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Measurement of Flow Components on Upland Areas Using Dye Dilution Techniques

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ABSTRACT

DYE dilution techniques can be used to measure rill, interrill, and interrill-to-rill flow rates on upland areas. Procedures and equations for making flow measurements are described along with equations for estimating interrill length and width. If measurements of interrill length and rill width are available, use of simplified flow equations is possible.

Water and dye continuity concepts were utilized to develop generalized interrill-to-rill flow relationships. Measurement of flow from interrill-to-rill areas requires information on the concentration and rate of dye injection, and flow rate and dye concentration on both rill and interrill areas at a downslope sampling location. Dye dilution techniques could be employed to expand information on flow characteristics on upland areas.

INTRODUCTION

Dye dilution techniques have been successfully utilized to characterize water movement. Floats, salts, actual contaminants and radioisotopes have all been utilized as tracers (Wilson, 1968). Fluorescent dyes have received extensive use in dye dilution studies (Chase and Payne, 1968). Recently, bromide salts have proven to be excellent tracer materials (Owens et al., 1985).

Flow measurements may be made using dye dilution techniques. A tracer of known concentration may be added to a channel and by knowing the degree of dilution at a downstream sampling point, the channel discharge can be determined (Replogle et al., 1966). Considerable information has been presented on fluorometric procedures for discharge measurement, velocity determination and dispersion testing (Wright and Collings, 1964; Replogle et al., 1966; Chase and Payne, 1968; and Hubbard et al., 1982). Use of dye-dilution techniques for flow measurement was described by Kilpatrick (1968) and Morgan et al. (1977). Kilpatrick (1970) also outlined dye requirements for slug injections into streams.

The best fluorescent dyes for use in water tracing are easily detectable, harmless in low concentration, inexpensive and stable (Wilson, 1968). An extensive evaluation of several fluorescent dyes used for water

tracing was conducted by Smart and Laidlaw (1977). Finkner and Gilley (1986) described difficulties which may be encountered in measuring flow due to adsorption of fluorescent dye onto sediment.

Use of dyes for upland flow characterization has considerable potential. Flow measurements on upland areas could be greatly expanded using dye tracing techniques. Dye dilution procedures could be utilized to make flow measurements which are difficult using other procedures. The objective of this study was to identify equations and procedures which could be used to measure rill, interrill and interrill-to-rill flow rates on upland areas using dye dilution techniques.

RILL AND INTERRILL FLOW MEASUREMENT

Procedures used for making flow measurements in channels have been well established. These techniques have been utilized extensively in field applications to successfully measure discharge. Similar procedures which can be used to measure flow on rill and interrill areas are described below.

Flow Measurement Equations

Either continuous or slug injection techniques may be used to make flow measurements. The continuous injection technique is frequently used to simplify data collection and analyses. For the continuous injection technique, a known concentration of dye is injected uniformly and continuously into a rill at a sufficient upstream distance to assure complete mixing. Flow rate is then determined using the following relationship (Replogle et al., 1966):

$$i C^o = (Q + i) C \dots\dots\dots [1]$$

where

- i = dye injection rate
- C^o = concentration of injected dye
- Q = flow rate
- C = concentration of dye at the point of measurement

For most conditions, the rill discharge rate is much larger than the dye injection rate. Thus:

$$Q \approx i \frac{C^o}{C} \dots\dots\dots [2]$$

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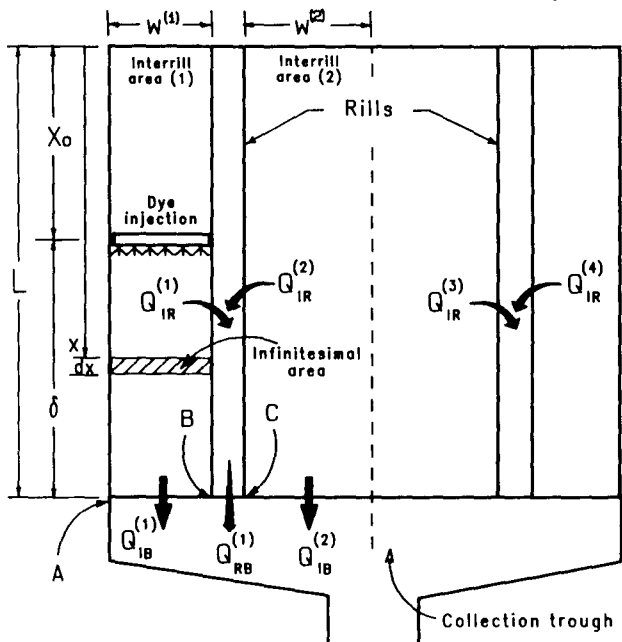


