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Tracer-Test Design for Losing Stream–Aquifer Systems

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Abstract:

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Hydrological tracer testing is an effective way for assessing the significance and extent of leakage through the bed of an influent (losing and sinking) stream. In karstic terranes, leakage from losing and sinking streams typically resurge at downstream springs, but flow may be intercepted by production wells. Although sinking streams that disappear into swallow holes and caves are relatively easy to trace, developing a tracer test design for a losing stream that allows slow percolation through its bed is complicated by the lack of basic knowledge regarding leakage rate, leakage locations along its length, and temporal variability. To overcome these complications, modification to the Efficient Hydrologic Tracer-test Design (EHTD) program were undertaken. Simultaneous use of both pumping wells and springs as sampling stations constituted initial modifications to EHTD. Additional modifications were then taken to address the problem of losing streams by using the total volume of flow leaking through the bed of a losing stream as determined by taking the difference between upgradient and downgradient discharge measurements or as estimated from the effective porosity of the stream bed. Leakage rate may be set if measured or may be taken as a function of the estimated mean travel time for the losing stream. These modifications are also effective for dry stream channel in which an artificial flow is necessarily added to facilitate a tracer test.

Keywords: tracer-test design, losing streams, leakage

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INTRODUCTION

Ground water recharged from influent (losing and sinking) streams, defined in the United States as "ground water under the direct influence of surface water" (CFR, 2002, p. 339), can potentially be subject to serious deleterious effects. Any contaminants released into an influent stream will percolate into the ground water and may adversely affect human health and the biota (Hoehn and Santschi, 1987) with minimal filtration (Pokrajčić, 1976; Yevjevich, 1981d; Ogden et al., 1993; Zwahlen, 2003, p. 12). In addition, losing reaches of surface streams often complicate the determination of ecologically acceptable flows (Bonacci, 1998). No where is this more significant than in karstic terranes where losing and sinking streams are common. Sinking streams typically disappear underground completely into dolines with defined ponors and caves or lose significant amounts of flow through small ponors along their course. Losing streams leak flow slowly through their beds. Concise discussions of losing and sinking streams may be found in Jennings (1985, pp. 42–45) and Ray (2004). Palmer (1972) provides a detailed discussion of the dynamics of a sinking stream–aquifer system in which a clear link between the surface and subsurface flows was established.

Comparatively, losing streams have not generated as much interest as have sinking streams, possibly because flow losses are difficult to determine and because subsurface recharge and flow measurements are not easily accomplished. For example, several methods for determining karst aquifer vulnerability have been recently developed, but all focus primarily on inflow via sinking streams with little mention of slow leakage along a stream reach (*e.g.*, Doerfliger, 1996; Doerfliger and Zwahlen, 1998; Doerfliger et al., 1999; Stokes et al., 2001; Daly et al., 2002; Davis et al., 2002; Goldscheider, 2002; Zwahlen, 2003; Tezcan and Ekmekci, 2004; Goldscheider, 2005). Although all karst vulnerability reports recognize the significance of losing streams, none has developed as much emphasis as was done with sinking streams because sinking streams are, by comparison, a more serious concern than is that posed by losing streams.

Evaluation of losing streams require complex and

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difficult simultaneous discharge measurements (Bonacci, 1987, pp. 124–130) commonly known as synoptic discharge measurements (SDM) and seepage runs (Duigon, 2001, p. 31). The problem of open streamflows in karstic terranes when there is no flow in the riverbed, as typically occurs during dry summer months, is a special problem (Bonacci, 1987, pp. 131–135). To analyze flows associated with streams that regularly dry up, Bonacci emphasizes the need to take a great number of discharge measurements along the stream length when there is flow and to have a dense network of piezometers for measuring ground-water levels. The importance of understanding the relation between losing streams and aquifer hydrology have been highlighted in the past (Yevjevich, 1981c, b, a).

Losing streams are also quite difficult to model mathematically (see for example, Strack, 1989, pp. 283–291). The physical measurements necessary for developing a model are very demanding and often seem unworthy of the collection expense (Lee, 1977; Haitjema, 1995, pp. 301–303). The method developed by Yamada et al. (2005) emphasizes this point. However, potentially serious contamination of a losing stream may warrant collection of the data necessary for modeling purposes.

Contaminant releases into losing streams will result in proportional contamination of both the losing stream and the underlying aquifer. Releases may take the form of continuous sources, such as may occur from wastewater treatment plants, or may be intermittent, such as may occur from an accidental chemical spill. Estimating exposures and risks posed by ground water under the influence requires substantial knowledge of the leakage rate of the losing stream and the transport velocities of both the losing stream and the underlying aquifer. Quantitative hydrologic tracing of losing streams provide the necessary information on flow trajectories and connections to downgradient wells and resurgences, transport velocities, pollutant dispersions, and mass proportions of each transport pathway. However, ground-water tracing design and analyses are extremely difficult for losing stream–aquifer systems. The difficulties arise because of the complex hydrological conditions and because of the typically poor tracer-mass recoveries (Bonacci, 1999).

The purpose of this paper is to document modifications to the Efficient Hydrologic Tracer-test Design (EHTD) program (Field, 2002a, b, 2003b) for the design of tracer tests using both wells and springs as sampling stations in losing stream–aquifer systems. The initial release of EHTD did not allow for consideration of both wells and springs as downgradient sampling stations for any given tracer test. Also, EHTD only addressed tracer tests in sinking streams. Modifications were effectively undertaken while maintaining backwards compatibility so that older input files do not need to be altered.

TRACER-TESTING LOSING STREAMS

Tracer testing of losing streams usually entails an instantaneous release of tracer in the stream at some location thought to be upgradient of one or more losing reaches and connected to one or more springs or wells of interest. This process may be refined by the taking of upstream and downstream discharge measurements, but such efforts are generally rare except for those instances where the tracing results may have far-reaching consequences (*e.g.*, highly contaminated sites or dam sites). Even rarer are those instances in which SDM are taken because of the difficulty and general notion that such difficult measurements are not warranted for successful tracer testing.

