A Synthetic Unit Sedimentgraph
for Ungaged Watersheds

by

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(ABSTRACT)

The concept of the unit sedimentgraph is important and useful in the study of non-point source pollutant transport, in the estimation of sediment yield and in the design of sediment basins. At the present time, a physically sound method of deriving unit sedimentgraphs for ungaged small watersheds is not available. Based on synthetic principles as well as linear and time-invariant principles, applied to the systems approach of hydrology, a synthetic model has been developed to derive the unit sedimentgraph and to generate the sedimentgraph for an ungaged watershed. The model is limited to the generation of single peak sedimentgraphs where the sediment particle sizes of interest range from 0.002 mm to 1.0 mm. Seven small watersheds located in the lower Potomac River Basin were selected for this study. For each watershed about 12 storm events were included in the study. Available hourly rainfall and streamflow data were collected and used for model calibration. Results of both "spatial" and "temporal" verification show that agreement between the synthetic and actual sedimentgraphs is fairly good.

A new rigorous definition regarding the unit sedimentgraph has been established. The study is based on a one-hour unit sedimentgraph which is defined as the direct sedimentgraph resulting from 1 unit of effective sediment yield of a storm of 1-hour duration generated uniformly over the basin at a uniform rate. Thus, the one-hour sedimentgraph of a storm for a specified watershed can be generated by convolving the one-hour unit sedimentgraph with the effective sediment erosion of one hour duration provided that the rainfall record and characteristics of that watershed are known.

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NOMENCLATURE

A - watershed area $[L^2]$

c - sediment concentration $[F/L^3]$

D - duration of each rainfall pulse [T]

E - mean basin elevation [L]

f - infiltration rate [L/T]

h - depth of flow [L]

H - the system function or system operation or operator

I or q - rainfall intensity [L/T] or $[L^3/T]$

K - soil erodibility factor

L - main channel length [L]

n - an exponent, $1<n<3$

Q - discharge of water per unit width $[L^2/T]$

S - main channel slope

t or τ - time [T]

U - unit hydrograph, ordinates in [1/T] or $[L^2/T]$

x - the system input; or distance, positive in the direction of flow [L]

y - the system output

Υ - depth vs. discharge relation $[L^{2-n}/T]$

η - a coefficient $[F/TL^{1+n}]$

θ - any positive scale ratio

ER - excess runoff or effective runoff or direct runoff volume (V) either in depth [L] or in $[L^3]$

ES - excess sediment yield or direct sediment mobilized or effective sediment yield (Vs) in weight [F]

NOMENCLATURE (continued)

k_1 - a coefficient $[F/L^3]$

k_2 - a coefficient $[1/L]$

q_s - ordinates of USG $[1/T]$

Q_s - ordinates of DSG $[F/T]$

t_s - abscissa of USG or DSG $[T]$

T_s - base time $[T]$

Vf - the volume of infiltration $[L^3]$ or $[L]$

Vr - the volume of total rainfall $[L^3]$ or $[L]$

DRH or $Q(t)$ - direct runoff hydrograph, ordinates in $[L/T]$ or $[L^3/T]$

DSG or $Q_s(t)$ - direct sedimentgraph, ordinates in $[F/T]$

ERI - effective rainfall intensities $[L/T]$

ERR - time rate of ER $[L/T]$

ESR - time rate of ES $[F/T]$

q_{sp} - peak of USG $[1/T]$

TRI - total rainfall intensities $[L/T]$

t_{sp} - time to peak (from the origin of the USG) $[T]$

USG - unit sedimentgraph, ordinates in $[1/T]$

a, b, α, β - regression coefficients

ESEI - effective sediment erosion intensities $[F/T]$

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CHAPTER I

INTRODUCTION

1-1. Background

A sedimentgraph associated with a hydrograph during a storm provides useful information to estimate sediment yield, to design a sediment basin, and to study transport of pollutants attached to the sediment. The use of an average sediment transport rate instead of a sedimentgraph is not adequate for estimating dynamic sediment and pollutant loads during a storm. A sedimentgraph is also required in designing efficient sediment control structures.

Sedimentgraph prediction can be achieved by employing either a physical approach or systems approach. Analytical solutions, in many cases, are not easily obtained by means of a physical approach. Hydrologists usually favor a systems approach in the study of sedimentation problems in which the spatial variation of sediment discharged into waterways and the detailed transport process can be lumped together into a single system. The sediment producing factors such as rainfall and runoff can be treated as inputs to the system and the sediment yield becomes the system output. The geomorphic characteristics and the hydrologic factors of a watershed are considered as a set of lumped system parameters which transform inputs to outputs through the system.

In natural settings, the watershed is a nonlinear system and therefore numerous complexities are involved in the derivation of a sedimentgraph. Fortunately, during the past years, there has been success in applying the linear and time-invariant assumptions to hydrology, making it possible to solve certain non-linear problems. In system theory, a system is referred to as linear if it satisfies the properties of proportionality and superposition. A system is said to be time-invariant when its parameters do not change with time. In other words, the form of the output depends only on the form of the input and not on the time at which the input is applied. With the assumption of time-invariance, it is possible to predict an output for a given input if that particular input has already occurred some time during the period of record. The assumption of linearity allows the prediction to be made even though the type of input that we are interested in has not occurred in the past (Dooge, 1973). Linearity and time-invariance are the bases for the development of the unit hydrograph. The same bases will be used to derive the unit sedimentgraphs for all small ungaged watersheds in this study.

1-2. Literature Review

A few conceptual models for predicting sedimentgraphs have been reported recently, of which only Williams' model (1978) was developed for ungaged watersheds.

Renard and Laursen (1975) computed sedimentgraphs by multiplying the flow rates provided in a storm hydrograph by sediment concentrations predicted from a sediment transport model. However, their sediment transport model is not generally applicable to watersheds because the sediment model does not take into consideration such source erosion parameters as watershed ground cover, land slope and conservation practices.

Bruce et al. (1975) constructed a sedimentgraph model based on sediment erosion and transport capacity. Rendon-Herrero (1974 and 1978) proposed a model based on the concept of unit sedimentgraph. Both of these models, however, require gaged data.

Although Williams' model is based on the instantaneous unit sedimentgraph (IUSG) and can be used for ungaged watersheds, the assumption that IUSG varies linearly with source runoff volume is questionable. Also, the dimensions are found to be inconsistent when storm sedimentgraphs are predicted by convolving source runoff by means of IUSG. This method has been applied and has yielded somewhat satisfactory results, but the procedure is cumbersome due to the difficulty and ambiguity in estimating the parameters needed for the model.

Musgrave (1947) and Wischmeier et al. (1978) have developed the so called Universal Soil Loss Equation (USLE). Although the equation was originally intended to predict the long term average upland soil losses associated with runoff, it has been applied, in some cases, to specific rainstorms using the product of kinetic energy (E) and 30-min. intensity of the rain (I_{30}), i.e. EI_{30}, to calculate the erodibility factor (K). But, due to the fact that the soil loss during a single storm event may differ widely from the averaged annual value, the USLE is unable to predict the sedimentgraph for a single storm unless gully erosion, sediment transport in channels, and delivery ratio are considered in addition to the upland soil erosion predicted.

1-3. Research Objectives

From the above description, it is evident that only Williams' model was developed to produce sedimentgraphs for ungaged watersheds. His method is based on the IUSG and hence can be convolved with the source runoff to produce sedimentgraphs. However, the convolution has been found inconsistent in its dimensions. For this reason, the major objective of this research is to establish a theoretically sound procedure which will make dimensions homogeneous. By taking the same assumptions that have been used successfully to derive synthetic unit hydrographs, the linear and time-invariant assumptions will be made again to derive the synthetic unit sedimentgraph. The only difference is that the proposed procedure involves both the water and the sediment, and therefore a different way of generating the input will be developed rather than using only the rainfall as the input.

The study will focus on how to devise a system which will transform a set of known inputs into a desired output within a certain degree of accuracy. Based on hourly rainfall records available from the National Weather Service, and hourly streamflow and sediment concentration data taken by the U.S. Geological Survey for small watersheds, an averaged or generalized dimensionless unit sedimentgraph will be sought. The base time, peak time, and peak sediment discharge will be correlated with the hydrologic parameters, soil properties and watershed geomorphic characteristics. The synthetic unit sedimentgraph can be derived if these physical parameters for a specified watershed are known. Furthermore, once the unit sedimentgraph for a specific watershed has been derived, the direct sedimentgraph of any storm event can be obtained.

CHAPTER II

THEORETICAL BACKGROUND OF THE MODEL

2-1. Linear and Time-Invarient System

What is a system? According to Dooge (1973) and Overton (1976) "A system is any structure, device, scheme, or procedure, real or abstract, that interelates in a given time reference, an input, cause, or stimulus, of matter, energy, or information , and an output, effect , or response, of information, energy, or matter." In applied science, the major concern in dealing with problems is to predict the output from the system of interest. Fig. 2-1 shows the three elements that determine what this output will be. In the classical approach (i.e. physical approach), certain assumptions are made regarding the nature of the system and the physical laws governing its behavior. These are then combined with the input to predict the output. To apply this classical procedure, it is necessary to know the physical laws or to be able to make reasonable assumptions about them. But in many scientific fields, the physical laws are either undetermined or difficult to apply. Sometimes it is the complex geometry of the system or the lack of homogeneity in dimension that prevents us from applying the classical methods to predict the behavior of the system. This holds true particularly in the field of hydrology. Many hydrologists have applied the systems approach to solve the problems caused by the complexity of the physical laws, the structure of the system, and the input. Fig. 2-2 illustrates the nature of the systems approach to problem solving. Also, it shows how the complexities arising from the physical laws involved and from the nature of the system being studied are combined into a single concept of the systems operation. When the nature of the system and the physical laws change, the systems operation also changes. However, in the systems approach, one is interested only in how the systems operation transforms the inputs into outputs, since the nature of the systems and the physical laws have been built into the systems operation itself.

The advantages of applying the systems approach to solve complex problems by dealing with the gross behavior rather than details can be exemplified by using the unit hydrograph in predicting storm runoff. In this example, rainfall excess is the input to the system and the direct runoff is the output. The systems operation, in this case the unit hydrograph, transforms the rainfall excess into the direct runoff. One is not concerned with the spatial distribution of interflow, or how the overland flow actually occurs. One may overlook his ignorance of the physical laws that determine the processes in various parts of the hydrologic cycle. It is not necessary, for example, to survey the entire watershed by taking profile measurements for many cross sections as we would have to do if we were to solve classical hydraulic problems. Instead of going through a detailed description, the complex basin geometry and physical processes in the watershed can be represented by a system in the rainfall-runoff process, i.e. the unit hydrograph.

A system is linear when it has the properities of proportionality and superposition. Proportionality means that the system input and output have the same scale ratio, i.e.:

$$y = H(\theta x) = \theta H(x) \tag{2-1}$$

where: x is the system input,

y is the system output,

H is the system function or operation,

θ, is any positive scale ratio.

Superposition means that the system output due to the sum of inputs is equal to the sum of the outputs. For example, if there are two input quantities as follows:

$$y_1 = H(x_1) \quad \text{and} \quad y_2 = H(x_2)$$

$$\text{Then,} \quad y_1+y_2 = H(x_1)+H(x_2) = H(x_1+x_2)$$

A system is linear if and only if it follows the properties of both proportionality and superposition; that is,

$$H(\theta_1 x_1+\theta_2 x_2) = \theta_1 H(x_1) + \theta_2 H(x_2) \tag{2-3}$$

Fig. 2-3 and Fig. 2-4 show inputs and outputs in a linear system following the principles of proportionality and superposition.

