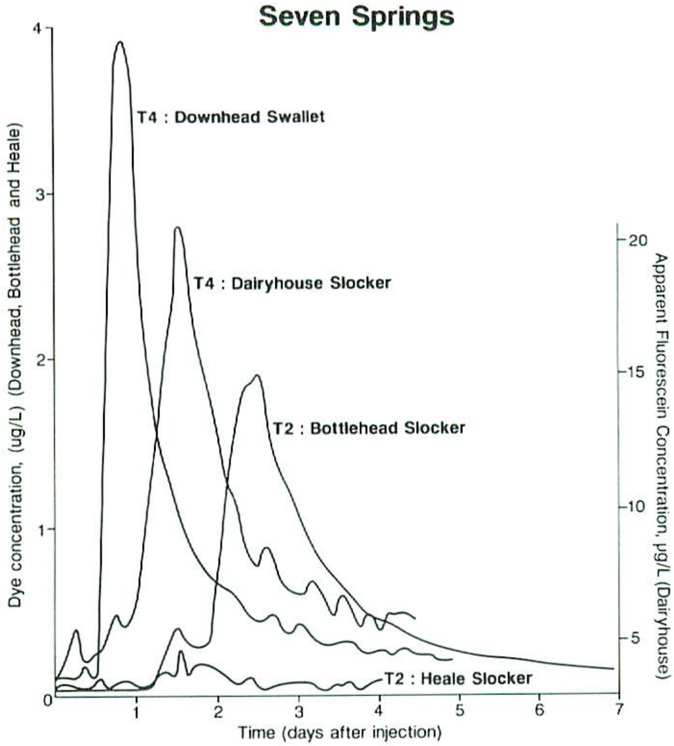

Figure 2. *Tracer breakthrough curves at Seven Springs. (Main Spring) for Rhodamine WT injected at Downhead Swallet and Bottlehead Slocker, and Fluorescein injected at Dairyhouse and Heale Slockers (Tests 2 and 4).*

different breakthrough curves (Figure 3). The main dye pulse is not transmitted to Pineroot Spring, but after a delay of some two days there is a gradual rise in dye concentrations, upon which are superimposed spikes of higher concentration related to the fluctuating water levels. It is clear that Pineroot Spring becomes decoupled from the main swallet conduit at low flows. The delayed response suggests that there is movement from the main conduit through the diffuse flow zone into the Pineroot conduit. It is interesting that while tracer introduced at Downhead and Dairyhouse swallets emerges from both springs, tracer from Bottlehead discharges only from Main Spring, as also reported by Atkinson *et al.* (1973). This difference suggests that the link feeding Pineroot Spring must diverge from a separate conduit draining Downhead plus Dairyhouse Swallets before the Bottlehead conduit is tributary to the Main Spring.

Dye recoveries calculated for Seven Springs have a relatively large uncertainty because of the difficulties in monitoring spring discharge discussed previously. Nevertheless, the differences between individual swallets are relatively large, and are probably real. Recoveries for Downhead Swallet (Table 1) are between 30 and 50% (3 tests), whereas the adjacent Dairyhouse Slocker gives complete

Table 2. *Flow velocities calculated using straight line distance with time of first arrival and time to peak dye concentration for a) swallet/Seven Springs conduits, b) boreholes and quarry sites*

a)

Stream Sink	Groundwater Flow Velocity (km/d) First Arrival	Peak	First Arrival+
Downhead	> 6.7 — 4.0	6.7 — 2.5	7.4 < V < 10.4
Dairy House	4.0 — 3.4	2.3 — 1.4	4.2
Bottlehead	> 2.4 — 1.9	2.4 — 0.9	2.4 < V < 2.8
Heale	? — 1.7	? — 1.6	3.1 < V < 3.7

+*From Atkinson et al (1973), Table 2*

b)

