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ANALYSIS AND INTERPRETATION OF DATA FROM TRACER TESTS IN KARST AREAS

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Qualitative tracer tests are used to determine flow connections between accessible input and output points and to delineate karst drainage basins for reconnaissance studies. Quantitative tests, which measure the amount of tracer recovered over time and the flow (discharge) of the input and output sources, provide additional insight into the flow processes and mechanisms within the aquifer. The processes acting on a conservative tracer determine the shape or pattern of the dye recovery curve. The dye recovery pattern is determined by 1) the conduit network pattern, 2) the flow characteristics of the aquifer, and 3) the adsorption and dispersion characteristics of the tracer.

Introduction

Dye tracer studies of subsurface water systems present a "black" box (literally and figuratively) problem in interpretation of the resulting data. The inputs and outputs are measured, and the researcher must attempt to reconstruct the invisible workings of the black box based on the changes in the output and any additional geologic and hydrologic information which may help to define the boundary conditions. The degree of success (or the amount of information gained) in interpretation of the groundwater flow system depends on 1) the complexity of the system under study, 2) the nature and quality of the tracer data, 3) the availability of geologic, topographic, speleologic, and hydrologic data for the study area, and 4) the researcher's familiarity with the study area and skill at working with the type of data available. As with the mechanics of performing the tracer tests, the interpretation of the results is often as much an art as a science. The main categories of tracer studies and data requirements are summarized in Table 1.

Reconnaissance Studies

Data from this type of study are needed to provide the necessary background for more sophisticated (and more expensive) quantitative studies. A tracer is generally injected in a sinking stream or siphon in a cave, and passive detectors are left in all the possible resurgences. These qualitative studies are used to determine underground connections and to help delineate karstic watersheds. The main weaknesses in the type of study are that little insight is gained as to the exact route or nature of the subsurface flow paths and, without the ability to calculate the amount of dye recovered from each resurgence, no clue is available as to whether the tracer may also be emerging at additional resurgences.

Table 1.

Purpose of Study	Type of Study	Analysis	Type of Data	Additional Data Requirements
Reconnaissance	Tracer with passive detectors	Visual or Fluorometric	Location of resurgencies & general flow direction	Topographic maps & maps of known cave passages
Water Budget Travel Time	Dye with direct sampling	Fluorometric	Recovery concentration & time of travel	Discharge at each resurgence and sink
Internal Flow Characteristics of Aquifer	Dye with frequent direct sampling	Fluorometric	Breakthrough curves time-recovery concentrations	All of the above and geologic structure & water chemistry data

Several short tracer tests generally provide a more detailed picture of an area than one long test. As shown in the illustration in the introduction to this issue, successive tests are based on earlier results and, when combined with maps of area caves, can present a detailed view of the karst drainage network (White and Schmidt, 1966; Jones, 1973).

Changing flow conditions can alter the apparent flow network by distributing water into higher "flood overflow" routes which may discharge to completely different springs or drainage basins from the low flow routes. In some areas, tracer tests must be conducted under high flow conditions and be redone during base flow to get a more complete assessment of the drainage network. The travel time for the tracer, even over the same flow route, may vary by as much as an order of magnitude between high and low flow conditions.

QUANTITATIVE TRACER TESTS

Quantitative tests require a considerably higher level of effort, for all of the resurgences must be continuously sampled for the entire length of time the tracer is emerging. The samples must then be analyzed against known standards to determine the dye concentration. This recovery concentration versus time is plotted to give recovery (sometimes called breakthrough) curves. Note that the sampling interval may itself influence the shape of the recovery curve.

Although several researchers have attempted to devise methods of quantifying the dye recovered in the elutant from charcoal detectors (Thrailkill, 1983) or from direct readings of fluorescent intensity of cotton detectors (Smart, 1976), no satisfactory substitute for continuous water sampling has been found. Also, the natural variation in background fluorescence may seriously compromise the procedure.

If dye injected at one point is found to resurge at several different points, then flow (discharge) during the dye recovery period is needed along with the dye recovery concentrations to determine the "water budget" for the sink. The term "water budget" as used here, refers to determining the relative percentages of water which a karst flow system distributes to the various springs. Examples of different karst flow patterns are illustrated in Figure 1. If the karst drainage system is characterized by a few large springs which act as "collectors" for a number of sinks and caves, the water budget can probably be inferred from completely qualitative tests. However, more complex drainage systems which utilize different routes under different flow conditions should be studied using quantitative methods.