Another concept involved in the present study via the system approach is time-invariance. A system is time-invariant if its input-output relationship does not change with time. The form of the output depends only on the form of the input and not on the time at which the input is applied. More specifically, a system having the input-output relation $y(t) = H[x(t)]$ is time-invariant if and only if $y(t\pm\tau) = H[x(t\pm\tau)]$ for any $x(t)$ and τ. This property can also be shown graphically as in Fig. 2-5.

2-2. Unit Hydrograph Theory

In linear system hydrology, the unit hydragraph plays an extremely important role. Since the physical characteristics of the watershed - shape, size, slope, etc. - are practically constants, one might expect considerable similarity in the shape of hydrographs from storms of similar rainfall patterns. This is the essence of the unit hydrograph as proposed by Sherman in 1932. A unit hydrograph, as stated before, is a system in which the complex basin geometry in the watershed and all the physical processes in the hydrologic cycle are described for that particular watershed by the unit hydrograph. It is called a unit hydrograph because, for convenience, the runoff volume under the hydrograph is commonly adjusted to one unit (1 cm or 10 mm or 1 inch) equivalent water depth over the watershed. In addition, the following basic assumptions constitute the unit hydrograph theory (Chow, 1964):

(1) The effective rainfall is uniformly distributed during the period of rainfall duration or a specified period of time.

(2) The effective rainfall is uniformly distributed over the entire area of the watershed.

(3) The base time of the hydrograph of direct runoff due to an effective rainfall of unit duration is constant.

(4) The ordinates of the direct runoff hydrographs of a common base time are directly proportional to the total amount of direct runoff represented by each hydrograph.

(5) For a given watershed, the runoff hydrograph of a given rainfall duration reflects all the combined physical characteristics of the watershed.

Assumption (1) implies that the storm selected for analysis should have a relatively short duration in which an intense and nearly uniform effective rainfall would generate a well-defined and single-peaked hydrograph having a short base time.

Assumption (2) implies that the watershed area to be considered cannot be too large.

For assumption (3), the base time of the unit hydrograph of a watershed for a given rainfall duration is considered constant. This is due to the fact that the baseflow remains constant for the watershed if only direct runoff is considered.

Assumption (4) is referred to as the "principle of linearity." The ordinates of the direct runoff hydrographs are mutually proportional and thus can be added or superimposed numerically in proportion to the total amount of direct runoff (i.e. effective rainfall).

Assumption (5) indicates the lumped property used in the development of a system. Also, the hydrograph resulting from a given pattern of effective rainfall at anytime is invariable. This is known as the "principle of time invariance."

It can be seen that the unit hydrograph is devised in compliance with the linear and time-invariant properties. Past observations indicate that, in the real hydrologic cycle, the system is nonlinear and time-variant and is difficult to analyze. In natural settings, the scale ratios of and ,as mentioned in section 2-1, are no longer constant and the watershed characteristics change with respect to seasons, man-made adjustments, conditions of the flow, and so forth. However, the assumptions of linearity and time-invariance do not greatly depart from the real situation and have been proven to be simple in application and to yield good approximations. Consequently, the technique of predicting direct runoff based on the information of rainfall excess by means of the unit hydrograph has been widely applied. The complexity of estimating baseflow and infiltration is not included in the system itself; they are treated separately from the system.

Thus, the unit hydrograph is clearly defined as the hydrograph of direct runoff resulting from an effective rainfall of one unit in volume occurring uniformly over the watershed in a specific rainfall duration. If a one-hour unit hydrograph has been established, the resulting direct runoff hydrograph due to a number of one-hour effective rainfall pulses for a watershed can be obtained by applying linear and time-invariant principles. It can be shown mathematically as follows:

$$Q(t)=\sum_{i=1}^{n} U[D,t-(i-1)D]*I_i*D$$

$$= U[D,t]\ I_1D + U[D,t-D]\ I_2D + \ldots + U[D,t-(n-1)D]\ I_nD$$

if n=3, then

$$Q(t)= U[D,t]\ I_1D + U[D,t-D]\ I_2D + U[D,t-2D]\ I_3D \qquad (2\text{-}4)$$

where: Q(t) is direct hydrograph,

U is unit hydrograph,

I is rainfall intensity,

D is time duration of each rainfall pulse.

The unit hydrograph of the above equation may involve dimensions of any one of the three cases:

Case	I	D	U[D,t-(i-1)D]	Q(t)
(1)	L/T	T	L^2/T	L^3/T
(2)	L^3/T	T	$1/T$	L^3/T
(3)	L/T	T	$1/T$	L/T

If dimensions in the third case are used, the relationships of the left and the right hand sides of the above equation can be further shown as in Fig. 2-6. Three rainfall excess blocks of I_1, I_2, I_3 are convolved by the unit hydrograph into a direct runoff hydrograph.

2-3. Mathematical Relationship Between Direct Runoff and Direct Sediment Yield

In 1974 and 1976, Rendon-Herrero introduced a method for the estimation of wash load sediment discharge produced by a storm for an upland watershed. The method requires the information from the log-transformed linear relationship between the volume of the direct or effective runoff (ER) and the direct or effective sediment yield (ES). His method was subsequently discussed by Laursen (1975) and tested by Kolar and Jicinsky (1975). Recently, the relationship was further tested by Rendon-Herrero, et al.(1980), and Singh and Chen (1981). The method has been proved to be valid and useful in sediment yield studies. The log-transformed linear relationship introduced in his method, is calibrated and extended in this disseration, and is described mathematically as follows.

For a specific watershed the ER-ES relationship reveals a straight line on a log-log plot. To explain this behavior, the continuity and momentum equations of overland planar flows related to sediment transport are considered as follows (Rendon-Herrero, et al., 1980):

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q - f \qquad (2\text{-}5)$$

$$Q = \gamma h^n \qquad (2\text{-}6)$$

$$\frac{\partial (ch)}{\partial t} + \frac{\partial (cQ)}{\partial x} = k_1 q + k_2(\eta h^n - cQ) \qquad (2\text{-}7)$$

$$Q_s = cQ \qquad (2\text{-}8)$$

Where h = depth of flow (L)

Q = discharge of water per unit width (L^2/T)

Q_s = sediment discharge per unit width (F/TL)

q = rainfall intensity (L/T)

c = sediment concentration (F/L^3)

γ = depth-discharge coefficient (L^{2-n}/T)

n = an exponent $1<n<3$

x = distance, positive in the direction of flow (L)

t = time (T)

k_1 = a coefficient (F/L^3)

k_2 = a coefficient (1/L)

η = a coefficient (F/TL^{1+n})

f = infiltration rate (L/T)

The quantities k_1q and $k_2(\eta h^n - cQ)$ account for the detachment of soil particles due to the impact of rainfall excess, transport of these particles by flow, and deposition of these particles during flow. In terms of physical processes, the terms of $k_1q + k_2(\eta h^n - cQ)$ represent the net sediment production from upland areas. The wash load sediment considered is in the range of fine grain size, 0.002 to 1.0 mm.

The initial and boundary conditions for equations (2-5)--(2-8) are as follows:

$$h\ (0,t) = 0, \quad t \geqslant 0$$

$$h\ (x,0) = 0, \quad x \geqslant 0$$

$$h\ (x,\infty) = 0, \quad 0 \leqslant x \leqslant L$$

$$c\ (0,t) \text{ is bounded for } t>0$$

$$c\ (x,0) \text{ is bounded for } x>0$$

Thus, these initial and boundary conditions together with equations (2-5)--(2-8) constitute a well defined problem and can be solved analytically.

Let V be the volume of effective runoff for a rainfall storm, Vr be the volume of total rainfall, Vs be the sediment yield, and Vf the volume of infiltration, the following equations are defined:

$$V\ (x) = \int_0^\infty Q\ (x,t)\ dt \tag{2-9}$$

$$Vr(x) = \int_0^\infty q\ (x,t)\ dt \tag{2-10}$$

$$Vs(x) = \int_0^\infty cQ(x,t)\ dt \tag{2-11}$$

$$Vf(x) = \int_0^\infty f\ (x,t)\ dt \tag{2-12}$$

Applying initial and boundary conditions and upon integrating equation (2-5) with respect to t, it follows:

$$\int_o^{\infty} \frac{\partial h}{\partial t}\, dt + \int_o^{\infty} \frac{\partial Q}{\partial x}\, dt = \int_o^{\infty} q(dt) - \int_o^{\infty} f(dt) \qquad (2\text{-}13)$$

or $$V'(x) = \frac{dV}{dx} = Vr(x) - Vf(x) \qquad (2\text{-}14)$$

$$= \text{volume of rainfall excess}$$

or $$V(x) = \int_o^{x} [Vr(x)-Vf(x)]\, dx \qquad (2\text{-}15)$$

For a given watershed, the volume of total rainfall Vr(x) is a constant and Vf(x) is dependent on soil physical characteristics, watershed slope and boundary distance. However, for mathematical simplification, it can be assumed to be constant for given soil conditions.

Hence, $$V(x) = x\,[Vr(x)-Vf(x)] = x\,[Vr-Vf] \qquad (2\text{-}16)$$

Similarly, integrating equation (2-7) with respect to t, the following equation is obtained:

$$\int_o^{\infty} \frac{\partial(ch)}{\partial t}\, dt + \int_o^{\infty} \frac{\partial(cQ)}{\partial x} = \int_o^{\infty} (k_1,q)\,dt + \int_o^{\infty} k_2(\eta h^n - cQ)\,dt \qquad (2\text{-}17)$$

where $$Vs'(x) = \frac{dVs(x)}{dx} = k_1Vr(x) + k_2[V(x) - Vs(x)] \qquad (2\text{-}18)$$

Let $$y\,(x) = Vs(x) - V(x) \qquad (2\text{-}19)$$

or $$Vs(x) = y(x) + V(x) \qquad (2\text{-}20)$$

it follows:

$$Vs'(x) = \frac{dVs(x)}{dx} = y'(x) + V'(x)$$

$$= k_1\ Vr(x) + k_2\ [V(x) - Vs(x)]$$

$$= k_1Vr(x) + k_2V(x) - k_2[y(x) + V(x)] \qquad (2\text{-}21)$$

or $$y'(x) + k_2y(x) = k_1Vr(x) - V'(x)$$

$$= k_1Vr(x) - Vr(x) + Vf(x)$$

$$= (k_1-1)Vr(x) + Vf(x) \qquad (2\text{-}22)$$

Equation (2-22) is a linear first order differential equation. The solution is:

$$y(x) = \exp(-k_2x)\ \{\int_o^x \exp(k_2x)\ [(k_1-1)Vr(x) + Vf(x)]\ dx\}$$

Since Vr (x) and Vf (x) are actually constants, the above equation becomes:

$$y(x) = \exp(-k_2x)\{[(k_1-1)Vr + Vf]\frac{1}{k_2}(\exp(k_2x)-1)\} \qquad (2\text{-}23)$$

or $$y(x) = (1-\exp(-k_2x))\{\frac{(k_1-1)Vr+Vf}{k_2}\} \qquad (2\text{-}24)$$

Substituting $Vr = \frac{V(x)+x\ Vf}{x} = \frac{V(x)}{x} + Vf$ into eq. (2-24)

$$y(x) = (1-\exp(-k_2x))\ \{\frac{(k_1-1)}{k_2}(\frac{V(x)}{x} + Vf) + \frac{Vf}{k_2}\}$$

$$= (1-\exp(-k_2x))\{\frac{k_1-1}{k_2} \cdot \frac{V(x)}{x} + (\frac{k_1-1}{k_2} + \frac{1}{k_2})\ Vf\}$$

$$= \frac{(k_1-1)(1-\exp(-k_2x))}{k_2x} V(x) + (\frac{k_1}{k_2})(1-\exp(-k_2x))Vf \qquad (2\text{-}25)$$

Substituting back into eq.(2-20) and setting x=L, the equation for Vs can be derived.

$$Vs\ (L) = [\frac{(k_1-1)(1-\exp(-k_2L)}{k_2L} + 1]\ V(L) + (\frac{k_1}{k_2})(1-\exp(-k_2L))Vf$$

$$= Vs \qquad (2\text{-}26)$$

This equation can be expressed in a simple form as:

$$Vs = a\ V + b'\ Vf \qquad (2\text{-}27)$$

Where a and b' are constants. If the quantity of Vf is small and can be neglected one can write:

$$Vs = a\ V \qquad (2\text{-}28)$$

If the quantity of infiltration cannot be neglected but one is only interested in the relationship between Vs and V, then equation (2-28) may be written in general form as :

$$Vs = a\ V^{b}, \text{ for } b' > b \geqslant 1. \qquad (2\text{-}29)$$

or

$$ES = a\ (ER)^{b} \qquad (2\text{-}30)$$

The equation $Vs = a\ V$, is a special case of (2-29) when $b=1$. To the author's knowledge, there is no analytic method to evaluate the constants a and b. However, one way to evaluate these constants is by means of regression analysis based upon the avaliable gaged event data. Moreover, from previous studies, it has been found (Singh and Chen, 1981) that the intercept "a" is different from one watershed to another and can be calibrated independently.