Test	Injection Site	Detection Site	Groundwater Flow Velocity (km/d) First Arrival	Peak
Test 1	Downhead	Neilson 1	10.2	2.04
		Tunscombe	0.96	0.63
		Shute 1	0.26	0.23
		Pineroot Sp	—	0.42
	Dairyhouse	Pineroot Sp	0.60	—
Test 5	Downhead	Pineroot Sp	0.70	—
		Ashley 1	2.37	0.082 (0.022)
		Secondary Sump	0.24	0.096
		Issues	0.14	0.11
	Bottlehead	Secondary Sump	0.45	0.17
	Heale	Borehole P2	> 0.85	0.85
		Sump	0.48	0.14
		Issues	0.11	0.050
		Tunscombe	0.13	0.045

recovery (2 tests). Results for Bottlehead Slocker are similar to those from Downhead Swallet in Test 2 (37%), but under high flow recovery is much higher (90%). In none of the tests was tracer detected at either the main or subsidiary Holwell Rising. These results are in agreement with the results of the previous spore tracing, but cast some doubt on the weak positive result from Dairyhouse Slocker obtained using charcoal detectors at Holwell Main Rising by Atkinson *et al.* (1973). However, there must be another outlet from the system to account for the consistently low recovery from Downhead Swallet and possibly also Bottlehead Slocker. There are two possibilities, either Torr Quarry is capturing significant flow (discussed in the following section) or a natural distributary branch is present in the conduit system which under-flows Whatley Brook, but continues to the northeast without connecting to Holwell Rising. The latter is certainly possible given the interpolated water table contours, and receives some support from the reported recovery of spores from Downhead Swallet and Heale Slocker at Westdown Quarry Borehole (Figure 1), which is unfortunately now no longer accessible.

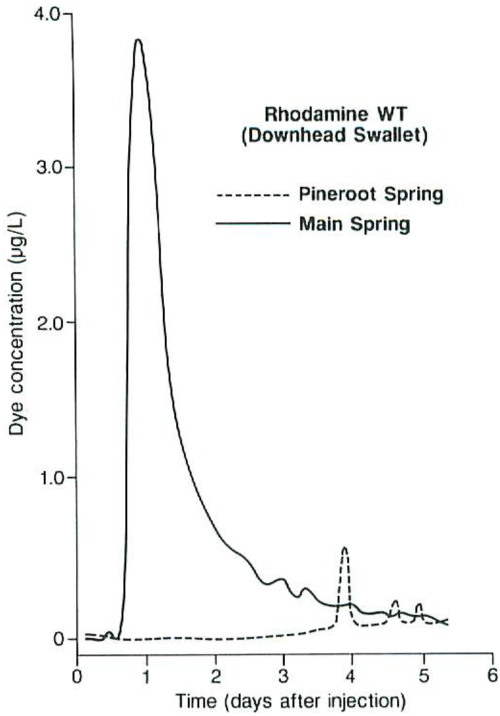

Figure 3. *Comparison of Rhodamine WT tracer breakthrough curves for injection at Downhead Swallet (Test 1) at Pineroot and Main Spring (Seven Springs).*

Influence of Torr Quarry on the Heale Slocker/Seven Springs Conduit

A major difference between our results and those obtained previously by Atkinson *et al.* (1973) prior to the sub-water table development of Torr Quarry, is the failure to detect tracer injected at Heale Slocker at Seven Springs (Table 1). During Trace 2, it appears that a very small amount of Tinopal CBS-X may have emerged from the spring some 2 days after injection (Figure 2). The tracer was not detected at any of the monitored boreholes, nor in the Torr Quarry sump. However, Tinopal CBS-X (a blue fluorescent tracer) has a low resistance to photo degradation (Smart and Laidlaw, 1977), and may therefore have been lost when exposed in the quarry sump, or simply diluted below minimum detection levels.