When using fluorescent tracers, a known quantity of a conservative dye is injected into the aquifer and water samples are collected at regular intervals at each resurgence (determined by previous qualitative tests). The samples are then analyzed using a fluorometer to determine dye concentration over the total recovery time (Figure 2). The discharge at each resurgence must be known for the entire dye recovery period. The total amount of dye recovered at each resurgence is found by integrating the area under the time concentration curve and multiplying by the discharge.

$$Wd = Q_0 C \, dt \qquad (1)$$

where Wd is the weight of the pure tracer and C is the dye concentration measured at the sampling site at time t (Figure 2). The percentage recovery (Rp) is computed as

$$Rp = 100 \bullet \frac{C \text{ observed}}{C \text{ conservative}} \qquad (2)$$

No tracer is 100% conservative. Some dye is always lost to adsorption, photochemical decay, and complexation and precipitation from solution. Tests conducted over short time periods (less than 2 days) and in relatively low sediment water should show minimal dye losses. Tests which take over a month or during which the discharge and sediment concentrations fluctuate greatly may be impossible to quantify. Data from surface water "time-of-travel" tests are often presented in a "normalized" form prepared by dividing the values from peak concentrations by values for the weight of the dye injected and adjusting the observed concentrations to conservative concentrations. The problem in karst tracer tests is that if some of the water flows to other resurgences with different travel times, only a rough estimate can be made of dye lost to adsorption versus the dye lost to other resurgences. The only result normalizing the data accomplishes in this case is to camouflage data which will not stand close inspection. Fortunately, time-of-travel can be determined from the general shape of the time-concentration curve, even if absolute values cannot be obtained.

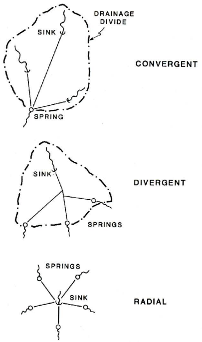

Figure 1. **Karst drainage patterns.**

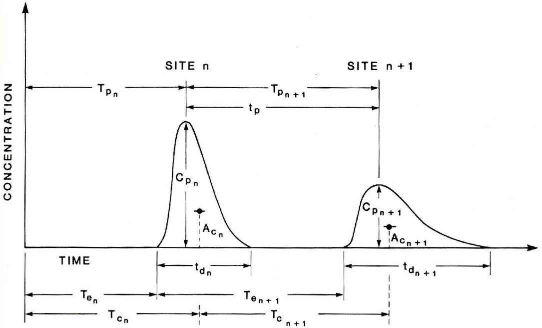

Figure 2. **Definition sketch of dye recovery curves resulting from instantaneous dye injection. Two sampling stations (site n and site n + 1) on an unbranched channel with no lateral inflows or outflows are shown. The principal components of the curves are: Time of first arrival (T_e), Time to peak concentration (T_p), Time to centroid (T_c), Total Time of dye passage (T_d), Peak (maximum) dye concentration (C_p), and point representing mean dye concentration (A_c). For a conservative tracer, the area under the curve at site n equals the area under the curve at site n + 1.**

Drainage Basins and Water Budgets

Discharge at the sinks and resurgences should be measured independently of the tracer. Figure 3 illustrates a simple cave passage which distributes water to three separate springs. The water emerging from the springs receives no lateral inputs past the point of divergence, so recovery data collected at one or two of the springs without independent discharge measurement will not yield any hint of the presence of additional springs for this distributory.

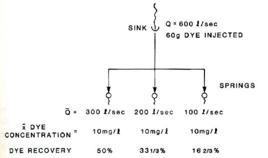

Figure 3. **Water budget calculation for a three-way distributory.**

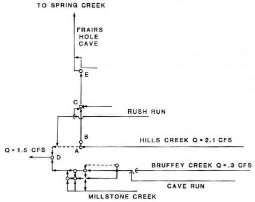

Figure 4. **Schematic drawing of drainage pattern of the upper Spring Creek-Locust Creek basins, West Virginia. Shown are Hills Creek Cave (A), Cutlip Cave (B), Clyde Cochran Cave (C), Locust Creek Cave (D), Upper Friars Hole Cave (E). (After Williams and Jones, 1983).**

The presence of additional springs is clearly shown in the data presented in Figure 4. In this example, it was long assumed from three qualitative tests that Hills Creek (point

A) discharged only to Locust Spring (point D). However, this quantitative test revealed that with a travel time of less than 24 hours only about 5% of the tracer was recovered at this spring. The remainder of the tracer was recovered at another spring a month later and 12 miles to the south of Locust Spring.