General Appearance of Losing Streams

Losing streams may appear as large rivers, small streams, and dry channels (Fig. 1) that only flow during periods of mild and extreme precipitation (Figs. 2 and 3). Figures 1–3 also depict a production test well and a

Fig. 1. Unnamed normally dry stream channel in a karstic terrane during extended periods of little or no precipitation. Note production test well surrounded by safety fencing (arrow) and gasoline service station in background (service station is upgradient of creek).

Fig. 2. Unnamed normally dry stream channel in a karstic terrane during a one-day period of mild precipitation. Note production test well surrounded by safety fencing (arrow) and gasoline service station in background (service station is upgradient of creek).

Fig. 3. Unnamed normally dry stream channel in a karstic terrane during a one-day period of heavy precipitation. Note production test well surrounded by safety fencing (arrow) and gasoline service station in background (service station is upgradient of creek).

gasoline service station in the background (the service station is upgradient of the unnamed creek). Leaking underground storage tanks and a ruptured solid waste sewer line are known problems in the area of this unnamed creek. Several production test wells have been shown by tracer tests to be connected to the unnamed creek.

Losing stream beds are typically alluviated, but may be rocky and/or vegetated depending on how often flow occurs and how strong the flows are in the channel. Beneath the general landscape lies the epikarstic zone (see Jones et al., 2004, for a detailed description of the epikarstic zone). A dominant fracture zone commonly lies beneath local stream channels as part of the epikarstic zone. This dominant fracture zone controls the stream channel orientation and form.

The underlying fractures that control a stream channel and that make up the epikarstic zone are characterized as grikes (solutionally-enlarged fissures) and clints. The fractures and grikes receive the water infiltrating through the bed of the surface stream and direct it to underlying solution conduits. Flow within the solution conduits then is discharged at downstream resurgences or is intercepted by pumping wells.

• Basic Leakage Theory

A schematic diagram of the basic mechanics of leakage of a losing stream–aquifer system in a simplified karstic terrane is shown in Fig. 4. Leakage is directed downwards to and through a grike that drains into a solution conduit. Assuming saturated conditions beneath the stream bed and atmospheric pore pressure ($p = 0$) (Haitjema, 1995, p. 238), leakage through the stream bed may be defined as

$$q_z = -K_z \frac{\Phi_s - \Phi_a}{d} = -K_z \frac{\Delta\Phi}{d} \qquad (1)$$

(see the Notations section for an explanation of equation parameters). The resistance to flow c is defined as (Haitjema, 1995, p. 236)

$$c = \frac{d}{K_z} \qquad (2)$$

so that if it is assumed that the resistance layer remains saturated and the pore pressure beneath the resistance layer is atmospheric then (Haitjema, 1995, p. 238)

$$-q_z = \frac{d}{c} \qquad (\Delta\Phi > d) \qquad (3)$$

The aquifer shown in Fig. 4 is unconfined. If the potentiometric surface rises to the bottom of the resistance layer or the resistance layer is taken as representing the depth to the potentiometric surface, then $\Delta\Phi = d$ which limits q_z to

$$q_z = \frac{\Delta\Phi}{c} = -K_z \qquad (4)$$

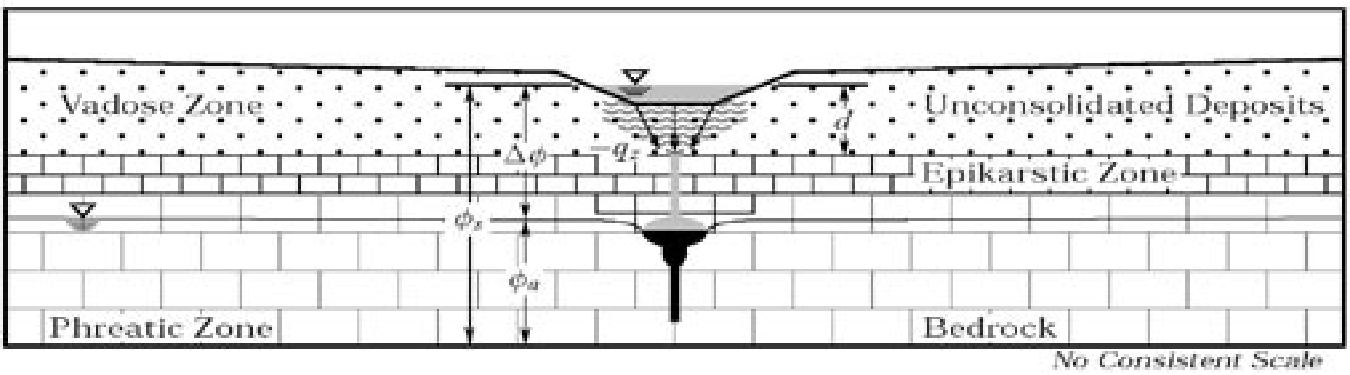

Fig. 4. Schematic cross section of a losing stream–aquifer system draining to a bedrock fracture. Leakage occurs through the stream bed alluvial deposits (resistance layer) below the stream bed, through the underlying grike, and to a solution conduit.

and follows from Equation (3). Equation(4) states that as $\Delta\Phi$ increases and/or c decreases then q_z increases. Equations (1)–(4) are an over simplification of the process. For example, K_z represents the hydraulic conductivity of the resistance layer (leakage), but does not represent the slow percolation through the epikarstic zone and tighter underlying bedrock around the grike or rapid percolation down the grike.