CHAPTER III

SYNTHETIC SEDIMENTGRAPHS

3-1. Derivation of the Unit Hydrographs

A sound and simple way to derive a unit hydrograph is based upon an observed hydrograph or hydrographs. In selecting a hydrograph for such an analysis, the assumptions involved in the unit hydrograph theory must be nearly satisfied. A hydrograph resulting from an isolated, intense, short-duration storm of nearly uniform distribution in space and time is the most desirable. By the unit hydrograph theory, the ordinates of the required unit hydrograph are simply equal to the corresponding ordinates of the given direct runoff hydrograph divided by the total amount of direct runoff, in inches or cm for example. In this procedure, the effective rainfall is assumed to be uniformly distributed. The specific steps are listed as follows (Viessman, 1977):

1. Separation of surface runoff from baseflow by means of a standard separation method. (Linsley 1982)
2. Estimation of the total volume of surface runoff (direct runoff, ER) by measuring the area under the hydrograph after baseflow has been separated.
3. The ordinates of the direct runoff hydrograph are divided by the total direct runoff volume and these results are plotted against time to yield a unit hydrograph for the

watershed.

4. The effective duration of the runoff-producing rain for this unit hydrograph must be found from the hyetograph of the storm used.

A unit hydrograph derived from a single storm may not be representative, and it is therefore necessary to average unit hydrographs from several storms of the same duration. This can be done by computing average peak flow and time to peak. An averaged unit hydrograph is obtained by sketching the graph to conform with the shape of the graphs used for averaging, passing through the computed average peak, and having the required unit volume.

3-2. Derivation of the Unit Sedimentgraph

Following the same principles and procedures used to obtain a unit hydrograph, the unit sedimentgraph can be derived in the same manner. The only difference is that the sediment discharge in weight per unit time, is obtained by multiplying the sediment concentration in weight per unit volume by the water discharge in volume per unit time. The data provided by the USGS normally represent total hydrographs. It is necessary to convert them into direct hydrographs. Applying the standard baseflow separation technique and the equation to separate the sediment associated with the baseflow as suggested by Rendon-Herrero (1974), the direct sedimentgraph of each storm can be determined. The equation is: $SD_i = (ST_i*QT_i - SB_i*QB_i)*0.0864$, in which SD_i=the direct sediment discharge in metric tons per day; ST_i=the total sediment concentration in ppm; QT_i= the total water discharge in cms; SB_i=the sediment concentration in the baseflow in ppm; QB_i=the baseflow in cms; i = the ordinate index. The factor of 0.0864 is used for converting the sediment discharge from cms into metric tons per day.

Baseflow is assumed to be comprised of both groundwater flow and interflow. In order to obtain an accurate direct sedimentgraph, the starting time of the effective rainfall is important and has to be matched with the starting point of the direct sedimentgraph. The effective rainfall is calculated by means of the ϕ-index method. By integrating the area under the direct sedimentgraph, the effective sediment yield ES, can be obtained and expressed in metric tons. The ordinates of the direct sedimentgraph are divided by the sediment yield and a unit sedimentgraph can be obtained. In this study, a one-hour unit sedimentgraph (1-hr. USG) has been selected which has the effective rainfall duration of one hour. A typical example of baseflow and base sediment concentration separation is shown in Fig. 3-1.

3-3. Synthetic Principles

Unit sedimentgraphs can be derived following the procedures described in the previous section only if gaged streamflow and sediment records are available. Since only a relatively small number of watersheds are gaged, some means of deriving unit sedimentgraphs for ungaged watersheds are necessary. In 1938 and 1939 McCarthy proposed a method of synthesizing of unit hydrographs. In his method, a correlation analysis was made for dependent variables of three unit hydrograph parameters (peak discharge, lag time from the beginning of rainfall to peak time, and base time) as functions of three watershed characteristics (area, slope of watershed area-elevation curve, and number of major streams in the watershed). Based on the results of correlation, it is possible to estimate the three parameters of a unit hydrograph for an ungaged area provided the three watershed characteristics are known. In the same year, Snyder (1938) introduced a well-known method of synthesizing Unit Hydrographs. Following the same approach, a number of developments have appeared in literature, such as by Linsley (1943), Taylor and Schwarz (1952), Gray (1970), and SCS (1972).

In order to develop a synthetic procedure for the unit sedimentgraph, the requirement of "similarity" of watersheds and the principle of "transposition" are important. There are three types of similarity: (1) geometric similarity in terms of watershed area, shape, main channel slope, and topography; (2) hydrologic similarity in terms of rainfall, snowfall, infiltration, and valley storage; and (3) geologic similarity regarding those variables which affect groundwater flow, soil erosion, sediment properties and sediment transport. Therefore, in "practical" applications, the synthetic model will yield better predictions if similarity requirements are met.

The principle of "transposition" is also called the principle of "transfer capability." The best way to apply this principle is to calibrate all coefficients in the system based on the data collected in gaged watersheds located in the vicinity of the ungaged watershed of interest. These properties are then transferred from the gaged watershed to the ungaged watershed by applying those calibrated coefficients. A technique for transposing unit sedimentgraphs, similar to the technique applied for hydrographs, is the use of a dimensionless unit sedimentgraph. The dimensionless unit sedimentgraph takes into account basin size and essentially eliminates the effect of basin shape, except as they are reflected in the estimate of basin lag time, t_{sp} and sediment yield volume (Linsley, 1982).

Hydrologists frequently attempt to simulate complex hydrologic systems by simpler models through the utilization of similarity and transposition principles. The main task of the synthetic process in this study is to devise a linear and time-invariant system which will transform known inputs into required outputs within a certain limit of accuracy thereby providing a reasonable degree of predictive capability.

3-4. Model Development

The system under consideration in this study is the synthetic unit sedimentgraph (USG). The output of interest is the sedimentgraph at a given location in a watershed. The necessary inputs to the system must be known in order to accomplish the prediction of a sedimentgraph. Based upon the data normally available through the U.S. Weather Bureau and the USGS, rainfall intensity, streamflow, and sediment concentration can all be considered as inputs. Of these, rainfall intensity is the primary input due to the following reasons: (1) It is the physical input to the watershed that causes the generation of direct runoff and sediment transport; (2) It provides effective sediment erosion intensity (ESEI) to the system; (3) ESEI can be used as an equivalent input to the system and makes the system dimensionally homogeneous, which will be proven subsequently.

Similar to the ER-ES regressional relationship, it was found by the author, that a regressional relationship also exists between the effective runoff rate (ERR) and the effective sediment yield rate (ESR). The relationship takes the form of $ESR = \alpha(ERR)^{\beta}$. Note that ERR responds according to the variation of the effective rainfall intensity (ERI), while ESR responds according to the variation of the effective sediment erosion intensity (ESEI). In other words, the effective rainfall, either depth or intensity, produces the direct runoff and in turn the direct runoff produces the direct sediment yield. Therefore, it is postulated conceptually that the effective rainfall intensity generates its counterpart the effective sediment erosion intensity which, through the unit sedimentgraph, results in a sedimentgraph. This can be schematically illustrated in Fig. 3-2. It can be seen that ERI and ESEI are causes which produce ERR and ESR. It is logical to assume that the relationship between ESEI and ERI should also take the same form as $ESR = \alpha(ERR)^{\beta}$. Since the ESEI values are not recorded in the field, the coefficients can not be evaluated through regression analysis. Therefore, let $ESEI = \alpha(ERI)^{\beta}$ be used to evaluate ESEI for approximation, of which α and β are taken as the same coefficients used in ESR-ERR relationship. It is further assumed that:

1. The sediment erosion intensities are directly related to the rainfall intensities. The duration for rainfall and for sediment erosion are the same. High rainfall intensities yield high sediment erosion intensities.
2. Effective sediment erosion occurs during the same period of effective rainfall. There is no sediment erosion if there is no rainfall.
3. The mass conservation law must be satisfied. That is, the sum of ESEI must be equal to ES during the effective rainfall period specified. This is the same requirement as for direct runoff, i.e. that the sum of ERI must be equal to ER. In other words, the pattern of ESEI is

transformed through the ESEI-ERI equation according to the known effective rainfall intensity pattern and the volume of sediment yield remains constant.

The proposed input,ESEI, can be shown to be dimensionally correct. Let $Q_s(t)$ be the ordinates of the direct sedimentgraph, ESEI be the effective sediment erosion intensity, USG be the ordinates of the unit sedimentgraph, D be the duration of each ESEI pulse, then:

$$Q_s(t) = \sum_{i=1}^{n} USG\ [D,t-(i-1)D]*ESEI_i*D \qquad (3-2)$$

If the third type of dimension is used, as in the case of the unit hydrograph (section 2-2) , the dimensions should appear as follows:

ESEI	D	USG[D,t-(i-1)D]	$Q_s(t)$
F/T	T	1/T	F/T

In this study, metric units are adopted. So ESEI is in metric tons/hr, ERI is in cm/hr, ERR is in cm/hr, ESR is in metric tons/hr, USG is in 1/hr, Q_s is in metric tons/hr, ER is in cm, and ES is in metric tons. Hence the above equation is dimensionally homogeneous.

A USG can be derived for any specified duration. In this study, it is only limited to the one-hour USG because of its ease of derivation and simplicity in application when it is coupled with the hourly ESEI. Thus, the one-hour USG is defined as the direct sedimentgraph resulting from 1 unit of effective sediment yield of a storm of 1-hour duration generated uniformly over the basin at a uniform rate. In rainfall-runoff modeling, it is a good approximation to consider hourly rainfall having uniform distribution during the one hour period. But, in order to satisfy the requirement of uniform rainfall distribution over the watershed, it is necessary to derive a USG limited to small watersheds. Different definitions concerning the size of small watersheds have been given by Chow (1964), Chebrtarev (1966), and Wisler & Brater (1967). In this study, the areas less than 500 square miles (1295 square kilometers) are considered as small watersheds.