Fig. 1—Rill and interrill flow components on an upland area.

added at the injection point (Replogle et al., 1966):

$$M^o = \int_0^t Q C dt \dots\dots\dots [3]$$

where t = time. Under steady state flow conditions, rill discharge rate at the sampling point is constant. Thus:

$$Q = \frac{M^o}{\int_0^t C dt} \dots\dots\dots [4]$$

Flow Measurement Procedures

A schematic diagram will illustrate rill and interrill flow measurement procedures. Fig. 1 shows an idealized flow system containing two rills. Although this diagram represents a simplified condition, the procedures which are described can be used on more complicated flow

networks. Flow measurement procedures using the continuous injection technique are described below.

Placement of a collection trough at the bottom of the plot, which diverts all of the discharge into a single channel, is suggested. Flow rate from the bottom of an interrill area, Q_{IB} , can be determined by continuously injecting dye into the collection trough between points A and B shown in Fig. 1, and obtaining a runoff sample in the collection trough just upstream from the rill discharge location at point B. In a similar fashion, the combined flow from the rill and interrill areas can be measured by collecting a sample from the collection trough just downstream from the rill discharge location at point C. The rill component of flow, Q_{RB} , can then be determined by subtracting the interrill flow component determined at point B from the combined discharge measured at point C.

To measure total flow rate, dye can be injected into the collection trough and a sample obtained at the collection trough outlet location, where the various flow components have converged. To compensate for potential difficulties relating to mixing of the dye, a sample from the entire flow cross section can be collected. As a check on the dye dilution procedure, total plot discharge could also be determined at the collection trough outlet location using another measuring device such as a flume or weir. To further check for possible errors, discharge measurements for the various flow components could be added and the sum compared to total measured discharge.

INTERRILL-TO-RILL FLOW MEASUREMENT

Dye dilution techniques can also be utilized to measure the lateral flow rate from an interrill region into an adjoining rill. An equation for determining interrill-to-rill flow rate is first obtained using water continuity concepts. In order to evaluate all of the variables found in the water continuity equation, additional analysis using dye continuity principles is required.

Water Continuity Equations

An infinitesimal interrill area shown in Fig. 2 with width, w, and length, dx, is used to derive the water

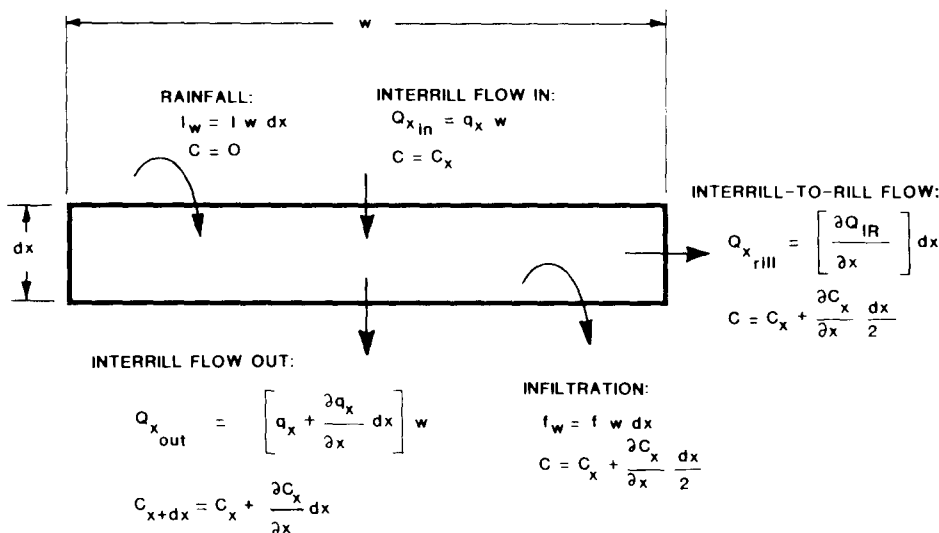


Fig. 2—Flow components and corresponding dye concentrations on an infinitesimal interrill area.

continuity equations. The flow components into and out of the infinitesimal interrill area are examined. There are five flow components to consider: (a) rainfall, (b) infiltration, (c) interrill flow into the area, (d) interrill flow out of the area, and (e) lateral flow into the adjacent rill.