• Leakage Time

Leakage time t_z will be dependent on the factors listed in Equations (1)–(4) as shown in Fig. 4. If percolation through the resistance layer and bedrock is assumed to not vary, then the velocity υ_z is obtained from

$$\upsilon_z = \frac{q_z}{n_e} \tag{5}$$

Assuming $\Delta\Phi = d$ and applying the data shown in Table 1 in Equation (5), the leakage velocity υ_z through the stream bed resistance layer will be much slower than if leakage were to only occur through the grike. The stream bed resistance layer then is the main controlling factor that determines how rapidly leakage actually occurs. However, the velocity will also be dependent on the vertical hydraulic conductivity according to Equation (4). Consequently, leakage time t_z will be much shorter if the grike exists without an overlying alluvial resistance layer.

Assuming the resistance layer remains saturated, $K_z = 10^{-7}$ m s^{-1}, $n_e = 0.1$, and $d = 3.0$ m (Table 1) then $\upsilon_z = 10^{-6}$ m s^{-1} and $t_z = 35$ d through the resistance layer (Table 2). Alternatively, if $K_z = 10^{-4}$ m s^{-1} and the other parameters remain the same (Table 1) then $\upsilon_z = 10^{-2}$ m s^{-1} and $t_z = 50$ min through the resistance layer (Table 2). The subsequent velocity and travel time through the grike to the potentiometric surface will then be almost unrestricted if there are no blockages and will be mostly a function of distance.

Although overly simplified, this example illustrates the significance of the type and thickness of material below the losing stream. The difference in leakage times can vary greatly and even simple determination of the leakage times is difficult to estimate.

Table 1. Representative losing stream leakage hydraulic parameters.

Parameter	Stream Bed Resistance Layer (Low K_z)	Stream Bed Resistance Layer (High K_z)
K_z, m s^{-1}	1.0×10^{-7}	1.0×10^{-4}
n_e, m m^{-1}	1.0×10^{-1}	1.0×10^{-1}
d, m	3.0×10^{0}	3.0×10^{0}

Table 2. Example losing stream leakage velocities and travel times.

Parameter	Stream Bed Resistance Layer (Low K_z)	Stream Bed Resistance Layer (High K_z)[a]
υ_z, m s^{-1}	1.0×10^{-6}	1.0×10^{-3}
t_z, d	3.5×10^{1}	3.5×10^{-2}

[a] t_z = 50 min for the Hight K_z resistance layer

Problems with Tracing Losing Streams

A basic problem that arises when tracing a losing stream is determination of the proper tracer mass to release. Tracing a losing stream requires that a sufficient quantity of tracer be released for downstream detection at one or more recovery stations, but release of excess amounts of tracer can have human health and environmental consequences (Field et al., 1995; Behrens et al., 2001; Field, 2005). Numerous efforts over many years have been undertaken to devise tracer-mass estimation equations that suggest the correct tracer mass to release at any given time and place (Field, 2003a, b). Interestingly, apparently none of the previous tracer-mass estimation equations was intended to address leakage through the bed of a losing stream.

Most of the tracer-mass estimation equations cited in Field (2003a, b) were primarily concerned with tracer releases into dolines or sinking streams with defined ponors while others addressed well-to-well tracing in porous media. Tracer release into an open ponor is fairly simple, relative to losing streams, in that the tracer-test design need concentrate on the downstream discharge and tracing distance for the most part. However, tracer-test design in losing streams needs to consider the rate and extent of leakage through the stream bed.

Losing streams rarely leak water along their entire length or at all times of the year. Typically, losing streams leak water along selected reaches (Bonacci, 1999, 1987, p. 117) which complicates where the tracer should be released. If the tracer is released downstream of significant losing reaches, then insufficient tracer mass will percolate to the subsurface and will not be detected at downstream sampling stations. Alternatively, releasing the tracer too far upstream beyond any significant losing reaches may also result in insufficient recoveries at downstream sampling stations because the tracer may decay, be retarded, and become too diluted along the water course for subsequent detection at downstream resurgences. Very large releases of tracer might negate the effect of releasing the tracer too far upstream, but is not desirable from an aesthetic, human health, or environmental perspective.

Temporal effects are also significant. Tracer testing during periods of sustained precipitation often results in poor tracer recoveries at downstream sampling stations because the potentiometric surface is very high and may be discharging ground water into the surface stream. During periods of sustained drought the special problem of dry stream reaches (Bonacci, 1987, pp. 131–135) typically occurs. Dry stream reaches require that artificial water sources be utilized to mobilize a released tracer. The artificial addition of water requires that tracer masses to be released be reasonably matched to the flow of water in the channel. However, the rate of water to release, total time of water release, and total volume of water released are generally unknown.

Conventional Methodology for Tracer Testing Losing Streams

Designing a tracer test for a losing stream reach involves identifying all potential downstream sampling stations, choosing an upstream location for releasing the tracer, determining how much tracer to release, and determining the mass of tracer to release.

In many instances, the mass of tracer to release is determined by the method of conjecture (see Field, 2003a, b, for a discussion of the method of conjecture). If the tracer test is to be qualitative, then sampling will usually occur on a weekly basis. A quantitative tracer test generally requires samples be taken on a more frequent basis.

Determination of appropriate tracer masses by methods other than conjecture are formidable because of the lack of knowledge of leakage rates and because there are no tracer-mass estimation equations intentionally designed for losing streams.

One method is to use tracer-mass estimation equations designed for surface-water tracing (*e.g.*, Equations (23)–(25) and (27) in Field, 2003a) and increase the calculated mass by some factor to account for losses due to sorption by the stream bed and infiltration to the subsurface. This procedure was implemented recently at a site in which Equation (27) in Field (2003a) (Kilpatrick and Wilson, 1989) and EHTD were both used. Equation (27) suggested a tracer mass range of 400 g to 1000 g, but the actual tracer mass to release would need to be arbitrarily determined based on observation and experience. EHTD suggested that ~1.3 kg of tracer would be appropriate to release, but EHTD was run using arbitrarily chosen decay factors of 0.03 h^{-1} for the losing stream and 0.05 h^{-1} for the resurgence. Although the tracer test was successful, determining the tracer mass by either of these methods is problematic because leakage through the stream bed is not considered so the factor by which the estimated mass should be increased is a matter of speculation with no supporting evidence for the increase.