The detailed procedures of model development are shown schematically in the block diagrams given by Fig. 3-3 and Fig. 3-4. Two stage computations are needed for the developed model. In this regard, Fig. 3-3 and Fig. 3-4 outline the computational procedures in the first and the second stages respectively. In order to have a valid model on a regional basis, the observed records must cover a number of watersheds in that region. Hence, in the first stage, many pairs of direct runoff hydrographs (DRH) and direct sedimentgraphs (DSG) should be used in the model development and calibration process. For each pair of DRH and DSG, the corresponding ER and ES can be evaluated from known ERR and ESR values. By running a log-transformed linear regression model, functions of $ESR = \alpha(ERR)^{\beta}$ and $ES = a(ER)^{b}$ can be established. Out of many DSG's for each watershed only a few one-hour USG's can be obtained. However, a representative one-hour USG can be averaged from those USG's obtained for each watershed. Averaging all the representative one-hour USG's from the gaged watersheds, a regional one-hour USG is obtained and expressed in dimensional and non-dimensional forms. Finally, with q_{sp} as the dependent variable, soil erodibility (I2) and geomorphic parameters (I3) as the independent variables, a linear regression function of the form $q_{sp} = f(I2,I3)$ can be derived. Similarly, $T_s = f(I2,I3)$ and $t_{sp} = f(I2,I3)$ can be obtained.

Before the model may be used for prediction, a procedure for model verification must be developed. In this second stage, previously saved events, which are not included in the data base for model development, were used. With known effective rainfall intensities of an event for a specific watershed, the corresponding ESEI can be evaluated through the ESEI-ERI regression equation. (Use the ES-ER regression equation for a one-hour input.) With known soil erodibility factor and geomorphic parameters of the specific watershed, the q_{sp} and T_s can be computed through regression equations of $q_{sp} =f(I2,I3)$ and $T_s = f(I2,I3)$. Consequently, knowing q_{sp} , T_s, and the dimensionless USG, the synthetic dimensional USG of that specific watershed is obtained. By using the ESEI and the synthetic USG, the synthetic DSG is obtained. Finally the synthetic DSG is compared with the actual DSG for error analysis.

CHAPTER IV

DATA COLLECTION AND COMPILATION

4-1. Potomac River Basin and Watersheds Used in Study

The Potomac River Basin (Army Corps of Engineers, August, 1979), located in the Mid-Atlantic Coastal Region of the United States, drains the eastern slopes of the Appalachian Highlands and the Atlantic Coastal Plain. The total drainage area of the river and its tributaries is approximately 14,670 square miles, encompassing 5,720 square miles in Virginia, 3,820 square miles in Marland, 3,490 square miles in West Virginia, 1,570 square miles in Pennsylvania, and the entire District of Columbia - 70 square miles. The basin is spread out over three major physiographic provinces: The Appalachian (composed of the Allegheny Plateau, the Ridge and Valley, and the Blue Ridge), the Piedmont, and the Coastal Plain Province. The basin location map is shown in Fig. 4-1.

The Potomac River Basin has a generally temperate climate with a mean annual temperature range from 51° F to 59° F. Precipitation is seasonally well distributed and abundant. The mean annual precipitation is about 42 inches. The average annual precipitation in the Piedmont province is about 40 inches.

Average annual runoff in the basin is about 18 inches. The months of greatest runoff are March and April, while the months of minimum runoff are usually August and September. Flow characteristics of the basin streams are related to the subbasin location and topography. The flow in the small mountain streams varies from zero during drought conditions to flood stage magnitudes during periods of short, intense rainfall. Throughout the basin, the average streamflow rate ranges from 0.7 cfs per square mile on the small tributariesto almost 2 cfs per square mile along the North Branch of the Potomac. Along the main stem of the river, the average streamflow rate is approximately 1 cfs per square mile. As a result of topographic differences and the distribution of average annual rainfall, more sustained flows are observed in the streams that discharge into the Potomac River from the Maryland side than those which discharge from the Virginia side.

The baseflow during drought periods, is not a guaranteed value for the Potomac River, due to the lack of natural or man-made water storage areas. Minimum daily flow rates throughout the basin range from 0 cfs per square mile during drought conditions on the small tributary streams, to 0.05 cfs per square mile along the main stem of the Potomac. Flood-producing storms occur in all seasons of the year in the basin. Those floods that occur during the summer and fall months are often related to tropical disturbances and bring with them intense but short periods of rainfall. These tropical disturbances usually affect only a part of the basin at a time. Winter and spring floods tend to be more widespread in nature. The sustained rainfall that occurs during the summer and fall seasons and the arrangement of sub-basins are such that tributary flood peaks often tend to synchronize and accentuate downstream flood flows.

The majority of the Potomac River Basin is included in the Ridge and Valley Province, which extends from the Allegheny to the Blue Ridge Mountains. This Province is composed of intensely folded and, in many cases, faulted sedimentary rocks. The eastern portion of the Province is a broad limestone valley collectively called the Great Valley (Shenandoah Valley) in Virginia and Maryland and the Cumberland Valley in Pennsylvania. The western portion of the Province is primarily composed of narrow ridges and valleys with shales evident in the valleys and sandstones generally forming the ridges. Rocks within the Piedmont Plateau Province are relatively resistant metamorphic schists and gneisses of Precambrain age (600 million years or older). On the uplands, these rocks are deeply weathered. At depth, these rocks are massive and highly resistant, and can be found in the stream and river valleys, such as Rock Creek and the Potomac River, where they have been stripped of cover by erosion.

In general, groundwater available in the Potomac Basin is of relatively good quality and of adequate quantity (Sinnott, 1978), although the surface water quality has degenerated due to pollutants. The further downstream one goes the greater the concentration of pollutants. For example, the sediment production from the District of Columbia area is 1,000 to 1,800 tons/square mile, an order of magnitude larger than that of upstream locations.

Seven small watersheds were picked for this study. Their areas and locations are shown in Table 4-1 and Fig. 4-2. The watersheds belong to the Piedmont Province of the Potomac River Basin and encompass five counties: Montgomery in Maryland; Loudoun, Fairfax, Fauquier, and Prince William in Virginia. Three of these watersheds, numbers 56650, 56960, and 56725, belong to the Occoquan subwatershed.

From the above description regarding the Potomac River Basin, it is understood that all seven watersheds are located in the same Piedmont Province and hence possess approximately the same characteristics, such as climate, geology, hydrology, and topography. In other words, the similarity criteria has been met, which is required in the synthetic process.

4-2. Streamflow and Suspended Sediment Data

Although a considerable amount of streamflow data is recorded throughout the country and collected by the U.S. Geological Survey, only a relatively small number of watersheds are monitored for suspended sediment on an hourly basis or less during the entire duration of a storm event.

Two basic types of sediment records, daily and periodic, are officially published by the USGS in the form of water supply papers. Due to the fact that periodic data are normally not taken at frequent intervals and are insufficient to provide a data base for the purpose of formulating the proposed model, and daily data is unsatisfactory in determining the peak time of hydrographs and sedimentgraphs, it was decided that data on an hourly basis would have to be used. Hourly data is not published officially or on a regular basis by the USGS, but can be requested through the USGS district offices. This is the manner in which the data have been collected in this study. It is a lengthy process in acquiring this type of data since the staff members in district offices have to search their old files in warehouses with great effort, particularly for the record period prior to 1965 when the automatic instruments were not in use.

As a standard procedure, depth-integrated suspended sediment samples were collected daily by the USGS if a sampling program was established for the gaging station. The particle sizes of the sediment range from 0.002 mm to 1.0 mm. During storm periods, samples were generally taken several times a day, in some instances, hourly. Unfortunately, some heavy storms made it impossible to take data manually in the field. Also, the time intervals of sampling for different storm events were not the same. This leads to the requirement for a set of rating curves of water stage, streamflow, and sediment concentration. Fortunately, most of the gaging stations operated by the USGS record water stage every 15 minutes using either a recording chart or an automatic recording machine. Therefore, total streamflow hydrographs and total sediment concentration graphs of storm events can be re-constructed by means of these rating curves. The direct sedimentgraphs can then be derived by employing a base sediment separation procedure as discussed in section 3-2.

4-3. Rainfall Records and Watershed Parameters

Hourly rainfall data for each of the storm events of the selected watersheds were requested from the Virginia Water Resources Research Center at Blacksburg, Virginia through the Hydrologic Information Storage and Retrieval System. (HISARS)

The U.S. National Weather Service has established recording and non-recording rainfall networks throughout the country. The hourly rainfall station belongs to the category of recording gages. Since the network of recording gages in the Piedmont Province of the lower Potomac River Basin is not very dense, one station must take care of several small watersheds. In this study, station no. 18-0700 at Beltsville, MD. was used for watershed 50085, station no. 44-8906 at Washington National WSCMO AP was used for watersheds 44291, 44295, and 45784. Station no. 44-8396 at The

Plains 2 NNE was used for watersheds 56650, 56960, and 56725.

Of the many parameters that can be used to describe the characteristics of a watershed, only one soil parameter and four parameters were carefully selected in this study. The four geomorphic parameters were: watershed area (A), main channel lenth (L), main channel slope (S), and mean basin elevation (E). These data are normally provided in professional papers published by the USGS. For some of the watersheds, the data were directly measured from pertinent topographic maps. The soil parameter, i.e. soil erodibility factor (K), values for most of the watersheds were provided by soil scientists of the various state's Soil Conservation Service offices. For some of the watersheds, they were simply determined from the pertinent soil survey maps. The geomorphic parameters and soil erodibility factors for the watersheds studied are listed in Table 4-2.

4-4. Data Compilation

Both the hourly stream flow and the houly sediment concentration data were required for this study. It was also required that watershed areas be small and that rainfall be recorded during the storm events when the streamflows and sediment concentrations were measured. The most important criterion of selecting records from the various watersheds is that all watersheds must satisfy the principle of similarity as described in section 3-3. Much effort has been put into data collection during the course of this research. Finally after the screening, only seven small watersheds in the lower Potomac River Basin in Northern Virginia and Maryland meet the above requirements.

For each watershed, about 12 storm events on an hourly basis occurring evenly throughout a calendar year have been selected. For each event both a direct streamflow hydrograph and a direct sedimentgraph were generated. Integrating the area under these hydrographs, the effective runoff ER and consequently effective sediment yield ES were obtained. Table 4-3 gives all the ES and ER values and their logarithmic values for storm events selected in the seven watersheds. The log-transformed relationship between ER-ES and ESR-ERR are shown in Figs. 4-3 and 4-4. These two figures illustrate the more or less parallel loci, which are determined by their intercepts and slopes. For Fig. 4-3, the data points are shown in the same figure. For Fig. 4-4, since the data points are too numerous to give a clear picture, their loci and data points are plotted separately in Fig. 4-5 to Fig. 4-11.

CHAPTER V

PROCEDURES OF MODEL ANALYSIS

5-1. Regression Analysis and Computation of Average USG

By using the calculated ES and ER values, regression analyses were run to determine coefficients a and b for each watershed. These coefficients are the intercepts and slopes of the log-transformed linear equation $\log(ES) = \log(a) + b \log(ER)$ or $ES = a\,(ER)^b$. Similarly, coefficients α and β were found for the log-transformed linear equation $\log(ESR) = \log(\alpha) + \beta \log(ERR)$ or $ESR = \alpha(ERR)^{\beta}$ of which ESR is the effective sediment yield rate and ERR is the effective runoff rate. The coefficients for the seven watersheds were summarized in Table 5-1.

Although about 12 events for each watershed have been used to generate direct sedimentgraphs, only a few one hour USG's were obtained due to the fact that only a few events have one hour effective rainfall. Table 5-2 listed all the one hour USG's with their three key parameters and the average USG of each watershed. The average USG of each watershed is the representative USG of that watershed. The seven USG's of the seven watersheds of the lower Potomac River Basin were then averaged again to give the representative USG of the region. Subsquently, the regional USG was sketched to conform with the shape of the seven USG's, passing through the computed average peak, and having the required unit volume. Figs. 5-1-5-6 give the averaged dimensional and dimensionless unit sedimentgraphs for the region. The three sets of graphs represent different data used in deriving the USG's.