The rainfall component, I_w , is given by:

$$I_w = I w dx \quad \dots \dots \dots [5]$$

where I = rainfall intensity; and dx = infinitesimal downslope distance. The infiltration component, f_x , in turn is represented by:

$$f_w = f w dx \quad \dots \dots \dots [6]$$

where f = infiltration rate. The product of interrill flow per unit width, q_x , and w yields interrill flow into the area, Q_{xin} , or:

$$Q_{xin} = q_x w \quad \dots \dots \dots [7]$$

Interrill flow out of the area, Q_{xout} , is given by:

$$Q_{xout} = \left[q_x + \frac{\partial q_x}{\partial x} dx \right] w \quad \dots \dots \dots [8]$$

Finally, flow from the infinitesimal interrill area into an adjacent rill, Q_{xfill} , is represented by:

$$Q_{xfill} = \left[\frac{\partial Q_{IR}}{\partial x} \right] dx \quad \dots \dots \dots [9]$$

where: Q_{IR} = flow from the entire interrill region into the rill from $x = 0$ to x .

Equating the flows entering and exiting the area and letting dx approach zero, yields:

$$\frac{\partial Q_{IR}}{\partial x} = \left[I - f - \frac{\partial q_x}{\partial x} \right] w \quad \dots \dots \dots [10]$$

For uniform soil conditions, it can be assumed that flow per unit width increases linearly with downslope distance, varying from zero at $x = 0$ to q_L at $x = L$, as shown in Fig. 1. Thus, the rate of change in flow with downslope distance becomes a constant, k_x :

$$\frac{\partial q_x}{\partial x} = k_x \quad \dots \dots \dots [11]$$

Integrating, with the boundary condition $q_x = 0$ at $x = 0$, yields:

$$q_x = k_x x \quad \dots \dots \dots [12]$$

Substituting k_x into equation [10] then yields:

$$\frac{\partial Q_{IR}}{\partial x} = (I - f - k_x) w \quad \dots \dots \dots [13]$$

or, for steady state conditions where I , f , and k_x are constant,

$$\frac{\partial Q_{IR}}{\partial x} = k_{IR} w \quad \dots \dots \dots [14]$$

where

$$k_{IR} = (I - f - k_x) \quad \dots \dots \dots [15]$$

Integrating equation [14] with the boundary condition $Q_{IR} = 0$ at $x = 0$, yields:

$$Q_{IR} = k_{IR} w x \quad \dots \dots \dots [16]$$

Other relations must be derived to solve for the variables shown in equation [16]. Dye continuity concepts will be utilized to obtain the required relationships.

Dye Continuity Equations

In order to identify interrill-to-rill flow, a line source of dye is injected across the interrill area at downslope distance X_0 , shown in Fig. 1. In general, mass flow rate, \dot{m} , is given by:

$$\dot{m} = Q C \quad \dots \dots \dots [17]$$

By injecting dye at a specific rate per unit width, the total mass flow of dye injected onto the interrill region, \dot{m}^0 , may be determined as:

$$\dot{m}^0 = q^0 w C^0 \quad \dots \dots \dots [18]$$

where q^0 = volumetric injection rate per unit width, and C^0 = concentration of injected dye.

The injected dye immediately mixes into the interrill flow. As it moves downslope, part of the dye is carried into the rill and flows to the bottom of the slope. Since no dye is injected into the rill, the mass discharge rate of dye from the bottom of the rill must be the same as that which flows into the rill from the adjoining interrill area. Having determined discharge from the bottom of the rill, Q_{RB} , using procedures described previously, the total mass flow rate of dye moving into the rill from the interrill region, \dot{m}_{IR} , is given as:

$$\dot{m}_{IR} = Q_{RB} C_{RB} \quad \dots \dots \dots [19]$$

where C_{RB} = measured concentration of dye in the rill at $x = L$.