IMPROVED METHODOLOGY FOR TRACING LOSING STREAMS

In order to better design tracer tests for losing stream–aquifer systems, it was first necessary to consider that in many instances nearby pumping wells might intercept ground-water flow prior to its eventual discharge at a downstream resurgence. To address this problem, EHTD was modified to allow for both springs and wells to be included in the same input file as downstream sampling stations.

It is also necessary to consider the rate of flow lost in a losing stream reach that constitutes the rate of flow entering the subsurface. When this leakage rate is multiplied by some time factor, a volume of water lost to the subsurface may be determined. Equating this volume with the surface flow and spring and/or well discharges allows determination of the extent of dilution so that a reasonable tracer mass to release may be calculated.

Wells and Springs as Simultaneous Sampling Stations

Ground water in karstic terranes typically discharges at seeps and springs at base level during low-flow periods. Moderate- and high-flow periods often result in ground-water discharge at one or more overflow seeps and springs. In either case, some ground-water flow may be intercepted by one or more pumping wells.

The nature of flow interception by a well is a man-induced distortion of the normal hydraulic gradient. Flow that normally converges into one or more conduits for discharge is pulled in a different direction at a different gradient by the pumping well(s). Modeling flow intercepted by a pumping well is then necessarily different from that of a spring. EHTD was developed by recognizing the differences, but did not consider the likelihood that wells and springs might be used as sampling stations in the same project. EHTD was modified in such a way that each input file could now be set to recognize flow to one or more springs and to one or more wells. This modification to EHTD also required modification of the standard input file. The modification to EHTD was done in such a way that backwards compatibility was maintained so that the older input-file structure may still be used if desired.

The modification to EHTD requires that each sampling station now be identified either as a spring or well as related to the relevant parameters for the type of flow specific to the sampling station. For example, flowing streams (*e.g.*, springs) require that flow discharge Q, cross sectional area A, and transport distance L be identified. Parameters relevant to flow to wells require pumping rate Q, effective porosity n_e, aquifer thickness b, and transport distance L be identified.

These are the same parameters for springs and wells applied globally in the original version of EHTD, but are now applied individually (locally) to each sampling station. Any additional complexity is minimized by the design.

Losing Stream Tracer-Test Design

Modification to EHTD also addressed the problem of tracing losing stream–aquifer systems. This modification to EHTD again required that each input file be modified so that leakage from a losing stream may be considered. Backwards compatibility was maintained as before so that the older input-file structure may still be used if desired.

Surface-water leakage through the bed of an alluviated channel significantly affects the quality and quantity of water in the underlying aquifer. The rate at which the leakage occurs is governed by the effective porosity n_e and thickness of the alluvium d and the underlying bedrock, the volume of water in the surface stream, and the elevation of the potentiometric surface relative to the stream. Periods of substantial recharge may raise the potentiometric surface to a level equal to that of the surface stream and causing the surface stream to temporarily receive ground-water inflow.

• *Application of Synoptic Discharge Measurements*

Leakage rate Q_z through the stream bed along selected reaches is the most basic and direct parameter to estimate, Bonacci's admonitions regarding losing stream-flow measurements (Bonacci, 1987, pp. 124–135) not withstanding. Physical discharge measurements are not very easy to obtain and will include at least an error of 10% for each measurement. Once SDM have been taken at appropriate locations, a general sense of the overall leakage rate at specific reaches will be known. Leakage rate to the subsurface is determined from Bonacci, 1987, pp. 116–117)

$$_j\Delta Q_i = {}_jQ_{i+1} - {}_jQ_i \quad (6)$$

where the subscripts i and j represent the locations of the discharge measurements and the day of the measurements, respectively. The change in stream discharge as related to leakage rate may then be evaluated as

$$Q_z = \begin{cases} 0 & ({}_j\Delta Q_i \geq 0) \\ |{}_j\Delta Q_i| & ({}_j\Delta Q_i < 0) \end{cases} \quad (7)$$

which states that only a negative stream discharge $_j\Delta Q_i$ represents leakage Q_z to the subsurface as a function of surface-water losses for the analyzed stream section i for a specific day j .

• *Leakage Rate Estimation by Mathematical Analysis*

Another method for estimating leakage rate may be accomplished using (Chen and Chen, 2003)

$$Q_z = -K_z A_s \frac{\Phi_s - \Phi_a}{d} \quad (A_s = R_L R_w) \quad (8)$$

which assumes considerable knowledge regarding the physical characteristics of the losing stream–aquifer system and is really the same as Equation (1). The physical characteristics listed in Equation (8) are much more difficult and expensive to measure than those listed in Equation (6). In addition, very large uncertainties will be associated with each parameter measured.

• *Leakage Rate Estimation by Supposition*

If SDM are not taken or cannot be taken (*e.g.*, as would occur with dry stream reaches) it is then necessary to approximate the leakage rate by some other means. The simplest means for estimating leakage rate is to just suppose some percentage of the total stream flow (*e.g.*, 10%).

Supposing a percentage of flow leaking to the subsurface is little different than multiplying an estimate of stream-bed effective porosity with that of the natural or artificial stream flow. The actual effective porosity is very difficult to measure, but an effective porosity for an alluvial channel consisting mostly of silt and clay may be approximated (*e.g.*, ~13%) (McWhorter and Sunada, 1977, pp. 28–31). The error associated with using an estimated effective porosity, whether 13% or different, is not expected to be much greater than if the effective porosity were measured (Stephens et al., 1998).