5-2. Procedures to Synthesize Sedimentgraphs

As mentioned earlier in section 4-3 , many parameters can be used to describe the characteristics of a watershed such as area, main channel length, main channel slope, mean basin elevation, forest area, detention storage area, soil erodibility factor, land use factor and so forth. The forest area depends on whole watershed area and thus should not be considered again. Some watersheds have no detention storage at all, so it is not a good parameter either. As to land use factor, whether one picks C or P as used in the Universal Soil Loss Equation, it changes from season to season and therefore does not display stable charasteristics. Finally, only four geomorphic parameters and soil erodibility factor were selected as independent variables to run regression analyses. Using the three key parameters of a unit sedimentgraph as the dependent variables, it was found that the dependent variables were linearly related with the independent variables significantly and took the form of:

$$\left.\begin{array}{l} t_{sp} \\ q_{sp} \\ T_s \end{array}\right\} = f\ (A,\ L,\ S,\ E,\ K) \qquad \begin{array}{r} (5\text{-}1) \\ (5\text{-}2) \\ (5\text{-}3) \end{array}$$

If the regional dimensionless unit sedimentgraph has been derived, the multiple linear regression equations can be applied to synthesize the unit sedimentgraph for a specific watershed. In other words, the key parameters of t_{sp}, q_{sp} and T_s for a specific watershed can be evaluated through equations (5-1) to (5-3). By multiplying q_{sp} by the ordinates and T_s by the abscissa of the dimensionless unit sedimentgraph, the synthetic unit sedimentgraph of that specific watershed can be obtained. The multiple linear regression equations are derived by using the Statistical Analysis System (SAS) package which is based on modern regressional techniques (Neter and Wasserman, 1974; Walpole and Myer , 1978; SAS , 1979; Draper and Smith, 1981). Major steps of the techniques involved are:

(1) Examinating R-square values and Mallow's C_p values to choose a possible best model from the five independent variables. R-square values indicate the correlation between dependent and independent variables. C_p values measure the biasedness of the regression model.

(2) Performing multiple linear regression analysis to check model significance (F distribution), interval of confidence limit, PRESS statistic which tells the predicting ability of the model, and coefficient of variation.

(3) Selecting the regression equation which is supposed to give the best predicting result based on the highest R-square value, the low C_p value about equal to the number

of regression coefficients, the smallest PRESS value, the smallest coefficient of variation, the narrowest interval of confidence limit, and the most significant F distribution.

(4) Performing multicollinearity diagnostics to the selected regression equation from step (3) and eliminating multicollinearity by using the principle component approach if it exits.

(5) If multicollinearity does exit, take the equation as the predicting model after elimination of multicollinearity. Otherwise, the equation already selected from step (3) is the best predicting model.

Once the one-hour unit sedimentgraph of a specific watershed is synthesized, the next step is the synthesis of a sedimentgraph based on the synthetic USG. As explained in previous chapters, the sedimentgraph of a storm for a specific watershed can be synthesized by the use of linear and time-invariant principles. The equivalent inputs can be evaluated by using the equation $ESEI = \alpha(ERI)^{\beta}$ borrowed from $ESR = \alpha(ERR)^{\beta}$ as pointed out in section 3-4. In practical computations, however, the ES value is used instead of ESEI. The reason is described as follows. Based on the mass conservation law, the summation of ESEI should be equal to ES (Fig. 3-3). However, for a storm event of one hour duration, ESEI equals ES. Furthermore, for final prediction purposes, there is no actual ES value which can be evaluated from record data and hence $\sum$ESEI=ES cannot be used. But there is an ES-ER relationship dervied from regressional analysis in each watershed. Thus the equation $ES=a(ER)^b$ is used in practical computations for one hour equivalent input ES. This is suitable for temporal verification (see section 6-1 for definition). But for spatial verification (see section 6-1 for definition), since that specific watershed is not included in the ESR-ERR regression analysis, no equation for that watershed is available for use. Although there are many ESR-ERR equations from the watersheds other than that specific one, the problem is which equation i.e., $ESR=\alpha(ERR)^\beta$ or $ESEI=\alpha(ERI)^\beta$, should be used . It is noted from Fig. 4-4 that all the equation loci are more or less parallel to each other but there is no good relationship between ESR and ERR on a regional basis, therefore a method has to be developed. After investigation, it was found that similarity and transposition principles can be applied. That is, the regression equation of a neighboring watershed having similar watershed characteristics can be used to calculate equivalent input ESEI for the watershed in question. But in practical computations, the equation $ES = a(ER)^b$ is still used to evaluate the equivalent input in stead of ESEI. This was the scheme used for model verification for watersheds 50085 and 44295 in Chapter six. A numerical example illustrating the steps in obtaining the actual USG and DSG as well as the synthetic

USG and DSG is included in the Appendix.

5-3. Disadvantages in Using Daily Data for Small Watersheds

As mentioned in section 4-2, daily streamflows and sediment concentrations are published and presented in Water Supply Papers officially and regularly by the USGS, hence, the daily data was used to synthesize the unit sedimentgraph and sedimentgraph during the early stages of this study.

Daily data can be easily acquired. Since both mean streamflow and sediment concentration are time-weighted mean daily values, the synthetic graphs can accurately simulate the peak discharge of hydrographs and sedimentgraphs as compared to the actual ones. But it is unsatisfactory in determining the peak time of hydrographs and sedimentgraphs. The reasons are:

(1) The daily mean values of hydrographs or sedimentgraphs, no matter how they are plotted, at the midpoint or at the end of the day, are always spaced 24 hours. There is no way to know the actual time that the peak occurs in a day. Since the end of the day is adopted as the plotting position in this study, the following discussion will be limited to this case only. For small watersheds under investigation, the peak time normally occurs in terms of hours from the beginning of the rainfall not in days. Hence in using daily data, when comparing the synthetic USG or DSG with the actual ones, if the peak does not

occur on the same day but instead one day earlier or one day later, then the error in predicting peak time may be out of ± 24 hours range. This error range is larger than the peak time itself which is in hours. Fig. 5-7 shows an example of a storm event that occurred during the period from June 25 to 29, 1978 in watershed number 45784. The peak time error of the USG is 18 hours, but referring to the same event as shown in Fig. 6-7 the peak time error of the USG is only 0.21 hours based on hourly data.

(2) Daily data only gives one point per day, which is insufficient to express the time variations between two successive days. This is a severe problem for small watersheds (Linsley, 1983). Also, the single peaked daily hydrographs or sedimentgraphs may have more than one peak as can be identified in hourly hydrographs or sedimentgraphs. Furthermore, the base time of daily hydrographs or sedimentgraphs are either longer or shorter than they should be as compared to hourly hydrographs or sedimentgraphs. Fig. 5-8 is a typical example of a storm event that occurred during Dec. 7 to Dec. 12, 1974 in watershed no. 45784. It shows the hourly hydrograph having 2 peaks with the base time lasting for 32 hours, although its daily hydrograph not only has one peak but also lasts 5 days.

(3) Further examination of water stage records leads to the

fact that water stage does not change significantly during a one hour period. Hence the hourly streamflow and sediment concentration data are accurate enough to generate the time scales of the hydrographs or sedimentgraphs. Therefore hourly data were finally adopted for small watersheds in this study.

CHAPTER VI

MODEL VERIFICATION

6-1. Spatial and Temporal Verification

In order to test the validity and assess the applicability of the model, model verification is important and necessary. Only a verified model can be used for prediction purposes. Two types of verification should be made. One is "spatial" and the other is "temporal". For spatial verification, events of a specific watershed are verified through the model which has been developed based on records from all the available watersheds except the "specific" one in the region. In other words, the specific watershed is located within the region, but its storm records are not used in the model development. For temporal verification, events are verified through the model which has been developed based on records from all the available watersheds in the region. But the events to be verified are not included in the model development. Therefore, in the model development stage, some randomly selected events to be verified shall be saved for later verification purpose.

6-2. Results of Model Verification

In this study, both types of verification have been carried out. For each type of verification, two kinds of comparison have been made for each event. The first kind of comparison was made for a unit sedimentgraph, the second kind of comparison was made for a direct sedimentgraph. The comparison results made for the direct sedimentgraph also reflect the scheme used (section 5-2) by adopting the ES-ER relationship to evaluate the equivalent one hour input.

For spatial verification, two events occurring on July 29, 1967 and June 19, 1968 in watershed 50085 were selected. The comparisons are shown in Tables 6-1 and 6-2, and Figs. 6-1 to 6-4. Another event occurring on May 12, 1974 in watershed 44295 was selected for spatial verification. The comparison is shown in Table 6-3 and Figs. 6-5 and 6-6. The derived dimensionless USG's used for synthesis in spatial verification are both based on data from 6 watersheds in the same region. For temporal verification, two events occurring on June 21, 1978 and June 27, 1978 in watershed 45784 were used. The comparison is shown in Tables 6-4 and 6-5 and Figs. 6-7 to 6-10. The dimensionless USG was derived based on 7 storm events occurring in this watershed.

The reason of selecting watersheds 50085 and 44295 for spatial verification is that both possess similar watershed characteristics as pointed out in section 5-2. Thus, equation $ES = 13.6606(ER)^{2.7683}$ which was derived from watershed 44295 was used for predicting the sedimentgraph in watershed 50085 and equation $ES = 9.5385(ER)^{2.3609}$ which was derivedfrom watershed 50085 was used for watershed 44295. As for the temporal verification, theoretically speaking, equations derived from any one of the 7 watersheds may be used for verification of storm events in the corresponding watershed. Since only watershed 45784 had extra events that were not used for model development, so this watershed was used for temporal verification.

The regression equations and the computed q_{sp}, T_s, ES values used for spatial and temporal verification in watersheds 50085, 44295, and 45784 are summarized as follows. t_{sp} is not required in plotting the USG and DSG and therefore is not shown.

watershed 50085

$$q_{sp} = -2.6845 + 0.0005\ A + 0.009\ L + 0.009\ E + 5.3285\ K = 0.5385\ (1/hr) \qquad (6\text{-}1)$$

$$T_s = 513.2645 - 0.8772\ L - 0.7449\ E - 1074.7038\ K = 25.68\ (hrs) \qquad (6\text{-}2)$$

$$\begin{aligned} ES &= 13.6606\,(ER)^{2.7683} \\ &= 13.6606(0.441)^{2.7683} \\ &= 1.4163\ \text{(metric tons)---event 7/29/67} \end{aligned} \qquad (6\text{-}3)$$

$$\begin{aligned} ES &= 13.6606\,(ER)^{2.7683} \\ &= 13.6606(1.112)^{2.7683} \\ &= 18.327\ \text{(metric tons)---event 6/19/68} \end{aligned} \qquad (6\text{-}4)$$

watershed 44295

$$q_{sp} = -3.0486 + 0.0006\ A + 0.0102\ L + 0.0081\ E + 6.6172\ K = 0.4582\ (1/hr) \qquad (6\text{-}5)$$

$$T_s = 385.582 + 0.9872\ L - 0.6538\ E + 0.581\ S - 808.2\ K = 15.83\ (hrs) \qquad (6\text{-}6)$$

$$\begin{aligned} ES &= 9.5385(ER)^{2.3609} \\ &= 9.5385(1.38)^{2.3609} \\ &= 20.404\ \text{(metric tons)---event 5/12/74} \end{aligned} \qquad (6\text{-}7)$$

watershed 45784

$$q_{sp} = -3.2177 + 0.0007\ A + 0.0128\ L + 0.0016\ S + 0.0083\ E + 6.8942\ K = 0.4776\ (1/hr) \qquad (6\text{-}8)$$

$$T_s = 505.405 - 0.8562\ L - 0.7778\ E - 1043.1972\ K = 14.20\ (hrs) \qquad (6\text{-}9)$$

$$\begin{aligned} ES &= 25.882(ER)^{2.065} \\ &= 25.882(0.967)^{2.065} \\ &= 24.149\ (\text{metric tons})\text{---event } 6/27/78 \end{aligned} \qquad (6\text{-}10)$$

$$\begin{aligned} ES &= 25.882(ER)^{2.065} \\ &= 25.882(0.274)^{2.065} \\ &= 1.786\ (\text{metric tons})\text{---event } 6/21/78 \end{aligned} \qquad (6\text{-}11)$$

