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Chemical Tracing Techniques for Evaluating Rill Hydraulics

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ABSTRACT: Development of water erosion and surface water quality control practices requires information concerning the hydraulic characteristics of upland areas. The relatively small flow rates normally found within rills make measurement of hydraulic parameters difficult. Chemical tracing procedures, originally developed for stream and river systems, have been successfully used to measure rill flow properties. A chemical tracer of known concentration is added to the rill and by knowing the degree of dilution at a downstream sampling point, flow rate can be calculated. Rill flow velocity can be measured by determining the time required for a slug of tracer material to travel a designated distance. Measurements of flow rate and velocity can be used to calculate other hydraulic variables. The ability to understand and properly model rill flow will improve as additional information

SOIL erosion is influenced by several interrelated hydrologic, soil, cropping, and management factors. Soil erosion models that simulate fundamental erosion mechanisms require knowledge of flow hydraulics. Information on rill flow characteristics could provide a more thorough description of the erosion process.

Surface water contaminants may move as either suspended or dissolved materials. Rill flow may serve as the transport mechanism for a variety of pollutants. Therefore, information on rill hydraulics also is important in surface water quality control practices.

Measuring the relatively small flow rates found within rills is difficult. Many of the routine procedures used to determine flow rates, such as the use of flumes or weirs, cannot be directly applied to rill flow. Thus, alternate techniques for measuring flow rate and velocity within rills must be employed.

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Chemical tracing

Chemical tracing techniques have been used to identify hydraulic characteristics of stream and river systems *(1, 9, 15, 19)*. A tracer of known concentration may be added to the flow and, by knowing the degree of dilution at a downstream sampling point, flow rate can be determined *(15)*. Chemical tracing techniques for flow measurement were described by Kilpatrick *(10)* and Morgan et al. *(13)*. Kilpatrick *(11)* also outlined requirements for injection of chemical tracers into streams. Tracers should be easily detectable, harmless in low concentrations, inexpensive, and stable.

Fluorescent dyes. Fluorescent dyes frequently have been used as tracer materials *(18)*. Fluorescence is the instantaneous emission of light from a molecule that has absorbed light. A fluorescent compound will absorb light at one wavelength and emit it at a longer wavelength. The device used to measure the intensity of emitted light is a fluorometer.

An extensive evaluation of several fluorescent dyes used for water tracing was conducted by Smart and Laidlaw *(17)*. Finkner and Gilley *(3)* described difficulties that may be encountered in measuring flow rate as a result of adsorption of fluorescent dye onto sediment. Rhodamine B, a once popular fluorescent dye, has been found to be carcinogenic. Thus, Rhodamine WT is now the fluorescent material of choice for flow measurement.

Runoff samples collected for measurement of flow rate are often stored for later analyses. If significant amounts of sediment are present in the runoff, sediment should be filtered from the solution. To reduce the potential for adsorption of the tracer material onto sediment, the samples should be filtered soon after collection.

A fluorometer may be very difficult to use for monitoring runoff velocity when significant amounts of sediment are present in runoff. A pumping device is required to continuously circulate runoff through the flow cell of the fluorometer. Suspended sediment has been found to affect fluorometer readings and to easily clog the circulation system.

Bromide salts. Bromide salts have also been employed as tracer materials. Bromide salts are generally highly soluble and non-degradable. The bromide ion is easily detected and can be quantitatively measured at concentrations low enough to not constitute a health or pollution problem *(16)*. Adsorption of bromide onto sediment was found by Gilley et al. *(8)* to be minimal and bromide background levels in soils are generally quite low *(12)*. Thus, bromide salts in dilute concentrations also appear to be well suited for measurement of rill hydraulics.

Large concentrations of bromide, however, may be toxic. Bromide has been found to affect the central nervous system of animals, causing sedation *(14)*. Therefore, caution must be exercised when using bromide salts, especially under field conditions.

Several types of instruments are available for determining bromide concentrations. For the quantitative measurement required to determine flow rate, an instrument such as a ion chromatograph is required. Runoff samples collected in the field must be brought to the laboratory for analysis.

Laboratory instruments used to make quantitative measurements of tracer concentration usually have an optimum range over which they can operate. If the sample concentration is too dilute, it may be outside the measurement range of the instrument. Conversely, if the tracer concentration is too large, the runoff sample must be diluted before measuring, which could introduce analytical errors. Therefore, the quantity of tracer material injected into the rill should be adjusted so the approximate diluted concentration of the tracer at the point of collection is within the instrument's optimum measurement range.