Estimating leakage rate through a stream bed by any means other than SDM will be a poor substitute for actually calculating flow differences between upstream and downstream reaches based on discharge measurements. In all instances, the error will be unquantifiable and will range from insignificant to severe.

Leakage Time Through a Stream Bed

A major problem with all leakage-rate estimation methods is the inability to determine the time it takes for the leaking water and tracer to infiltrate through the stream bed and to reach the underlying aquifer. In general this will be a relatively slow process so modeling tracer release would suggest that this process should be treated as a pulse function (slow release over some finite period of time) rather than as an impulse function (instantaneous release defined mathematically as a Dirac (δ) function) even if an instantaneous release were planned and implemented. However, for a dry stream reach leakage time will have to be guessed.

• *Leakage Time for a Flowing Losing Stream*

For losing streams in which flow is continuous, the time for leakage may be approximated by taking the losing stream mean travel time $\bar{t}$ as the leakage time $\bar{t}(\bar{t} \equiv t_z)$. Although there is no theoretical or physical basis for this approximation, it is reasonable because it is highly unlikely that leakage to the subsurface will occur equivalently to the commonly assumed instantaneous release. By equating mean travel time with leakage time, a short-pulse release time may be approximated.

• *Leakage Time for a Dry Losing Stream*

If a stream goes dry along much of its length, because of leakage or lack of recharge, there is no means by which leakage time may be approximated. In this instance, leakage time must be arbitrarily guessed with the hope that the error will not be too great. Leakage-time estimates can range from instantaneous to infinite which is obviously problematic. Usually, a very short but not instantaneous leakage time would be considered most appropriate.

• *Tracer-Test Design Modifications*

EHTD was modified to address the problem of tracing ground-water flow that is connected to losing streams and dry stream beds. Modification of EHTD also required additional modification of each input file so that leakage from a losing stream may be considered. However, backwards compatibility was again maintained so that the older input-file structure may still be used if desired.

Losing Stream Reaches: The simplest scenario considers the situation in which SDM for a losing stream have been made and a leakage rate Q_z for one or more reaches have been defined. In this instance, EHTD will solve for the mass required to trace the losing stream while considering the need for increased tracer mass because of an estimated loss due to the leakage. When leakage rate cannot be estimated from discharge measurements, it must be estimated by use of Equation (8), multiplying the stream discharge by some effective porosity value, or by simple supposition.

After solving for the tracer mass and travel times for the losing stream, EHTD will then begin solving for the tracer mass for each connected sampling station. This is accomplished by increasing the estimated downstream discharge by the leakage rate. The increased volume requires that a proportionally larger mass of tracer be released.

Leakage time is approximated by taking the mean travel time of the surface stream and treating it the same as a pulse release of tracer to the subsurface. For long travel times, this could cause the subsurface tracer-breakthrough curve (BTC) to appear to have a plateau rather than a peak. Occurrence of a BTC with a plateau will frustrate accurate BTC analysis in which an impulse release was implemented (*e.g.*, Field, 2002c).

Dry Stream Reaches: A much more difficult tracer-test design scenario presents itself when dry stream-bed reaches are found to exist. Because SDM are not possible, some leakage rate must be arbitrarily estimated. If a release of a substantial quantity of water is released by some artificial means, then the infiltration rate may be approximated.

If there is some flow in the upper reaches of the stream prior to complete drying further downgradient, EHTD accepts that all measured stream-flow equals leakage rate and solves for tracer mass only for the subsurface sampling station. The time for leakage must be estimated by some arbitrary value. This is best accomplished by using the estimated mean travel time between the upstream injection point and the point at which stream-flow ceases. If there is no flow in the stream (natural or artificial) then the time for leakage to the subsurface must be supposed.

SYNTHETIC EXAMPLE RESULTS AND DISCUSSION

To test the modifications to EHTD, the sampling station data shown in Table 3 were developed from the actual tracer test briefly described earlier. Leakage from a losing stream was assumed to be 10% of the losing-stream flow 3060 m^3 h^{-1} because SDM could not be readily taken. Tracer release into the losing stream was instantaneous and upstream of a losing reach.

Tracer-Test Results

Tracer-test results were developed using the data shown in Table 3 in which no leakage through the stream bed is considered in EHTD. Results were also developed for the same data, but allowing for leakage through the stream bed as a function in EHTD (Tables 4–6).

Table 3. Losing stream and resurgence tracer design specifics for synthetic example.

Parameter	Losing Stream	Resurgence
Q, m^3 h^{-1}	3.06×10^4	2.45×10^3
L, m	4.83×10^3	2.41×10^3
A, m^2	1.68×10^1	7.00×10^0
$\overline{C}^a$, μg L^{-1}	3.00×10^1	3.00×10^1

[a] User-set mean tracer concentration

Solute-transport characteristics for the losing stream show no differences from the condition of no leakage assumed in EHTD and the condition of leakage being assumed in EHTD whereas the solute-transport characteristics difference are evident for the two conditions for the resurgence (Tables 4–6) except for mean travel time and mean velocity (Tables 4–5). The estimated mass is slightly greater for the losing stream for the case of leakage being assumed in EHTD relative to the case of no leakage being assumed, but with no difference for the initial and peak concentrations (Table 6). However, the estimated mass, initial concentration, and peak concentration for the resurgence are all greater for the case of leakage being assumed in EHTD when compared with the case for when no leakage is assumed in EHTD (Table 6).

Table 4. Comparison of tracer test solute travel times and sample collection times for when no leakage is assumed and for when leakage is assumed in EHTD.