6-3. Discussion of Model Verification

It can be seen from Figs. 6-1 through 6-10, that the developed model performed very well in terms of the shapes of the synthetic graphs. For further error analysis, it is necessary to evaluate the absolute relative errors of peaks and peak times of both the USG and DSG. The absolute relative error in percent is calculated by means of the following equation :

$$\begin{array}{l}\text{absolute}\\ \text{relative}\\ \text{error in \%}\end{array} = \left| \frac{\text{actual quantity} - \text{synthetic quantity}}{\text{actual quantity}} \right| \times 100 \qquad \ldots\ldots\ldots\ldots(6\text{-}12)$$

These calculations are shown in Tables 6-6 and 6-7. It is noted that the errors of the USG peak times are the same as the DSG peak times. But the errors of USG peaks are less than DSG peaks. This is because synthetic DSG's are subject to one more step of convolution which introduces additional error. Recall that the DSG was obtained by employing the equivalent input and the USG. The equivalent one hour inputs are evaluated through the borrowed regression equation $ES=a(ER)^b$. Because regressional equations are not analytic functions, errors are introduced due to convolution. By examining the USG peaks, it was found that the average error of spatial verification is greater than the average error of temporal verification. But referring to the USG peak times, it is just the opposite, the average error of spatial verification is less than the average error of temporal verification. The same situation holds true for the DSG. Overall speaking, the errors of spatial verification are about the same as temporal verification.

CHAPTER VII

CONCLUSIONS AND FUTURE RESEARCH

7-1. Conclusions

Sediment transport plays one of the major roles in both hydraulic and hydrologic modeling of a watershed. The sedimentgraph is a time history of sediment transport during a storm at a given location. A unit sedimentgraph, similar to a unit hydrograph in concept, represents one unit of sediment yield from a watershed just the same as one unit of direct runoff corresponds to a unit hydrograph. Therefore, once the unit sedimentgraph (USG) for a specific watershed has been derived, the direct sedimentgraph (DSG) of any storm event can be obtained.

Although the same basic assumptions of linear and time-invariant principles as applied to the unit hydrograph are adopted in the development of unit sedimentgraph in this study, a new method of deriving inputs to the unit sedimentgraph has been developed. The inputs are called effective sediment erosion intensities (ESEI) which are the counterpart of the effective rainfall intensities in the process of producing hydrographs.

Generally speaking, unit sedimentgraphs can be derived only if gaged streamflow and sediment records are available. Since only a relatively small number of watersheds are gaged, some means of deriving unit sedimentgraphs for ungaged watersheds are necessary. In this study, a correlation analysis was performed for dependent variables of three unit sedimentgraph parameters (peak, peak time, and base time) as functions of five watershed characteristic parameters (area, main channel length, main channel slope, mean basin elevation, and soil erodibility factor). Based on the results of correlation, it was feasible to synthesize the unit sedimentgraph for a particular watershed of interest. However, the developed synthetic model required the use of hourly data for streamflow and sediment concentration in small watersheds rather than daily data.

In order to test the validity and assess the applicibility of the model, both "spatial" and "temporal" verifications have been carried out. Good results were obtained when the synthetic graphs are compared with the actual graphs. A numerical example is given in the Appendix to illustrate the computational steps in obtaining the actual USG and DSG as well as the synthetic USG and DSG. Derivation of a one-hour USG is demonstrated in this study. The same methodology and procedures can be extended to generate USG's other than the one hour USG.

From this study the following highlights can be drawn:

(1) Application of systems approach in developing synthetic sedimentgraphs has been proven to be successful and worthy of devoting further effort in model refinement.

(2) The predictive capabilities provided by the developed

model are very promising in providing a direct sedimentgraph for the study of sediment yield, sediment basin design, and non-point source pollutant transport.

(3) A precise definition regarding the unit sedimentgraph has been given. Once the USG has been constructed, the sedimentgraph of a storm for a specific watershed can be synthesized provided that rainfall patterns of the event as well as watershed geomorphic and soil erodibility parameters are known.

(4) From this study, it has been shown that errors generated by comparing synthetic graphs with actual graphs are more or less the same for spatial and temporal verification.

(5) An examination of the data suggests that predictive capabilities of the sedimentgraph can be improved if the quality of the field measurement is improved in terms of smaller sampling time interval.

(6) Continuing effort is needed in the verification work for other watersheds in the future.

7-2. Future Research

A synthetic model to derive a sedimentgraph based on a linear and time-invariant system has been developed. The one-hour unit sedimentgraph under study has homogeneous dimensions and therefore is theoretically sound. From the results of model verification, it is clear that the developed model performs well and can be used for prediction purposes, either spatially or temporally. However, in this research, only the Potomac River Basin was used. More watersheds and more events of each watershed from different basins should be examined in the future to further test the proposed model. Also, at the present time the developed model is limited to a one-hour USG and a one pulse superposition only. Should the ϕ-index method be improved for the computation of the effective rainfall intensity, the application would be enlarged to include more than just one-hour USG and to give multiple pulse superpositions. Other approaches for calculating effective rainfall intensities would be evaluated if watershed infiltration data could be obtained.

Regression analysis techniques have been extensively used as a tool in this study. For future studies, updated regression techniques, if any, should be used. It should be noted here that no matter how fancy the regression techniques may be in the future, no precise estimation of sediment yields can be made. This is because regressional equations are not analytic functions.

As mentioned in section 3-4, ESEI values are not recorded in the field. Hence, for the time being, ESEI are evaluated by using the borrowed regression equation from the ESR-ERR relationship, which gives a satisfactory approximation. Nevertheless, the author strongly believes that some kind of measuring device can be developed in the future so that the sediment erosion intensities due to different pulses of rainfall intensities can be directly measured in the field. Thus the error involved in the evaluation of ESEI by using the regression equation can be eliminated.

Finally, an important point concerning the direction for future research is worth noting here. Referring to section 5-2 and Figs. 4-3 to 4-4 that there is no regional relationship between ES-ER and ESR-ERR or ESEI-ERI, therefore the regression equation of a neighboring watershed having similar watershed characteristics was used to evaluate the ESEI values. In practical computations for one hour equivalent input, ES was used for ESEI. The basis for doing this relys on the principles of similarity and transposition. On the other hand, the USG being used was synthesized from an averaged dimensionless USG which is obtained on a regional basis. Is this "regional basis" a necessary requirement? In other words can the principles of similarity and transposition also be applied to a synthetic USG borrowed from neighboring watershed directly? The answer is most likely affirmative, but further study is needed.

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Appendix--Background Information and Problem Development.
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APPENDIX

Numerical Example

This example illustrates the steps in obtaining the actual USG and DSG as well as the synthetic USG and DSG. The storm event occurred from June 27 to 28 of 1978 in watershed 45784.

I. The computational steps to derive the actual USG and DSG are:

(1) Separate baseflow from total runoff and evaluate the volume under the direct runoff hydrograph. The calculated ER of 0.967 cm is plotted in Fig. A.

(2) Separate baseflow sediment concentration from total sediment concentration and evaluate the direct sediment discharge in m.tons/day by using the following equation:

$$SD_i=(ST_i*QT_i - SB_i*QB_i)*0.0864$$

The volume under the direct sedimentgraph is ES= 15.584 m.t. These results are plotted in Fig. B and Fig. C.

(3) Evaluate ϕ- index (see Fig. D)

effective runoff = 0.967 cm

$$\text{basin recharge} = (1.626 + 0.025 + 0.025) - 0.967$$
$$= 1.676 - 0.967 = 0.709 \text{ cm}$$

$$\phi_1 = 0.709/3 = 0.236 \text{ cm/hr}$$

$$\text{modified } \phi\text{-index} : \phi_2 = 0.709-(0.025 + 0.025)/1$$
$$= 0.659 \text{ cm/hr}$$

check : effective runoff =1.626 - 0.659= 0.967 cm O.K.

(4) From Fig. D, it can be seen that the effective rainfall only lasts one hour with a depth of 0.967 cm, hence the last two columns of Table A are referred to as actual one-hour DSG and USG.

II. The computational steps to derive the synthetic USG and DSG are:

(1) Substitute the one-hour effective rainfall 0.967 cm into the equation $ES=25.882(ER)^{2.065}$, which is the ES-ER regressional relationship obtained from watershed 45784, and get ES=24.149 m.ton.

(2) The geomorphic parameters and erodibility factor of watershed 45784 are : A = 2.046, L = 6.035, S = 10.160, E = 121.951, K = 0.375. Substituting these values into the equations $q_{sp}= -3.2177+0.0007A+0.0128\ L+0.0016\ S +0.0083\ E+6.8942\ K$ and $T_s= 505.405-0.8562\ L-0.7778\ E -1043.1972\ K$; the regression equations derived from the 7 watersheds including 45784, resulting in q_{sp} and T_s of 0.4776 (1/hr) and 14.20 (hr) respectively.

(3) Multiply q_{sp} by the ordinates and T_s by the abscissa of the one-hour dimensionless USG based on 7 watersheds including 45784 (i.e. Fig. 5-6), the one-hour synthetic USG is obtained.

(4) From step (1), the one-hour ESEI equals ES and is 24.149 m.ton. Superimposing 24.149 m.ton to the one-hour synthetic USG, the synthetic DSG isobtained. The results are shown in Table 6-4 and in Figs. 6-7 and 6-9.