For Test 5 Rhodamine WT, which has a low and stable background fluorescence and is resistant to photodecomposition, was injected at Heale Slocker. It was not detected at Seven Springs (although the initial tracer breakthrough was inadequately sampled), but was detected in hand samples from borehole P2 (Figure 1) some

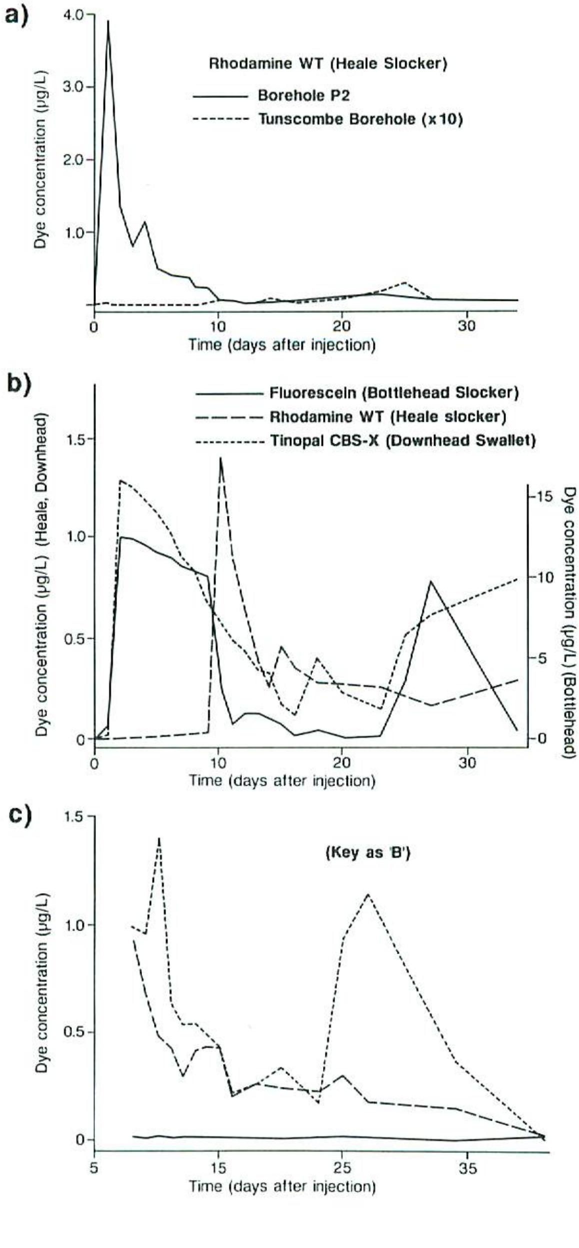

Figure 4. *Tracer breakthrough curves for Test 5:*

a) *Borehole P2 Torr Quarry and Tunscombe borehole for injection of Rhodamine WT at Heale Slocker.*

b) *Secondary sump outflow Torr Quarry for Fluorescein (Bottlehead Slocker), Rhodamine WT (Heale Slocker) and Tinopal CBS-X (Downhead Swallet).*

c) *Strong Spring issues Torr Quarry for Fluorescein (Bottlehead Slocker) and Rhodamine WT (Heale Slocker).*

25 hours after injection (Figure 4a). The dye breakthrough curve rose rapidly to a peak then dropped exponentially, the same response as the other swallets at Seven Springs and strongly suggestive of conduit flow. Borehole P2 is cased to a depth of 50 m, but is then open to a depth of c 200 m (c. - 50 m AOD; all other boreholes sampled are uncased or have slotted casing). Therefore the Heale conduit apparently tapped by the unpumped borehole P2 is at some depth below the quarry floor, and has not yet been intersected by removal of limestone.