Condition	Solute Travel Times				Sample Collection Times		
	$\bar{t}$, h	σ^2, h^2	t_p, h		t_1, h	t_{sf}, h	t_f, h
Losing Stream Downstream Sampling Station							
No leakage	2.65×10^0	7.89×10^{-2}	2.62×10^0		1.37×10^0	7.46×10^{-2}	6.15×10^0
Leakage	2.65×10^0	7.89×10^{-2}	2.62×10^0		1.37×10^0	7.46×10^{-2}	6.15×10^0
Resurgence Sampling Station							
No leakage	6.91×10^0	1.36×10^1	6.77×10^0		2.83×10^0	2.60×10^{-1}	1.95×10^{-1}
Leakage	6.91×10^0	6.80×10^1	8.08×10^0		2.19×10^0	3.85×10^{-1}	2.68×10^{-1}

Table 5. Comparison of tracer test solute velocities and dispersive effects for when no leakage is assumed and for when leakage is assumed in EHTD.

Condition	Solute Travel Times				Solute Dispersal Effect		
	υ, m h^{-1}	υ_p, m h^{-1}	υ_m, m h^{-1}		D_L, m^2 h^{-1}	α_L, m	P_e, dimen.
Losing Stream Downstream Sampling Station							
No leakage	1.82×10^3	1.84×10^3	3.52×10^3		6.59×10^4	3.62×10^1	1.34×10^2
Leakage	1.82×10^3	1.84×10^3	3.52×10^3		6.59×10^4	3.62×10^1	1.34×10^2
Resurgence Sampling Station							
No leakage	3.50×10^2	3.57×10^2	8.52×10^2		9.92×10^3	2.84×10^1	8.51×10^1
Leakage	3.50×10^2	2.99×10^2	1.10×10^3		1.58×10^4	4.53×10^1	5.33×10^1

Table 6. Comparison of tracer test mass and concentration results for when no leakage is assumed and for when leakage is assumed in EHTD.

Condition	M^a, g	C_i, µg L^{-1}	C_p, µg L^{-1}
Losing Stream Downstream Sampling Station			
No leakage	7.43×10^2	9.17×10^{-3}	3.02×10^1
leakage	8.17×10^2	9.17×10^{-3}	3.02×10^1
Resurgence Sampling Station			
No leakage	1.94×10^2	1.15×10^{-2}	3.03×10^1
leakage	3.94×10^2	2.33×10^{-2}	4.18×10^1
[a] M_{T_N} = 937 g; M_{T_L} = 1.21 kg; ΔM_T = 274 g			

Initial concentration C_i does not change for the losing stream whether leakage is considered or not because the volume of water at the point of release remains unchanged between the two situations. However, C_i increases for the resurgence when leakage is assumed because the modifications to EHTD allow for recognition of water leaking through the bed of the losing stream into the underlying aquifer and requiring increases in tracer mass as necessary to account for this recharge.

Total tracer mass for the case of no leakage assumed in EHTD is 937 g and the total tracer mass for the case of leakage being assumed in EHTD is 1.21 kg.

The difference, 274 g, is a significant increase reflecting the loss of some tracer from the losing stream and the assumed pulse-type of release (leakage) for the resurgence.

• *Expected Losing Stream Tracer-Test Results*

Figures 5 and 6 depict BTCs for the losing stream. In Fig. 5, a BTC in which no leakage through the stream bed is assumed in EHTD is shown whereas Fig. 6 shows a BTC in which 10% of the surface-water flow was assumed to leak through the stream bed in EHTD. The only obvious difference between Figs. 5 and 6 is the estimated tracer mass for each BTC. More tracer mass is required for a losing stream because of tracer losses due to leakage through the stream bed.

Figure 7 emphasizes the fact that absolutely no difference exists when tracing a losing stream whether leakage is considered or is not considered in EHTD. It will be noted in Fig. 7 that both BTCs and suggested sampling times for both leakage and no leakage conditions are identical (*i.e.*, both curves plot one atop the other).

The increased tracer mass (ΔM_L = 74 g) stems from the recognition that some tracer is assumed to leak through the stream bed. Loss of tracer through the subsurface requires that more tracer be released (Table 5) so that the expected downstream mean concentration match the user-set downstream mean concentration (Table 3).

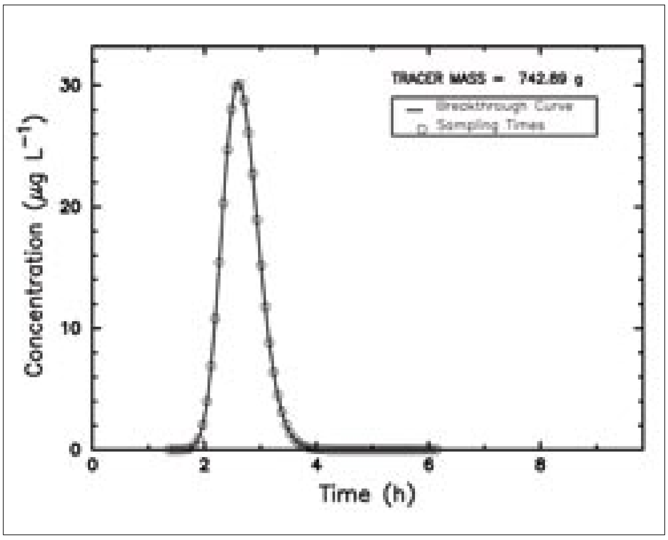

Fig. 5. Breakthrough curve for the losing stream assuming no leakage through the stream bed in EHTD.

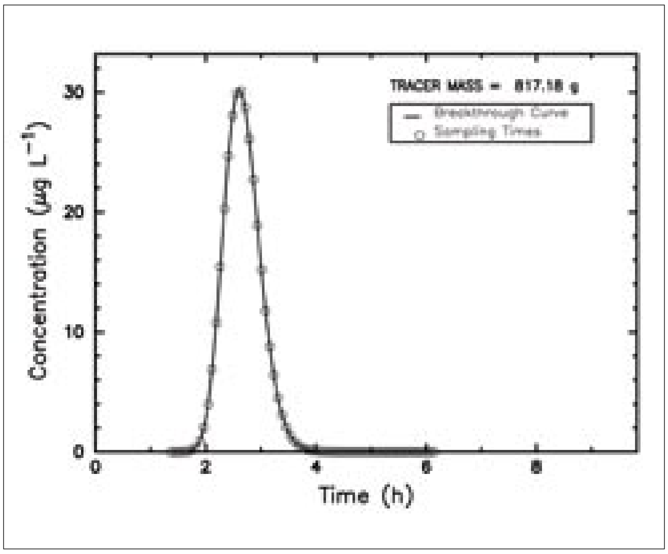

Fig. 6. Breakthrough curve for the losing stream assuming leakage through the stream bed in EHTD.