Table 4-1. The area and location of the watersheds in the lower Potomac River Basin

Watershed Number	State and Name	Area (mi)	Location Description	Classified Basin
50085	Nursery Run at Cloverly, MD.	0.35	Lat 39 07'05",long 77 00'24", Montgomery County, at gaging station 300 ft upstream from culvert on Bryants Nursery Rd. 350 ft upstream from confluence with Browns Creek, 0.8 mile northwest of Cloverly, and 2.4 mile southeast of Sandy Spring.	Potomac River Basin
45784	Snakeden Branch at Reston, VA.	0.79	Lat 38 55'48", long 77 20'43", Fairfax County, Hydrologic Unit 02070008, on right bank at upstream side of culvert on Soapstone Drive, 1.1 mi. upstream from Lake Elsa Dam, and 1.7 mi south of Sunset Hills in Reston.	Potomac River Basin
44291	Stave Run Near Reston, VA.	0.08	Lat 38 56'56", long 77 22'16", Fairfax County, at gaging station on left bank 0.31 mile upstream from mouth and 1.4 mile southwest of Sunset Hills in Reston.	Potomac River Basin
44295	Similar Branch at Reston, VA.	0.32	Lat 38 57'10", long 77 22'04", Fairfax County at gaging station on right bank 100 ft upstream from Dulles Airport Rd. etc.	Potomac River Basin

Table 4-1. (continued)

56650	Broad Run Near Bristow, VA.	89.58	Lat 38 44'56", long 77 33'50", Prince William County, Hydrologic Unit 02070010, on left bank 50 ft downstream from bridge on State Hy. 619, 2.3 mi northwest of Briston.	Potomac River Basin
56960	Cub Run Near Johnsons Corner, VA.	49.81	Lat 38 48', long 77 28', Fairfax County, about 4 miles southwest of Centreville.	Potomac River Basin
56725	Bull Run Near Conklin, VA.	25.79	Lat 38 50', long 77 33', Loudoun County, about 4 miles south of Conklin.	Potomac River Basin

Table 4-2. The geomorphic parameters and soil erodibility factors of watersheds studied

Watershed Number	Location State	Area A(km)	Main Channel Length L(km)	Main Channel Slope S(m/km)	Mean Basin Ele. E (m)	Soil Factor K
50085	MD.	0.9065	1.7703	24.6220	147.5203	0.350
44291	VA.	0.2072	0.5633	31.5540	121.9200	0.375
44295	VA.	0.8288	1.2875	23.6750	124.9680	0.375
45784	VA.	2.0460	6.0350	10.1600	121.9512	0.375
56960	VA.	129.0000	20.9214	5.0000	83.8200	0.320
56725	VA.	66.8000	11.2654	10.0000	88.3920	0.340
56650	VA.	232.0000	10.0000	10.0000	85.4500	0.330

Table 4-3. The ER and ES values and their logarithmic values of storm events selected from seven watersheds

Watershed Number	Location State	Event Date	ER (cm)	ES (m.t.)	log ER (cm)	log ES (m.t.)
50085	MD.	03/06/67	1.706	17.952	0.232	1.254
		05/06/67	0.616	1.700	-0.210	0.231
		06/22/67	0.457	2.850	-0.340	0.455
		07/29/67	0.441	2.435	-0.356	0.386
		08/04/67	0.526	6.522	-0.279	0.814
		10/10/67	0.079	0.022	-1.104	-1.664
		11/02/67	0.181	0.145	-0.741	-0.839
		12/10/67	0.408	0.719	-0.390	-0.143
		01/14/68	1.719	18.170	0.235	1.259
		05/27/68	0.514	0.947	-0.289	-0.023
		06/19/68	1.112	13.574	0.046	1.133
		12/14/68	0.138	0.064	-0.859	-1.195
44291	VA.	01/04/72	0.148	0.551	-0.831	-0.259
		02/12/72	1.063	13.187	0.027	1.120
		03/16/72	1.282	43.981	0.108	1.643
		04/22/72	0.707	5.696	-0.151	0.756
		05/03/72	1.279	61.128	0.107	1.786
		10/06/72	0.299	1.804	-0.524	0.256
		10/28/72	1.492	36.604	0.174	1.564
		11/14/72	1.604	77.471	0.205	1.889
		06/22/73	0.174	4.490	-0.759	0.652
		07/26/73	0.240	5.024	-0.620	0.701
		08/13/73	0.054	0.479	-1.267	-0.320
44295	VA.	03/16/72	1.296	43.697	0.113	1.640
		04/21/72	0.698	10.080	-0.156	1.003
		05/03/72	0.679	21.162	-0.168	1.326
		11/25/72	0.819	9.437	-0.087	0.975
		12/08/72	1.512	73.621	0.179	1.867
		05/27/73	0.846	5.510	-0.073	0.741
		07/20/73	0.445	3.494	-0.351	0.543
		09/13/73	2.110	126.998	0.324	2.104
		01/21/74	0.557	0.921	-0.254	-0.036
		05/12/74	1.380	16.768	0.140	1.224
		12/08/74	0.268	0.353	-0.571	-0.452
		03/14/75	0.983	1.628	-0.008	0.212
45784	VA.	11/09/73	0.125	0.781	-0.107	-0.903
		12/08/73	1.166	30.275	1.481	0.067
		01/01/74	0.099	0.196	-0.709	-1.003
		03/21/74	0.605	8.130	0.910	-0.218
		04/08/74	0.562	4.693	0.671	-0.251

Table 4-3. (continued)

45784	VA.	05/12/74	2.012	77.097	1.887	0.304
		06/15/74	0.714	24.940	1.397	-0.146
		07/10/74	0.149	1.520	0.182	-0.826
		08/04/74	0.680	30.165	1.480	-0.168
		09/06/74	2.247	81.455	1.911	0.352
		10/09/75	0.386	7.210	0.858	-0.413
		02/18/76	0.121	0.030	-1.517	-0.917
56650	VA.	03/23/75	0.647	88.013	-0.189	1.945
		08/30/75	1.753	468.34	0.244	2.671
		01/26/76	2.039	280.77	0.309	2.448
		02/01/76	0.313	20.871	-0.504	1.320
		03/31/76	0.778	208.32	-0.109	2.319
		07/16/76	0.174	20.860	-0.761	1.319
		10/02/76	0.532	61.914	-0.274	1.792
56960	VA.	06/28/75	0.586	61.402	-0.232	1.788
		08/16/75	0.093	14.481	-1.032	1.161
		09/18/75	0.131	4.762	-0.884	0.678
		10/17/75	1.313	204.20	0.118	2.310
		01/03/76	1.243	38.848	0.095	1.589
		03/11/76	0.494	28.757	-0.306	1.459
		05/01/76	0.152	2.400	-0.818	0.380
		10/02/76	0.533	111.65	-0.273	2.048
56725	VA.	07/13/75	0.292	9.330	-0.535	0.970
		07/17/75	0.966	40.170	-0.015	1.604
		10/17/75	2.060	194.78	0.314	2.290
		11/12/75	0.711	19.427	-0.148	1.288
		01/27/76	1.673	186.29	0.224	2.270
		06/18/76	0.110	5.101	-0.961	0.708
		09/16/76	0.216	32.313	-0.665	1.509
		10/22/76	1.240	29.450	0.094	1.469

Table 5-1. Regression and correlation Coefficients of ES-ER and ESR-ERR relationships

Watershed Number	State	Area (km)	a	b	Slope Angle	r	α	β	Slope Angle	R
50085	MD	0.91	9.538	2.361	67	0.952	2.906	1.433	55	0.941
44291	VA	0.21	22.627	1.448	55	0.924	2.500	0.971	44	0.765
44295	VA	0.83	13.661	2.768	70	0.845	2.700	1.169	49.5	0.796
45784	VA	2.05	25.882	2.065	64	0.934	4.066	1.192	50	0.889
56650	VA	232.	170.498	1.330	53	0.941	5.228	0.495	32	0.616
56960	VA	129.	84.574	1.203	50	0.806	6.765	0.719	36	0.800
56725	VA	66.8	53.730	1.024	46	0.842	4.555	0.711	35	0.869

Remarks: $ES = a * ER^{b}$

$ESR = \alpha * ERR^{\beta}$

r = correlation coefficient of ES-ER relationship.

R = correlation coefficient of ESR-ERR relationship.

Table 5-2. Individual and average one hour USG with their three key parameters

Watershed Number	State	Area (km)	1-hr USG events	t_{sp} (hr)	ave.	q_{sp} (1/hr)	ave.	T_s (hr)	ave.
50085	MD	0.91	07/29/67	2	2	0.473	0.486	24	24
			06/19/68	2		0.498		24	
44291	VA	0.21	07/26/73	.5	.5	0.448	0.444	16	17
			08/13/73	.5		0.439		18	
44295	VA	0.83	05/12/74	1	1	0.453	0.453	17	17
45784	VA	2.05	11/09/73	1	1	0.472	0.481	16	15
			08/04/74	1		0.490		14	
56650	VA	232.	10/02/76	8	12	0.064	0.069	72	87
			03/31/76	14		0.075		94	
56960	VA	129.	06/28/75	7	8.5	0.055	0.048	72	88
			09/18/75	10		0.041		104	
56725	VA	66.8	11/12/75	6	4	0.078	0.068	72	72
			06/18/76	2		0.058		72	
average:					4.14		0.293		47.29
average with #50085 excluded:					4.50		0.261		51.17
average with #44295 excluded:					4.70		0.266		50.51

Table 6-1. USG and DSG spatial verifications for the event occurred on 7/29/67 in watershed 50085

Dimensionless USG		Synthetic USG		Actual USG		Synthetic DSG (ES=1.4163)		Actual DSG	
t_s/T_s	q_s/q_{sp}	t_s	q_s	t_s	q_s	t_s	Q_s	t_s	Q_s
0.000	0.000	0.0	0.000	0	0.000	0.0	0.000	0	0.000
0.039	0.192	1.0	0.103	2	0.473	1.0	0.146	2	1.200
0.088	1.000	2.3	0.539	4	0.0244	2.3	0.763	4	0.059
0.118	0.613	3.0	0.330	6	0.0014	3.0	0.467	6	0.0034
0.157	0.046	4.0	0.025	8	0.00043	4.0	0.035	8	0.0010
0.196	0.027	5.0	0.014	10	0.00025	5.0	0.020	10	0.0006
0.314	0.023	8.1	0.012	12	0.00014	8.1	0.017	12	0.0004
0.431	0.019	11.1	0.010	14	0.00010	11.1	0.014	14	0.0003
0.549	0.015	14.1	0.008	16	0.00008	14.1	0.011	16	0.0002
0.667	0.012	17.1	0.006	18	0.00006	17.1	0.008	18	0.00015
0.784	0.010	20.1	0.005	20	0.00004	20.1	0.007	20	0.00008
0.902	0.008	23.2	0.004	22	0.00003	23.2	0.006	22	0.00007
1.000	0.000	25.7	0.000	24	0.00000	25.7	0.000	24	0.00000

Remarks: (1) The dimensionless USG used in this Table is the averaged one based on data from 6 watersheds (50085 excluded)

(2) $q_{sp} = -2.6845 + 0.0005\ A + 0.0091\ L + 0.0091\ E + 5.3258\ K = 0.5385$ (1/hr)

$T_s = 513.2645 - 0.8772\ L - 0.7449\ E - 1074.7038\ K = 25.68$ (hrs)

$ES = 13.6606\ (0.441)^{2.7683} = 1.4163$ (metric tons)

Table 6-2. USG and DSG spatial verifications for the event occurred on 6/19/68 in watershed 50085

Dimensionless USG		Snythetic USG		Actual USG		Synthetic DSG (ES=18.327)		Actual DSG	
t_s/T_s	q_s/q_{sp}	t_s	q_s	t_s	q_{sp}	t_s	Q_s	t_s	Q_s
0.000	0.000	0.0	0.000	0	0.000	0.0	0.000	0	0.000
0.039	0.192	1.0	0.103	2	0.498	1.0	1.888	2	6.719
0.088	1.000	2.3	0.539	4	0.0013	2.3	9.878	4	0.053
0.118	0.613	3.0	0.330	6	0.0002	3.0	6.048	6	0.0068
0.157	0.046	4.0	0.025	8	0.00008	4.0	0.458	8	0.0031
0.196	0.027	5.0	0.014	10	0.00005	5.0	0.257	10	0.0020
0.314	0.023	8.1	0.012	12	0.000035	8.1	0.220	12	0.0014
0.431	0.019	11.1	0.010	14	0.000024	11.1	0.183	14	0.0010
0.549	0.015	14.1	0.008	16	0.000018	14.1	0.147	16	0.0007
0.667	0.012	17.1	0.006	18	0.000010	17.1	0.110	18	0.0004
0.784	0.010	20.1	0.005	20	0.000008	20.1	0.092	20	0.0003
0.902	0.008	23.2	0.004	22	0.000005	23.2	0.073	22	0.0002
1.000	0.000	25.7	0.000	24	0.000000	25.7	0.000	24	0.0000

Remarks: (1) The dimensionless USG used in this Table is the averaged one based on data from 6 watersheds (50085 excluded)

(2) q_{sp} = -2.6845+ 0.0005 A+ 0.0091 L+ 0.0091 E+ 5.3285 K = 0.5385(1/hr)