At the time of Test 5 a secondary sump had been excavated on the quarry floor north west of the main sump, and water was pumped from this via a pipe and open channel to the main sump when required to clear standing water on the quarry floor at 146-147 m AOD. Traces of Rhodamine WT from Heale Slocker were detectable in the secondary sump 4 days after injection at very low but rising concentrations which are indicative of highly dispersed diffuse flow (Figure 4b). Nine days after the injection an intense 25 mm rainstorm affected the East Mendip area, substantial areas of the north western part of Torr Quarry were flooded to depths up to 1 m. Water was observed to discharge at specific points from rubble masking the north western wall of the quarry (Figure 1). Tracer concentrations in one such issue ('Strong Spring') are shown in Figure 4c. Much higher concentrations of Rhodamine WT were present initially than in the secondary sump, but these declined progressively with continued flow. Tracer was still present in the issues some 40 days after injection when flow ceased, and was also detected when flow recommenced after heavy rain 52 days after injection. The recovery of Rhodamine WT was budgeted using the rating for the pump discharging water from the secondary sump, which operated from days 10 to 19 after injection. The dye concentrations mirrored those from the issues, peaking initially as tracer was flushed out by the recharge event, then declining slowly, as would be expected for a diffuse flow system. Tracer recovery was estimated as 30% on cessation of pumping, but at this time hand samples from standing water on the quarry floor, combined with the observed extent and depth of flooding suggest an additional 2.5% to 3% of the tracer was present, which declined to about 0.5% on cessation of sampling. Significant tracer discharge also continued for the next 37 days (Figure 4c), but could not be formally budgeted as dilution in the main sump, which has a large volume (274 x 10^3 m^3) was too great. A maximum additional recovery of 12.5% is estimated from the observed tracer concentrations in the issues and their estimated combined discharge. Thus the total estimated recovery of the tracer injected at Heale Slocker is 45.5% all of which appears to have reached the quarry sumps via diffuse flow routes.

One other sample location Tunscombe borehole, showed the presence of the tracer from Heale Slocker (Figure 4a), although concentrations were very low. Tracer was first detectable following the heavy rainstorm on day 9. Then concentrations increased gradually until a further period of rain which commenced with 15 mm on day 23 and continued with smaller totals until 27 days after injection. This recharge event caused a second pulse of tracer to move into the borehole, but concentrations then fell to previous levels. Dye was no longer detectable 42 days after injection. Thus in addition to that discharged into Torr Quarry, some of the tracer from Heale Slocker underflowed the Quarry and was moving down the regional hydraulic gradient towards Seven Springs, apparently as a diffuse plume. No tracer was however detected at Seven Springs, probably because of high dilutions in the swallet conduits feeding the springs.

Influence of Torr Quarry on the Downhead and Bottlehead Conduits

Fluorescein dye from Bottlehead Slocker was detected during Test 5 in the secondary sump in Torr Quarry within 48 hours of injection, indicating a very rapid transmission. However, it was not present in any of the quarry floor issues, and hence was rapidly diluted once these entered the sump and pumping commenced. It was no longer detectable 16 days after injection. Recovery was estimated at 4.3%, giving a total tracer recovery of 90%. This is not significantly different from 100% given the probable gauging errors involved, but it is noteable that concentrations rose again in the secondary sump after pumping ceased, suggesting that unrecovered tracer remained in storage, either in the aquifer, or more probably the quarry sub-floor. No fluorescein was detected at any of the borehole sampling sites. The essentially complete recovery in Test 5 compared with only 37% recovery in Test 2 is significant and will be discussed further below.

During the 1987 (Tests 1-4), tracer injected in Test 1 at Downhead Swallet was not detected at the Torr Quarry main sump, but was detected in several boreholes (Figure 5). At Manor Farm, a peak occurred some 12 hours after injection, followed by a plateau-like low concentration tail. A similar tail was also observed at Tunscombe and Shute 1 boreholes, 1 and 3 days respectively after injection. The clearance of dye from the observation boreholes coincided with a decline of tracer concentrations at the Pineroot Spring (Figure 5), which has been shown above to be decoupled from the swallet conduit at low flow. This suggests that a pulse of tracer may have been moving in the diffuse flow part of the aquifer towards the spring, an observation similar to that made for the Heale Slocker (Test 5) test at Tunscombe borehole.