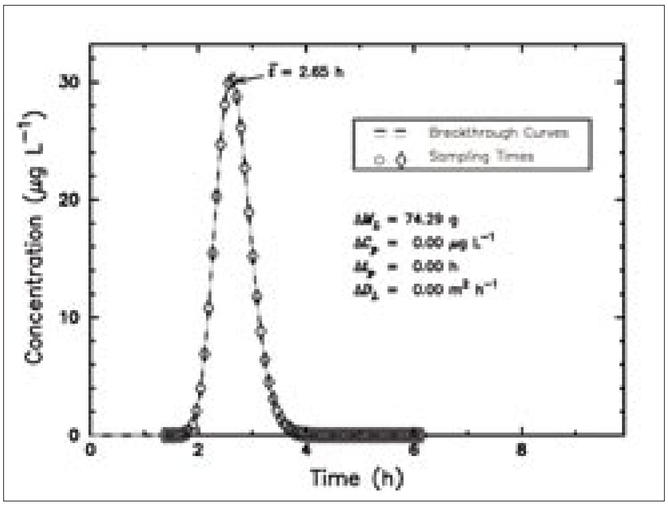

Fig. 7. Comparison of breakthrough curves for the losing stream assuming no leakage and assuming some leakage through the stream bed in EHTD. Note that the two curves, recommended sampling times, and transport parameters are identical for the two breakthrough curves.

• *Expected Resurgence Tracer-Test Results*

Figures 8 and 9 depict the BTCs for the resurgence recharged, at least in part, by the losing stream. In Fig. 8, a BTC in which no leakage through the overlying stream bed is assumed in EHTD is shown whereas Fig. 9 shows a BTC in which leakage through the overlying stream bed is assumed in EHTD. The only obvious differences between Figs. 8 and 9 are the estimated tracer mass and the later solute-arrival times shown in Fig. 9. More tracer mass is required because leakage is treated as a pulse release that slowly infiltrates through the stream bed.

Figure 10 emphasizes the differences that results when recharge from a losing stream to the underlying solution conduit is considered when tracing the leakage through the stream bed and recovery is at a downstream resurgence. From Fig. 10 it is apparent that when leakage is considered a greater tracer mass is required, axial dispersion is greater, peak concentration is greater, peak arrival time is later, and Péclet number is lower when leakage is not considered in EHTD. The mean travel time ($\bar{t}$ = 6.91 h) occurs on the descending limb of the BTC in which no leakage is assumed because EHTD treats a no leakage occurence as an impulse (instantaneous) release. However, the mean travel time ($\bar{t}$ = 6.91 h) for the BTC in which leakage is assumed in EHTD occurs on the ascending limb because EHTD treats leakage as a pulse (slow) release.

Along with the increased tracer mass (ΔM_R = 200 g) for the case in which leakage is considered in EHTD, is an increase in peak travel time (t_p = 131 h) and longitudinal dispersion (D_L = 5.92 × 10^3 m^2 h^{-1}), but not for the mean travel time or mean transport velocity for the resurgence (Table 4). The apparent increase in peak travel time is a result of tracer leakage being treated as a pulse release. Even though the leakage travel time (pulse time) is relatively short (t_z= 2.65 h) (Table 4), it is sufficiently long enough to cause an apparent later arrival for peak travel time and greater longitudinal dispersion.

CONCLUSIONS

Leakage through the bed of losing streams is extremely difficult to assess. Although various methods

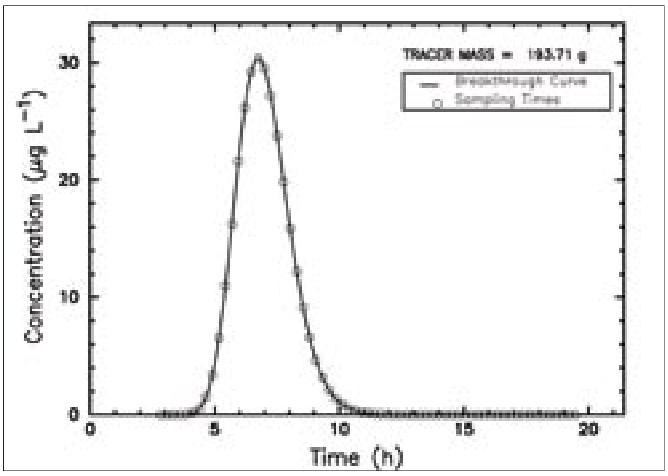

Fig. 8. Breakthrough curve for the resurgence assuming no leakage through the stream bed in EHTD.

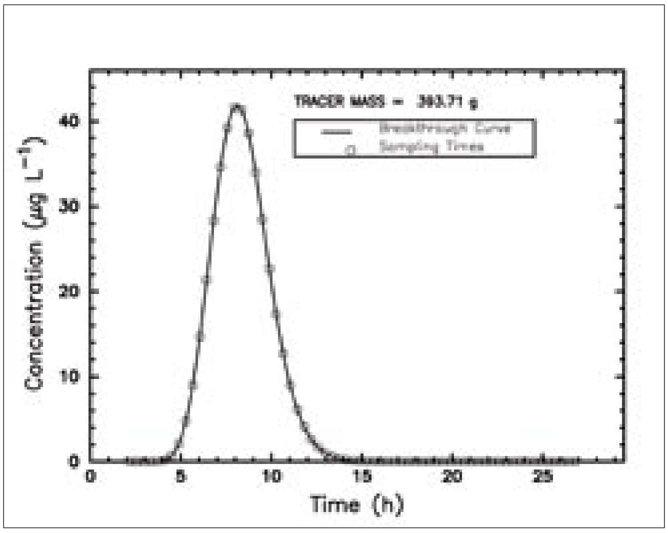

Fig. 9. Breakthrough curve for the resurgence assuming leakage through the stream bed in EHTD.