The mass flow rate of dye from the interrill area into the rill may also be determined by integrating the product of the interrill-to-rill flow and dye concentration over the range X_0 to L , as shown in Fig. 1. The flow and dye concentration may be described as functions of downslope distance by utilizing the same infinitesimal area examined previously. This area is located at a distance x from the top of the interrill region, with $x > X_0$. The components of flow into and out of this area, along with corresponding dye concentrations are illustrated in Fig. 2.

If the dye concentration, C_x , of the interrill flow entering the area is assumed to be uniform across the flow width, then the dye concentration of the flow leaving the area, C_{x+dx} , can be written as:

$$C_{x+dx} = C_x + \frac{\partial C_x}{\partial x} dx \quad \dots \dots \dots [20]$$

Having previously identified the flow components and the dye concentration of each component, a mass balance of dye can now be performed. Under steady state flow conditions, the mass flow of dye entering and exiting the infinitesimal interrill area shown in Fig. 2 can be equated:

$$Q_{x_{in}} C_x = Q_{x_{out}} \left[C_x + \frac{\partial C_x}{\partial x} dx \right] + f_w \left[C_x + \frac{\partial C_x}{\partial x} \frac{dx}{2} \right] + Q_{x_{rill}} \left[C_x + \frac{\partial C_x}{\partial x} \frac{dx}{2} \right] \dots \dots \dots [21]$$

By letting $dx \rightarrow 0$, the following relationship is obtained:

$$\frac{\partial C_x}{\partial x} = \frac{-1 C_x}{q_x} \dots \dots \dots [22]$$

Substituting for q_x from equation [12], and integrating with the boundary condition, $C_x = C_L$ at $x = L$ yields:

$$C_x = C_L \left[\frac{x}{L} \right]^\beta \dots \dots \dots [23]$$

where

$$\beta = 1/k_x \dots \dots \dots [24]$$

and $C_L =$ concentration of dye in the interrill runoff at $x = L$. This relationship defines the concentration of dye in the interrill flow at any downslope distance, x , where $x > X_o$.

At the dye injection location, the mass flow rate of dye on the interrill area immediately after injection must equal the mass flow rate from the injection device, or:

$$q^0 w C^0 = q_{X_o} w C_{X_o} \dots \dots \dots [25]$$

where $q_{X_o} =$ interrill flow per unit width at $x = X_o$ and $C_{X_o} =$ concentration of dye at $x = X_o$. Using equation [12] to evaluate q_x at X_o and rearranging yields:

$$C_{X_o} = \frac{q^0 C^0}{k_x X_o} \dots \dots \dots [26]$$

Equating this result with equation [23] evaluated at X_o gives:

$$\frac{q^0 C^0}{k_x X_o} = C_L \left[\frac{X_o}{L} \right]^{-\beta} \dots \dots \dots [27]$$

The values of L and X_o may be written in terms of k_x as follows:

$$L = \frac{q_L}{k_x} \dots \dots \dots [28]$$

where δ is the distance from the dye injection point to the bottom of the interrill area. Substituting for X_o and L in equation [27] and rearranging yields:

$$k_x = \frac{1}{\delta} \left[q_L - \frac{q^0 C^0}{C_L} \left(1 - \frac{\delta k_x}{q_L} \right) \right] I/k_x \dots \dots \dots [30]$$

Equation [30] may be solved for k_x using numerical procedures.

The mass flow rate of dye from the interrill into the rill area may now be evaluated by integrating the product of the interrill-to-rill flow and concentration of dye in the flow from $x = X_o$ to $x = L$, or:

$$\dot{m}_{IR} = \int_{X_o}^L \frac{\partial Q_{IR}}{\partial x} C_x dx \dots \dots \dots [31]$$

Substituting for Q_{IR} and C_x from equations [16], and [23], respectively, the integral in equation [31] reduces to:

$$\dot{m}_{IR} = \frac{k_{IR} w C_L}{L^{-\beta}} \int_{X_o}^L X^{-\beta} dx \dots \dots \dots [32]$$

This expression may be evaluated and solved for the width of the interrill area that contributes to rill flow from one side of the rill:

$$w = \frac{\dot{m}_{IR} (1-\beta)}{C_L k_{IR} L} \left[1 - \left(\frac{X_o}{L} \right)^{1-\beta} \right]^{-1} \dots \dots \dots [33]$$

Because of difficulties encountered in accurately identifying the interrill areas contributing runoff to a given rill, analytical relationships are utilized to obtain values for L , X_o , and w , as well as other parameters in equation [33].