An ion electrode can be used to determine relative concentrations needed for velocity measurements. The price of an ion electrode with auxiliary equipment is only a few hundred dollars. Runoff samples collected in the field can be brought to the laboratory for analysis, or an ion electrode can be used in the field for continuous monitoring.

Flow rate and velocity

Flow rate and velocity are important hydraulic variables used to characterize rill flow. Chemical tracing techniques can be used to identify each of these parameters. Different equations and chemical tracing procedures, however, are required to measure these two variables.

Measurement of flow rate. A continuous injection technique can be used to measure rill flow rate. A known concentration of tracer material is injected uniformly and continuously into a rill at a distance sufficiently upstream from the sampling point to assure complete mixing. Difficulties relating to mixing can be overcome by sampling flow from the entire rill cross section.

A narrow, relatively long plastic bag has been found to work well for sampling rill flow. The bottom of the plastic bag can be made to easily conform to the rill contour. Rill discharge should be allowed to flow into the plastic bag without disturbance.

Flow rate can be determined using the following equation *(15)*:

$$i\,C_i = (Q + i)\,C_m \qquad [1]$$

where i = tracer injection rate; C_i = concentration of tracer material; Q = flow rate; and C_m = concentration of tracer at the point of measurement. For most conditions, rill flow rate is much larger than the tracer injection rate. Thus, rill flow rate can be approximated by:

$$Q = \frac{i\,C_i}{C_m} \qquad [2]$$

When using dilution techniques to measure rill flow rate, it is assumed that the loss of tracer material through infiltration is minimal. For most field conditions, the volume of water infiltrated during the measurement period is small compared to the rill flow volume.

Equation [2] is derived assuming conservation of mass for the tracer material. Adsorption of the chemical tracer onto soil or sediment would result in calculated flow rates larger than actual values. Therefore, use of a tracer material that is not easily adsorbed onto sediment is essential for accurate measurement of flow rate. Soil analysis should be performed to verify that the background level of the tracer in soil is minimal.

Measurement of flow velocity. Flow velocity can be determined using a slug injection technique. A slug of tracer material is injected into the rill at a distance sufficiently upstream from the sampling point to assure complete mixing. For turbulent flow conditions, a one-meter mixing distance should be sufficient. Continuous monitoring of the flow provides a time-concentration curve. By dividing tracer travel distance by travel time, flow velocity can be calculated.

Various points on the time-concentration curve are used to identify travel time *(9)*. For a symmetric time-concentration curve, time-of-travel of peak concentration corresponds with mean travel time. In hydrologic studies, time-of-travel for the concentration peak is frequently used to measure mean flow velocity.

Adsorption of tracer material onto sediment is usually not critical in the measurement of flow velocity. Only estimates of peak tracer concentration, not absolute concentration, are required. Thus, an instrument adapted to continuously monitor tracer concentration is best suited to measure flow velocity.

Visual estimates of flow velocity. Visual techniques can be employed to identify advance time, which is the period required for the dye front of a chemical tracer injected upstream to first reach a given downstream point. The time needed for the most rapidly advancing portions of the dye front to reach the sampling point is less than the travel time for the concentration peak. Thus, advance flow velocity is greater than mean flow velocity. Visual measurements of advance flow velocity must be multiplied by a correction factor of less than one to obtain estimates of mean flow velocity.

Measurements of advance velocity for rill flow were made by Gilley et al. *(6)* at 11 sites located throughout the eastern United States. A fluorometer was also employed to identify corresponding mean flow velocity. The following equation was obtained by Gilley et al. *(6)* for relating mean flow velocity to advance flow velocity:

$$\text{mean flow velocity} = 0.742 \times \text{advance flow velocity} \qquad [3]$$

This equation was developed for advance velocity values ranging from 0.10 to 0.95 m/sec (0.3 to 3 ft/sec). An r^2 value of 0.818 was found for equation [3].

The use of a fluorometer or ion electrode to determine flow velocity of rill flow may be expensive and difficult. However, visual measurements of advance flow velocity can be obtained much more easily using dyes or food coloring. Equation [3] can then be used to predict mean flow velocity.