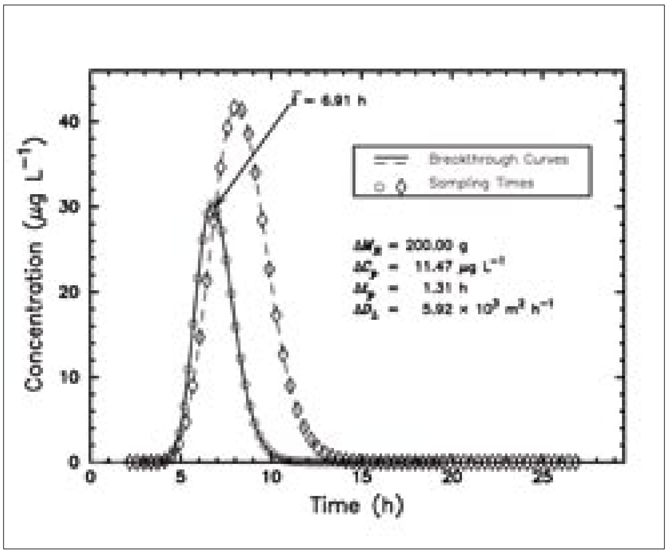

Fig. 10. Comparison of breakthrough curves for the resurgence assuming no leakage and assuming some leakage through the stream bed in EHTD. Note the difference in breakthrough position for the mean travel time even though the mean travel time is the same for both breakthrough curves ($\bar{t}$ = 6.91 h).

have been developed to measure the rate of leakage through losing stream beds, nothing is as effective as conducting tracer tests. Conducting tracer tests for the purpose of evaluating leakage through a losing stream bed provides information on the leakage through the losing stream and the recharge to the aquifer system and the trajectory of ground-water flow as related to the losing stream. However, designing tracer tests in losing stream–aquifer systems is complicated by the lack of *a priori* knowledge of specific leakage characteristics.

The EHTD program was modified to allow for the design or tracer tests to allow the simultaneous use of both wells and downstream resurgences as sampling stations; a difficiency in the earlier development of EHTD. A more significant alteration of EHTD allows for the consideration of leakage through the bed of a losing stream and adjusts the estimated tracer mass for both the stream flow and other sampling stations accordingly.

A synthetic example based on an actual tracer test was used to evaluate the losingstream modification to EHTD. Original tracer mass estimates for the site suggested that between 400 g and 1000 g of tracer would be needed based on arbitrary decisions regarding the actual selected tracer mass to release. Use of the original version of EHTD suggested that between 800 g and 1.3 kg might be appropriate, but only after allowing for an arbitrary estimate of tracer decay.

Applying the modified version of EHTD to the site as a synthetic example resulted in a tracer mass equal to ~1.2 kg without any consideration for tracer decay. Based on the observations and determinations of the actual tracer test EHTD appears to produce reasonable approximations if good measurements or estimates for stream-flow losses are available. However, leakage time, taken as the mean travel time for the stream flow, continues to be problematic because there is no physical or theoretical basis for this assumption.

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Notation

α_L	longitudinal dispersivity (L)
A	cross-sectional area of sampling station (L^2)
A_S	cross-sectional area of losing stream section (L^2)
$\overline{C}$	mean tracer concentration (M L^{-3})
C_i	initial tracer concentration upon injection (M L^{-3})
C_p	peak tracer concentration (M L^{-3})
d	depth to the bottom of the resistance layer from stream bed (L)
D_L	longitudinal dispersion (L^2 T^{-1})
ΔC_p	peak concentration difference for leakage and no leakage (M L^{-3})
ΔD_L	longitudinal dispersion difference for leakage and no leakage (L^2 T^{-1})

ΔM_L losing stream tracer mass difference for leakage and no leakage (M)

ΔM_R resurgence tracer mass difference for leakage and no leakage (M)

ΔM_T total tracer mass difference for leakage and no leakage (M)

$\Delta \Phi$ head difference between stream and ground-water elevations (h)

Δt_p peak concentration difference for leakage and no leakage (T)

K_z leakage hydraulic conductivity (L T^{-1})

L transport distance (L)

M recommended mass of tracer to release (M)

M_{TL} total recommended mass of tracer to release for leakage (M)

M_{TN} total recommended mass of tracer to release for no leakage (M)

n_e effective porosity (dimen.)

p pore pressure (M L^{-1} T^{-2})

p_e Péclet number (dimen.)

q_z specific discharge through stream bed (L T^{-1})

Q stream-flow discharge (L^3 T^{-1})

Q_z leakage rate through stream bed (L^3 T^{-1})

R_L leaking stream reach length (L)

R_w leaking stream reach width (L)

Φ_a ground-water elevation at reach location (L)

Φ_s surface-water elevation at reach location (L)

σ^2_t mean travel time variance (T^2)

$\bar{t}$ mean travel time (T)

t_1 recommended time for first sample collection (T)

t_f recommended final sample collection time (T)

t_p peak travel time (T)

t_{sf} recommended sample collection frequency (T)

t_z leakage time through the stream bed to the potentiometric surface (T)

v mean transport velocity (L T^{-1})

v_m maximum transport velocity based on first measurable arrival time (L T^{-1})

v_p peak transport velocity (L T^{-1})

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