Equation [30] can be utilized to solve for k_x which when substituted into equation [15] yields k_{IR} . Also, β , L and X_o may be determined from equations [24], [28] and [29], respectively. Equations [19] and [33] can then be used to calculate width of the interrill region. Finally, the quantity of flow moving from an interrill area into the adjacent rill can be determined from equation [16].

Using the above equations and procedures, interrill-to-rill flow can be determined for any downslope distance. Total interrill and rill flow at the sampling location is first identified. Dye is then injected above the interrill area of interest along a cross section extending from the adjacent rill to a point beyond the drainage divide. By measuring the degree of dilution at the downstream sampling location, flow from the interrill area into the adjoining rill can be determined.

Simplified Equations

In developing the previous equations the only interrill dimension required was δ , the distance from the dye injection location to the sampling point. If interrill length, L , is known, equation [28] can be used to obtain a closed form solution of k_x . This relation is much easier

to solve than equation [30] and does not require measurement of interrill dye concentration. Once k_x has been identified, the remaining parameters can be determined as before.

If interrill length and rill width are both known, simplified flow measurement equations may be used. Many upland erosion studies are performed under controlled situations where the plot dimensions are fixed, allowing physical measurements of rill and interrill dimensions. Under these circumstances, slope and soil characteristics may also be nearly uniform over the entire plot area. Thus, interrill discharge per unit width, q_x , may be assumed constant along any particular cross section. When a line source of dye is injected across an interrill area, the concentration of dye can also be shown from equation [22] to be uniform along a particular cross section.

The two interrill areas adjacent to a rill may be labeled with superscripts as shown in Fig. 1. The mass flow rate of dye into a rill when dye has been injected across the first interrill area may be written from equation [31] as:

$$\dot{m}_{IR}^{(1)} = \int_{X_0}^L \frac{\partial Q_{IR}^{(1)}}{\partial x} C_x dx \dots\dots\dots [34]$$

Substituting for the rate change of interrill-to-rill flow from equation [10] yields:

$$\dot{m}_{IR}^{(1)} = w^{(1)} \int_{X_0}^L \left(1 - f - \frac{\partial q_x}{\partial x}\right) C_x dx \dots\dots\dots [35]$$

Likewise, when injecting dye across the second interrill area:

$$\dot{m}_{IR}^{(2)} = w^{(2)} \int_{X_0}^L \left(1 - f - \frac{\partial q_x}{\partial x}\right) C_x dx \dots\dots\dots [36]$$

Since the discharge per unit width and dye concentration are the same for both interrill areas at a particular downslope distance, dividing equation [35] by equation [36] yields:

$$\frac{\dot{m}_{IR}^{(1)}}{\dot{m}_{IR}^{(2)}} = \frac{w^{(1)}}{w^{(2)}} \dots\dots\dots [37]$$

Rainfall, infiltration, and interrill flow are all proportional to the width of the interrill area, so the interrill-to-rill flow must also be proportional to width. Thus, based on equation [37]:

$$\frac{\dot{m}_{IR}^{(1)}}{\dot{m}_{IR}^{(2)}} = \frac{Q_{IR}^{(1)}}{Q_{IR}^{(2)}} \dots\dots\dots [38]$$

By measuring the average width and length of each rill, the rill surface area may be estimated. If rainfall and infiltration are uniform along the rill, then rainfall excess originating in each rill can be determined. The combined interrill-to-rill flow from both sides of a rill, Q_{IR}^T may then be identified by subtracting the rainfall excess that originated in a rill from the rill discharge measured at the sampling location. This combined interrill-to-rill

flow may then be proportioned using equation [38] to determine the separate flow from each adjoining interrill area as:

$$Q_{IR}^{(1)} = Q_{IR}^T \left(\frac{\dot{m}_{IR}^{(1)}}{\dot{m}_{IR}^{(1)} + \dot{m}_{IR}^{(2)}} \right) \dots\dots\dots [39]$$

$$Q_{IR}^{(2)} = Q_{IR}^T \left(\frac{\dot{m}_{IR}^{(2)}}{\dot{m}_{IR}^{(1)} + \dot{m}_{IR}^{(2)}} \right) \dots\dots\dots [40]$$

Equation [19] can be used to determine $\dot{m}_{IR}^{(1)}$ when a line source of dye is injected across interrill area (1) (Fig. 1). Likewise, $\dot{m}_{IR}^{(2)}$ can be determined from area (2). Flow from interrill areas into a rill can thus be determined from equations [39] and [40]. Total rill discharge and the mass flow of dye into the rill is measured following injection of dye across the interrill areas. Note that in this analysis, when rill length and width are known, no determination of the discharge per unit width at the bottom of the interrill area or of the dye concentration as a function of downslope distance is necessary.