Other hydraulic variables

If rill flow rate and velocity are measured, hydraulic variables often can be calculated. This additional hydraulic information can be used to provide a more thorough description of the flow process. If parameter values for basic hydraulic equations can be identified, rill hydraulics can be predicted for widely varying flow conditions.

Basic hydraulic equations. The continuity equation for steady flow is given as:

Legend. The following symbols are used in this paper.

A	cross sectional flow area
b	flow width
C_i	concentration of tracer material
C_m	concentration of tracer at the point of measurement
f	Darcy-Weisbach roughness coefficient
g	acceleration due to gravity
i	tracer injection rate
n	Manning roughness coefficient
P	wetted perimeter
Q	flow rate
R	hydraulic radius
S	average slope
V	flow velocity
y	flow depth

$$Q = VA \quad [4]$$

where V = mean flow velocity and A = cross sectional flow area. For a rectangular channel:

$$A = by \quad [5]$$

where b = flow width and y = flow depth.

Measurement of relatively shallow rill flow depths under field conditions is difficult. Accurate identification of the soil surface-flow interface for eroding situations is not always possible. Thus, water depth can be determined indirectly using equations [4] and [5] and measurements of discharge rate, flow velocity, and flow width.

Hydraulic radius, R, is the ratio of cross sectional flow area to wetted perimeter, P:

$$R = \frac{A}{P} \quad [6]$$

For a rectangular channel:

$$R = \frac{by}{b+2y} \quad [7]$$

Darcy-Weisbach and Manning equations. The Darcy-Weisbach and Manning equations have been widely used to calculate flow velocity. Both of these relations can be derived from basic principles of fluid mechanics *(2)*. These equations can be used to represent the effects of varying water depth, slope gradient, and surface roughness on flow velocity, and to develop runoff hydrographs.

The Darcy-Weisbach equation is given as:

$$V = \left[\frac{8gRS}{f}\right]^{1/2} \quad [8]$$

where g = acceleration due to gravity; S = average slope; and f = Darcy-Weisbach roughness coefficient. Flow velocity also can be estimated from the Manning equation:

$$V = \frac{R^{2/3} S^{1/2}}{n} \quad [9]$$

where n = Manning roughness coefficient.

Equations [8] and [9] both contain roughness coefficients. The roughness coefficients are inversely proportional to velocity and represent resistance to flow. Manning and Darcy-Weisbach roughness coefficients can be related using the following equation:

$$n = \left[\frac{f R^{1/3}}{8g}\right]^{1/2} \quad [10]$$

To use equations [8] and [9], roughness coefficient values must first be estimated. Factors such as soil surface roughness, surface residue, gravel or cobble cover, and standing plants may contribute to hydraulic roughness. Regression equations for estimating roughness coefficients on upland areas have been identified *(4, 5, 7)*.

Summary

Identification and quantification of rill flow characteristics is essential in water erosion models that simulate fundamental erosion processes. Information on rill flow characteristics also is important in developing surface water quality control practices. Measurement of the relatively small rill flow rates, however, is difficult.

Chemical tracing procedures, originally developed for stream and river systems, have been successfully used to identify rill flow characteristics. Fluorescent dyes and bromide salts are often used as tracer materials. A chemical tracer of known concentration is added to the flow and, by knowing the degree of dilution at a downstream sampling point, flow rate can be calculated.

Flow velocity can be determined using a slug injection technique. A chemical tracer is injected into the flow and by dividing travel distance by travel time, flow velocity can be calculated. Continuous sampling techniques are identified for measuring flow velocity. A simple procedure is also described for making visual estimates of flow velocity.

If flow rate and velocity are known, other hydraulic parameters can be determined. Equations are presented for calculating cross sectional flow area and hydraulic radius. These additional hydraulic parameters provide a more thorough description of the upland flow process.

The Darcy-Weisbach and Manning equations have been widely used to calculate flow velocity. Both of these relations contain hydraulic roughness coefficients that represent resistance to flow. Factors such as soil surface roughness, surface residue, gravel or cobble cover, and standing plants may contribute to hydraulic roughness. If parameter values for basic hydraulic equations can be identified, rill hydraulics can be predicted for widely varying flow conditions. The ability to understand and properly model upland flow processes will improve as additional information on rill hydraulic characteristics becomes available.

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