The pitfalls of interpreting the drainage network with a minimal number of qualitative tests in a complex karst basin are further illustrated by results from this area. Figure 5

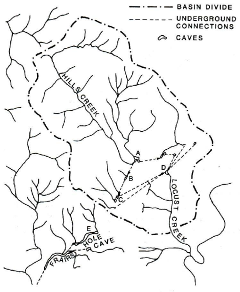

Figure 5. **Interpretation of Upper Spring Creek-Locust Creek drainage based on one qualitative dye test (dye injected at point A). Compare to Figure 4 (After Coward, 1975).**

shows the earlier interpretation of the flow routes based on one qualitative test and the later interpretation (Figure 4) based on a quantitative test.

The first interpretation of this area was based on the injection of fluorescent dye at point A and its apparent sequential recovery at points B, C, and D (Coward, 1975). These earlier tests were qualitative, so no data were available for dye recovery concentrations or stream discharge. A later quantitative test (Williams and Jones, 1983) involved simultaneous injection of three different tracer dyes, CWT at A, RWT at B, and FL at E. Discharge measurements indicated that, under base flow conditions, the stream flow at point A was greater than at D and therefore the spring at D could not account for all of the water from this sink. The water budget shows that at low flow only 5% of the water from sink A resurges at spring D. Furthermore, dye injected in cave B was not recovered at all at spring D, but was found over a month later at springs 12 miles to the south of spring D. The earlier test was not wrong, but the results were misinterpreted due to lack of quantitative data and not enough resolution in the reconnaissance tracing data.

The drainage divides may be hard to define and impossible to delineate in karst areas with a high density fracture network where groundwater has much more freedom of movement than in an area dominated by dendritic conduit flow routes. Smart (1976) suggested defining the groundwater divide between two basins as the location from which 50% of the tracer moves to one spring and 50% to the second spring. The concept of a separate drainage basin for each major spring may be meaningless in an area characterized by a radial groundwater drainage pattern.

Time-of-Travel

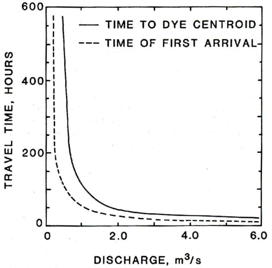

Figure 6. **Discharge versus time-of-travel (After Smart, 1981).**

A time-of-travel determination may be calculated from the dye recovery curves. When concentration (or relative intensity) versus time is plotted for systems characterized by unbranched, open channel flow conduits, the recovery curve will usually be skewed to the left (Figure 2). The time-of-travel may be expressed in terms of time from (instantaneous or slug) dye injection at sink to first appearance, time to peak concentration, or time to centroid (50% of the dye recovered). With increasing travel time (or distance) the recovery curves show increasingly lower peak concentrations and longer recession tails. With a conservative tracer, the total amount of dye passing any point remains the same, but the peak concentration becomes progressively lower with increasing dispersion of dye into, and slow release from, dead zones. This implies that traces conducted during low flow conditions will produce much lower relative peak concentrations than tests conducted at high flows (after normalizing the curves to adjust for volumes).

Data from Smart (1981) are presented in Figure 6 which shows an exponential relationship between discharge and travel time. Data from constant width rectangular conduits in the Mendips (Great Britain) show that increasing velocity accounts for two-thirds of the discharge increase and cross-sectional area accounts for one-third. In a closed channel conduit, velocity change must account for all the change in discharge, while velocity typically accounts for one-third of the change in discharge in surface streams. If log discharge is plotted against log travel time, for entirely phreatic conduits, the line will have a slope of −1.0, while the slope for entirely vadose passages will be about −0.3 or greater (Smart, 1981). Smart used the dye centroid travel time versus discharge to determine if the conduits were vadose or phreatic and attempted to calculate the conduit volume as well. It is interesting to note that travel time may be calculated from the shape of the recovery curves even if the dye budget values do not balance well.