Test 5 was undertaken under similar groundwater level conditions as Test 1, but tracer from Downhead Swallet was not detected in either the Manor Farm or Tunscombe Boreholes (Shute 1 was not sampled). This may be partly because of the high and more variable background fluorescence at the Tinopal CBS-X (blue) waveband. In the recently drilled Ashley 1 borehole fluorescence readings in the blue waveband showed a double peak before declining to lower values 16 days after injection (Figure 6b). These peaks coincide with and lag recharge events associated with rainstorms. There is however no comparable change in apparent concentration at the rhodamine (orange) waveband, and the changes associated with the third rainy period (days 23 to 27 after injection) are much smaller (although sample frequency is much lower). This suggests that we are not simply monitoring changes in background fluorescence associated with organic-rich soil water arriving at the watertable, but that some of the labelled Downhead Swallet water moved from the conduit into the aquifer during recharge events. Confirmation of this association of tracer breakthrough and recharge is also apparent during Tests 1 and 3, which were undertaken during a period of generally falling groundwater-levels, onto which minor recharge events were superimposed.

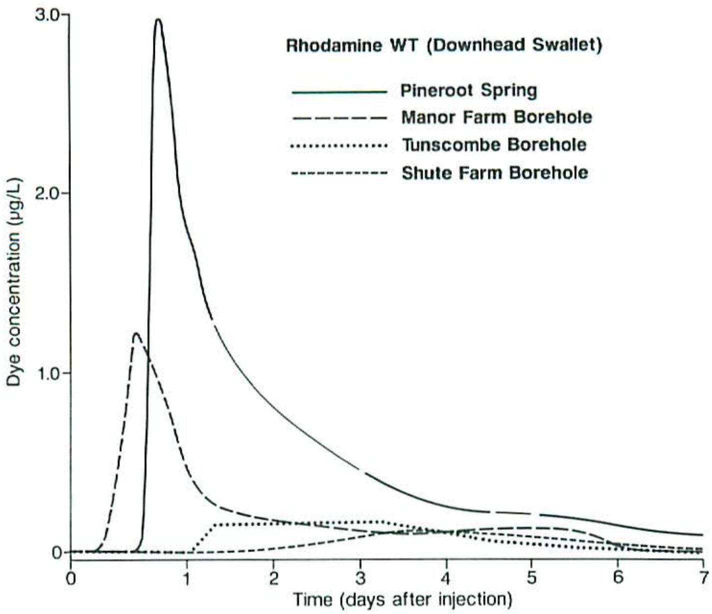

Figure 5. *Tracer breakthrough curves for Rhodamine WT injected at Downhead Swallet (Test 1) at Pineroot Spring, Manor Farm, Tunscombe and Shute Farm 1 boreholes.*

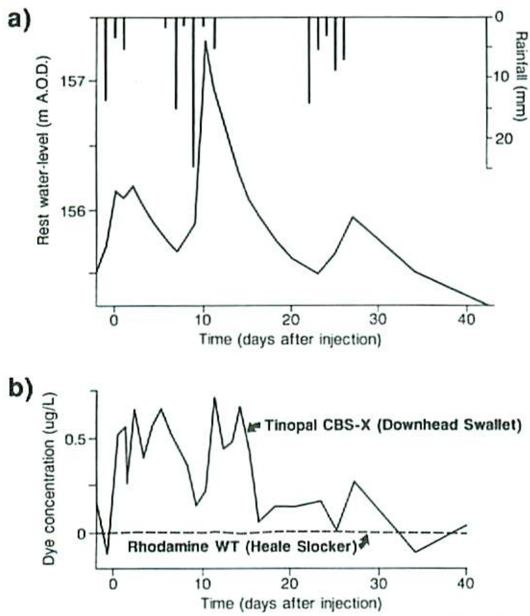

Figure 6. a) *Rest water level in Ashley 1 borehole and daily rainfall at Torr Quarry.* **b)** *Apparent concentrations of Tinopal CBS-X injected at Downhead Swallet in Test 5 and Rhodamine WT (background fluorescence) in the Ashley 1 borehole.*

No tracer was detected at either the boreholes or the quarry sump for Test 3 (freezing of the samplers precluded determination of the tracers at the springs), which took place when swallet flows were in recession. In contrast Test 1, which proved positive, was associated with a minor recharge event and high swallet flows (50 L/s at Downhead compared to 24 L/s during Test 3).