SUMMARY AND CONCLUSIONS

Flow characterization using dye dilution techniques has received limited use on upland areas. To determine flow rate using dye dilution techniques, dye is injected into the flow and the diluted concentration is measured at a downstream sampling point. Since flow rate at any downslope distance is influenced by the area contributing to runoff, the length and width of the interrill area supplying runoff may be estimated using dye dilution techniques.

If dye is injected as a line source at a given rate and concentration on an interrill area, part of that dye will move downslope as interrill flow with the remainder moving into an adjoining rill. By knowing the rill and interrill flow rates and dye concentrations at a given downslope distance, interrill-to-rill flow rate can be determined. This information would be useful in modeling activities where downslope routing of water occurs.

Procedures and equations for measuring rill and interrill flow were presented. Generalized equations for determining interrill-to-rill flow and interrill length and width were developed using water and dye continuity concepts. If interrill length and rill width are known, simplified equations can be used to estimate interrill-to-rill flow.

Use of dye dilution techniques for flow characterization on upland areas has considerable potential. Dye tracers can be used to estimate the source of interrill flows and to predict their final discharge location. Information concerning hydraulic parameters on upland areas could be greatly expanded using dye dilution techniques.

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LIST OF SYMBOLS

C	Dye concentration, M/L ³
C _L	Dye concentration of interrill flow at x = L, M/L ³
C ⁰	Concentration of injected dye, M/L ³
C _{RB}	Dye concentration in the rill at x = L, M/L ³
C _x	Dye concentration of interrill flow at x, M/L ³
C _{x₀}	Dye concentration of interrill flow at x = X ₀ , M/L ³

C _{x+dx}	Dye concentration of the interrill flow at x = x + dx, M/L ³
d x	Infinitesimal downslope distance, L
f	Infiltration rate, L/T
f _w	Infiltration component of flow, L ³ /T
i	Volumetric injection rate of dye, L ³ /T
I	Rainfall intensity, L/T
I _w	Rainfall component of flow, L ³ /T
k _{IR}	Rate change of Q _{IR} with respect to downslope distance per unit plot width, L/T
k _x	Rate change of interrill flow per unit width with respect to downslope distance, L/T
L	Slope length, L
m	Mass flow rate of dye, M/T
m ⁰	Mass injection rate of dye, M/T
m _{IR}	Mass flow rate of dye from an interrill area into a rill from x = x ₀ to L, M/T
M ⁰	Mass of dye injected by slug injection, M
q _L	Flow rate per unit width across an interrill area at x = L, L ² /T
q ⁰	Volumetric injection rate of dye per unit width, L ² /T
q _x	Flow rate per unit width across an interrill area at x, L ² /T
q _{x₀}	Flow rate per unit width across an interrill area at x = X ₀ , L ² /T
Q	A volumetric flow rate, L ³ /T
Q _{x_{in}}	Flow into an infinitesimal interrill area, L ³ /T
Q _{x_{out}}	Flow out of an infinitesimal interrill area, L ³ /T
Q _{x_{rill}}	Flow into an adjacent rill over the distance, dx, L ³ /T
Q _{IB}	Flow from bottom of an interrill area, L ³ /T
Q _{IR}	Flow from an interrill area into the adjacent rill from x = 0 to x, L ³ /T
Q _{IR^T}	Combined interrill-to-rill flow from both sides of a rill from x = 0 to x, L ³ /T
Q _{RB}	Flow from the bottom of a rill, L ³ /T
t	time, T
w	Width of the interrill area, L
x	Downslope distance, L
X ₀	Downslope dye injection distance, L
β	Ratio of rainfall intensity, I, to the rate change in interrill flow, k _x
δ	Distance from dye injection location to sampling location in a rill, L