Dye Recovery Patterns

The typical dye recovery pattern from vadose conduits is similar to patterns from surface streams studies, but underground diverging and converging, lateral inputs and outflows, alternating vadose and phreatic flow conditions, and increased opportunities for adsorption and dispersion of the tracer alter the characteristic recovery patterns. The appearance of the dye recovery curve is determined by 1) the conduit network pattern itself, 2) the flow type, conditions, and variation during the test, and 3) the adsorption and dispersion characteristics of the tracer. The interpretation of multiple peak tests is especially subjective because it is often difficult to determine the exact causes of fluctuating dye recovery curves.

Five types of flow networks with discrete inputs and outputs were suggested by Brown (1969) and are presented in Figure 7. Note that for a type 4 flow network, the lateral inputs and outflows could cancel each other, and the measured discharge at the inlet and outlet would be equal. The dye budget, however, should suggest a water loss from the system. Conduits which have anastomosing flow patterns should show multiple dye concentration peaks representative of the dye traveling different distances to the resurgences. Much of the interpretation of multiple peak recovery curves suggested branching and converging of the conduit flow routes.

The flow type (vadose or phreatic), the variation in flow during the test (changes in discharge and velocity), the

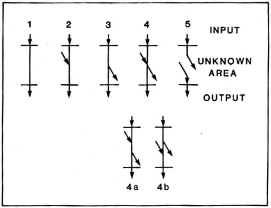

Figure 7. **Five types of Karst flow systems (Black box model) (After Brown and Wigley, 1969).**

Type 1—Single input to single output.
Type 2—Unknown lateral input.
Type 3—Unknown additional outputs.
Type 4—Additional unknown inputs and outputs.
Type 5—Input unknown, output unknown.

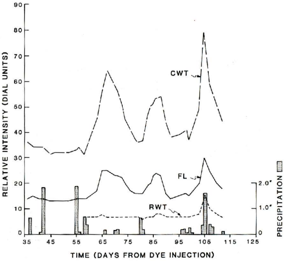

Figure 8. **Dye recovery curves and rainfall. JJ Spring, Spring Creek, West Virginia. Dye injection points are shown in Figure 4: Calcoph White (CWT) was injected at point A, fluorescein (FL) at point E, Rhodamine WT (RWT) in Rush Run (After Williams and Jones, 1983).**

amount of dead zone storage, and the amount of dye trapped in intermittently active conduits create complex tracer recovery patterns. Tracer tests having long flow-through times (one month or longer) often exhibit multiple peak recovery curves which correlate well with storm events (Figure 8). This suggests either a flushing of the tracer by increasing discharge with the subsequent loss of dead zone storage, or the remobilization of dye trapped in the intermittently active conduits. If dead zone storage is the primary mechanism, the peak will be attenuated and followed by a long recession tail. If the dye is trapped in intermittently active conduits, the peaks should correlate with storm events. Unfortunately, both storage mechanisms are usually active, and the evidence used to determine the responsible processes for multiple peaks is often ambiguous.

Smart and Ford (1982) suggested some simple shaft interpretations (Figure 9) of dye tracer experiments in a glacierized alpine karst area. These interpretations were not based on the dye recovery and discharge data alone, but also on a knowledge of the geology, morphology, and observations of the accessible caves in the region.

CONCLUSIONS

Water tracing and the interpretation of the data is often a somewhat subjective art, even if absolute values are available. The researcher must integrate the tracer test and hydrologic data with the study area's topographic and geomorphic patterns. As more quantitative data from different hydrogeologic regions becomes available, the interpretative techniques should become more sophisticated, if not more exact.

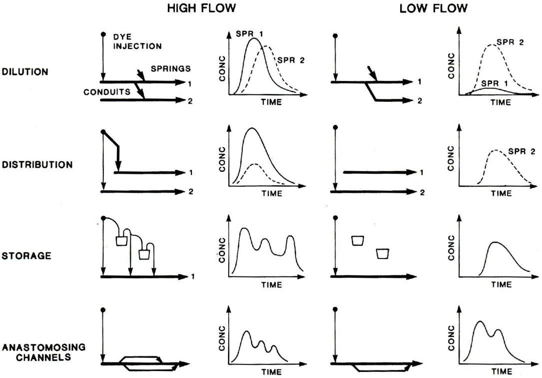

Figure 9. **Simple shaft-conduit interpretations of dye recovery patterns (After Smart and Ford, 1982). The expected dye recovery curves influenced by changing hydrologic conditions (high to low flows) and geometry of the conduit system is illustrated. Note that multiple peak recovery curves may be due to flushing of dye from dead zone storage or anastomosing conduit routes.**

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