In Test 5, the behaviour of the Downhead Swallet Tinopal CBS-X tracer in Torr Quarry was initially similar to the fluorescein from Bottlehead Slocker (Figure 4b), with rapid initial arrival. However, Tinopal CBS-X was also present in the new issues, (Figure 4c), thus concentrations in the sump fell less rapidly after the onset of pumping. Despite this, the tracer was rapidly exhausted, and recovery was only about 2% of the injected mass. Concentrations only rose again when pumping stopped. There is thus a clear contrast between the style of breakthrough from Bottlehead Slocker and Downhead Swallet, where diversion from the conduits is minor and a single short pulse reaches the quarry, and Heale Slocker, where capture of the conduit flow is complete and a sustained discharge of tracer occurs via the quarry.

DISCUSSION

The Conduit System

The conduit network deduced from the tracer tests is shown schematically in Figure 1. Downhead Swallet, and prior to dewatering by Torr Quarry, Heale Slocker join in a common conduit with a distributary which directs 30 to 50% of the combined flow below the Whatley Brook and Seven Springs. This conduit was tapped by the Westdown Quarry borehole, but its ultimate outlet is not proven. It may conduct water down the hydraulic gradient towards Frome. The failure to recover tracer from Downhead Swallet at Holwell Rising strongly suggests that this is not the outlet for the distributary, while the consistant 100% recovery of dye from Dairyhouse Slocker casts doubt on the validity of the connection to Holwell suggested by Atkinson *et al.* (1973). It seems more probable that Holwell Rising drains water recharged in the block of limestone east of Torr Quarry and south of Seven Springs, but this suggestion should be tested by tracing.

Downhead Swallet, Dairyhouse Slocker and, before quarrying, Heale Slocker feed both Pineroot and Main Springs. We have not computed recoveries for the two springs separately, but the general pattern of tracer breakthrough from the two swallets is similar at them both, and it seems probable that the Dairyhouse conduit is tributary to the combined Downhead/Heale conduit below the Seven Springs underflow distributary, but prior to the split feeding the two springs. At low flow only the Main Springs branch functions, and Pineroot Spring then serves only as an outlet for diffuse flow. Results for Bottlehead Slocker are consistantly negative at Pineroot Spring indicating that it is not tributary to the combined Downhead/Heale/Dairyhouse conduit, but feeds the Main Spring conduit below the Pineroot distributary. Prior to dewatering it is suggested that this is the only outlet from the conduit, as indicated by complete recovery in Test 5.

Although we have relatively few repeat traces, and controls on the conditions for each are poor, we can examine the time of travel/spring discharge relationship to infer if the conduit is water-filled (phreatic) or has an open water-surface (vadose) (Stanton and Smart, 1981). The results of Tests 1 to 4 suggest that the Downhead conduit is essentially vadose (gradient log time of travel time log spring discharge 0.5), as is the Dairyhouse conduit (gradient 0.7). The higher figure for Dairyhouse infers that part of this conduit prior to the junction with the Downhead conduit is phreatic. Test 5 gives a much faster travel time for Downhead Swallet, implying that under very wet conditions it may become phreatic, but further work is needed to confirm this. At low flow when dye recovery is incomplete (37% Test 2), Bottlehead Slocker shows a very slow travel time (Table 2A), compared with that for higher flow when recovery is complete (86%, Test 5). It is thus not possible to determine the type of conduit. The rapid recovery of tracer injected at Heale Slocker in the deep borehole P2 in Torr Quarry suggests that the Heale conduit is deep below the water table and hence phreatic in nature.

These results accord well with expectations based on the known structural control of cave passages (Ford and Ewers, 1978). Strike directed flow may utilise bedding planes which are laterally continous in the direction of flow, and allow development of solution conduits with relatively minor loops (state 3 or watertable cave of Ford and Ewers, 1978). Conversely flow down-dip, or in the case of Heale and Bottlehead Slockers up-dip, must utilise infrequent and discontinous joints to pass through the dipping limestones. This results in deep looping phreatic passages (state 1 or 2 of Ford and Ewers 1978), which are hydraulically much less efficient than strike conduits because of their greater length and the high probability of sediment constrictions at the bottom of the loops. This may explain why the *Lycopodium* trace results show lower velocities for Bottlehead and Heale Slockers with a high up-dip conduit component, compared to Downhead and Dairyhouse (Table 2A). Farrant (1991) illustrates precisely this structural control in the newly discovered Cheddar Springs conduit.

Dewatering of the Conduit Systems by Torr Quarry

The tracing results show an increasing degree of functional change in the conduits as a result of dewatering with distance from the quarry, and coincidentally between phreatic (near) and vadose (far) conduits. The Heale Slocker conduit no longer discharges to the Downhead Swallet conduit feeding Seven Springs, but there is no evidence that it has been directly intercepted by quarrying. Rather it appears that leakage by diffuse flow from the conduit under the steepened hydraulic gradient associated with pumping from the quarry prevents development of sufficient head within the conduit to enable pressure-flow over the downstream loop thresholds. This interpretation is supported by the widespread distribution of tracer from the Heale conduit within the Torr Quarry issues adjacent to borehole P2, which is indicative of diffuse flow, and by the movement of tracer down the natural hydraulic gradient north east of the quarry to the Tunscombe borehole. Note also that the quarry issues and Tunscombe borehole show 'flushing' of the tracer in response to rainfall events as swallet recharge pushes more dye tracer through the diffuse flow zone of the aquifer.

The Bottlehead Slocker conduit, which lies further to the north than Heale Slocker, is less directly influenced by dewatering. During Test 5 conditions were particularly wet and swallet flows high. A small pulse of tracer moved initially to the sump, suggesting leakage into the diffuse flow zone as for Heale Slocker, but the majority of the dye injected was discharged through the conduit to Seven Springs. During Test 2 swallet recharge was much less, and the hydraulic gradient towards Torr Quarry was higher because the sump was at a low level. As a result, tracer recoveries at Seven Springs were much lower (37%), the major part of the dye moving towards the quarry by diffuse flow according to the Heale Slocker model. This interpretation is supported by the very much slower travel time suggesting impairment of transmission along the conduit. In fact no tracer was recovered in the quarry, possibly because of high dilutions in the main sump, or because sampling was not continued for sufficient time. Calculated velocities for diffuse groundwater flow based on the tracer tests are typically an order of magnitude lower than for conduit flow using first arrival (Table 2A and B). However, given the much greater dispersion in diffuse flow, time to peak (or ideally time to centroid) velocities are more representative.

The Downhead Swallet conduit is least affected by quarry dewatering both because it is furthest away from the quarry, and because it is predominatly vadose. Thus although some leakage from the conduit into the diffuse flow zone occurs, as indicated by detection of tracer in the observation boreholes during Test 1, this water is not drawn towards Torr Quarry, but follows the natural hydraulic gradient to discharge from Seven Springs (Figure 5). In a vadose conduit leakage is independent of the head differential in the saturated zone and essentially constant. In fact the tracer evidence from Test 5 suggests that pulses of dye are expelled from the conduit during high flows, perhaps when pipe-full flow conditions occur. The movement of these pulses in the diffuse flow zone appears to be complex, and further tests are necessary to determine if the results reported are reproducible, and explainable in terms of differential head conditions imposed on the general regional hydraulic gradient towards both quarry and natural outlet.

CONCLUSIONS

To our knowledge this is the first well-documented example of change in the function of a conduit network as a result of quarry dewatering. Given the increasing use of this option in extraction of limestones it is therefore of some interest. Changes in the conduit behaviour clearly occur even though direct intersection by the quarry void has not occured. This appears to be the result of diffuse leakage of water from the conduit which prevents pressure flow over phreatic loop-tops. Similar leakage from vadose conduits will have much less effect on conduit function because pressure flow is not involved. Despite tracer tests being the tool preferred by karst hydrologists for the study of karst conduits, hydrogeologists assessing the impact of quarry dewatering have generally adopted more conventional approaches. Perhaps the information obtained in this study may encourage a more wider utilisation of water tracing techniques for improving our understanding of both conduit and diffuse flow in karst terrains.

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