T_s = 513.2645- 0.8772 L- 0.7449 E- 1074.7038 K = 25.68(hrs)

ES = $13.6606\ (1.112)^{2.7683}$ = 18.327(metric tons)

Table 6-3. USG and DSG spatial verifications for the event occurred on 5/12/74 in watershed 44295

Dimensionless USG		Synthetic USG		Actual USG		Synthetic DSG (ES=20.404)		Actual DSG	
t_s/T_s	q_s/q_{sp}	t_s	q_s	t_s	q_s	ts	Qs	ts	Qs
0.000	0.000	0.0	0.000	0	0.000	0.0	0.000	0	0.000
0.039	0.188	0.62	0.086	1	0.453	0.62	1.758	1	7.580
0.092	1.000	1.46	0.458	2	0.023	1.46	9.345	2	0.390
0.118	0.602	1.87	0.276	4	0.012	1.87	5.632	4	0.190
0.157	0.045	2.49	0.021	6	0.0049	2.49	0.428	6	0.080
0.196	0.026	3.10	0.012	8	0.0026	3.10	0.245	8	0.040
0.314	0.019	4.97	0.009	10	0.0018	4.97	0.018	10	0.030
0.431	0.015	6.82	0.007	12	0.0013	6.82	0.143	12	0.020
0.549	0.011	8.69	0.005	14	0.0009	8.69	0.102	14	0.018
0.667	0.009	10.56	0.004	16	0.0008	10.56	0.082	16	0.010
0.784	0.008	12.41	0.003	18	0.0005	12.41	0.061	18	0.008
0.902	0.004	14.28	0.002	20	0.0003	14.28	0.041	20	0.005
1.000	0.000	15.83	0.000	22	0.0000	15.83	0.000	22	0.000

Remarks: (1) The dimensionless USG used in this Table is the averaged one based on data from 6 watersheds (44295 excluded)

(2) $q_{sp} = -3.0486 + 0.0006\ A + 0.0102\ L + 0.0081\ E + 6.6172\ K = 0.4582$ (1/hr)

$T_s = 385.582 + 0.9872\ L - 0.6538\ E + 0.5810\ S - 808.2\ K = 15.83$ (hrs)

$ES = 9.5385\ (1.380)^{2.3609} = 20.404$ (metric tons)

Table 6-4. USG and DSG temporal verifications for the event occurred on 6/27/78 in watershed 45784

Dimensionless USG		Synthetic USG		Actual USG		Synthetic DSG (ES=24.149)		Actual DSG	
t_s/T_s	q_s/q_{sp}	t_s	q_s	t_s	q_s	t_s	Q_s	t_s	Q_s
0.000	0.000	0.0	0.000	0	0.000	0.0	0.000	0	0.000
0.043	0.172	0.61	0.082	1	0.497	0.61	1.980	1	7.800
0.085	1.000	1.21	0.478	2	0.0014	1.21	11.543	2	0.022
0.127	0.483	1.80	0.231	4	0.00063	1.80	5.578	4	0.010
0.170	0.052	2.41	0.025	6	0.00030	2.41	0.604	6	0.005
0.213	0.031	3.02	0.015	8	0.00014	3.02	0.362	8	0.002
0.340	0.024	4.83	0.012	10	0.00009	4.83	0.290	10	0.0015
0.468	0.021	6.65	0.010	12	0.00004	6.65	0.241	12	0.0006
0.596	0.014	8.46	0.007	14	0.00000	8.46	0.169	14	0.0000
0.723	0.009	10.27	0.004			10.27	0.097		
0.851	0.007	12.08	0.003			12.08	0.072		
1.000	0.000	14.20	0.000			14.20	0.000		

Remarks: (1) The dimensionless USG used in this Table is the averaged one based on data from 7 watersheds (no exclusion)

(2) $q_{sp}=-3.2177+0.0007\ A+0.0128\ L+0.0016\ S+0.0083\ E+6.8942\ K=0.478$ (1/hr)

$t_s = 505.405 - 0.8562\ L - 0.7778\ E - 1043.1972\ K = 14.20$ (hrs)

$ES = 25.882\ (0.967)^{2.065} = 24.149$ (metric tons)

Table 6-5. USG and DSG temporal verifications for the event occurred on 6/21/78 in watershed 45784

Dimensionless USG		Synthetic USG		Actual USG		Synthetic DSG (ES=1.786)		Actual DSG	
t_s/T_s	q_s/q_{sp}	t_s	q_s	t_s	q_s	t_s	Q_s	t_s	Q_s
0.000	0.000	0.0	0.000	0	0.000	0.0	0.000	0	0.000
0.043	0.172	0.61	0.082	2	0.476	0.61	0.146	2	0.690
0.085	1.000	1.21	0.478	4	0.022	1.21	0.854	4	0.031
0.127	0.483	1.80	0.231	6	0.0015	1.80	0.413	6	0.0022
0.170	0.052	2.41	0.025	8	0.0004	2.41	0.045	8	0.00064
0.213	0.031	3.02	0.015	10	0.0000	3.02	0.027	10	0.00000
0.340	0.024	4.83	0.012			4.83	0.021		
0.468	0.021	6.65	0.010			6.65	0.018		
0.596	0.014	8.46	0.007			8.46	0.013		
0.723	0.009	10.27	0.004			10.27	0.007		
0.851	0.007	12.08	0.003			12.08	0.005		
1.000	0.000	14.20	0.000			14.20	0.000		

Remarks: (1) The dimensionless USG used in this Table is the averaged one based on data from 7 watersheds (no exclusion)

(2) $q_{sp} = -3.2177 + 0.0007\ A + 0.0128\ L + 0.0016\ S + 0.0083\ E + 6.8942\ K = 0.478\ (1/hr)$

$$t_s = 505.405 - 0.8562\ L - 0.7778\ E - 1043.1972\ K = 14.20\ (hrs)$$

$$ES = 25.882\ (0.274)^{2.065} = 1.786\ (\text{metric tons})$$

Table 6-6. USG and DSG peak verifications on watersheds 50085, 44295, and 45784 in the Potomac River Basin

Spatial Verification

Watershed Number	Date of Event	USG Peak (1/hr) Synthetic	USG Peak (1/hr) Actual	USG Peak (1/hr) ARE* (%)	DSG Peak (m.t./hr) Synthetic	DSG Peak (m.t./hr) Actual	DSG Peak (m.t./hr) ARE* (%)
50085	7/29/67	0.539	0.473	12.24	0.763	1.200	36.42
	6/19/68	0.539	0.498	7.61	9.878	6.719	31.98
44295	5/12/74	0.458	0.453	1.09	9.345	7.580	18.89

Temporal Verification

Watershed Number	Date of Event	USG Peak (1/hr) Synthetic	USG Peak (1/hr) Actual	USG Peak (1/hr) ARE* (%)	DSG Peak (m.t./hr) Synthetic	DSG Peak (m.t./hr) Actual	DSG Peak (m.t./hr) ARE* (%)
45784	6/21/78	0.478	0.497	3.82	11.543	7.800	32.43
	6/27/78	0.478	0.476	0.42	0.890	0.690	22.47

$$* \ \text{ARE} = \begin{array}{l}\text{Absolute}\\ \text{relative}\\ \text{error in \%}\end{array} = \left| \frac{\text{actual quantity} - \text{synthetic quantity}}{\text{actual quantity}} \right| \times 100$$

Table 6-7. USG and DSG peak time verifications on watersheds 50085,44295, and 45784 in the Potomac River Basin

Spatial Verification

Watershed Number	Date of Event	USG Peak Time (1/hr) Synthetic	Actual	ARE* (%)	DSG Peak Time (m.t./hr) Synthetic	Actual	ARE* (%)
50085	7/29/67	2.3	2.0	13.04	2.3	2.0	13.04
	6/19/68	2.3	2.0	13.04	2.3	2.0	13.04
44295	5/12/74	1.46	1.0	31.51	1.46	1.0	31.51
			Temporal Verification				
45784	6/21/78	1.21	1.0	17.36	1.21	1.0	17.36
	6/27/78	1.21	2.0	39.50	1.21	2.0	39.50

* ARE = Absolute relative error in % = $\left|\frac{\text{actual quantity} - \text{synthetic quantity}}{\text{actual quantity}}\right| \times 100$

Table A. Computation of the actual USG and DSG for the Event Occurred on 6/27/78 in watershed 45784

Event Time M/D/Hr	Total Runoff (cms)	Base Flow (cms)	Direct Runoff (cms)	Direct Runoff (cm/hr)	Total Sediment Con.(ppm)	Baseflow Concent. (ppm)	Direct Sedimentgraph (mt/D)	Direct Sedimentgraph (mt/hr)	U S G (1/hr)
6/27/18	0.020	0.020	0.000	0.000	22	22	0.000	0.0000	0.00000
20	2.564	0.031	2.533	0.446	840	25	186.016	7.8000	0.49700
22	0.125	0.031	0.093	0.016	56	25	0.535	0.0220	0.00140
24	0.088	0.031	0.057	0.010	40	25	0.236	0.0100	0.00060
6/28/02	0.062	0.031	0.031	0.005	35	25	0.121	0.0050	0.00030
04	0.048	0.031	0.017	0.003	29	25	0.053	0.0022	0.00010
06	0.042	0.031	0.011	0.002	28	25	0.035	0.0015	0.00009
08	0.037	0.031	0.006	0.001	26	25	0.015	0.0006	0.00004
10	0.031	0.031	0.000	0.000	25	25	0.000	0.0000	0.00000

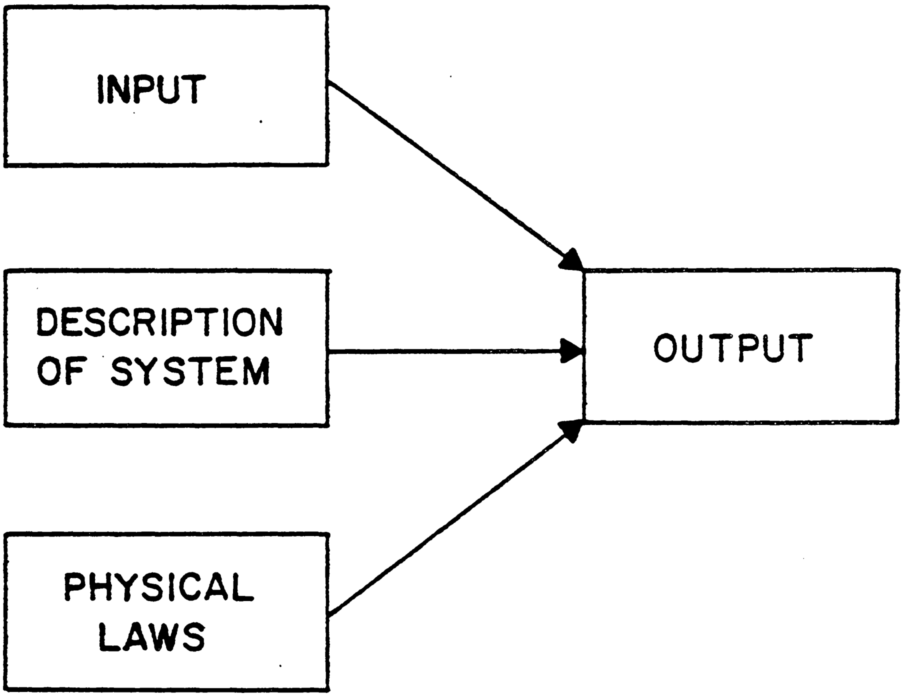


Fig. 2-1. Factors affacting output in the system operation (Dooge, 1973)

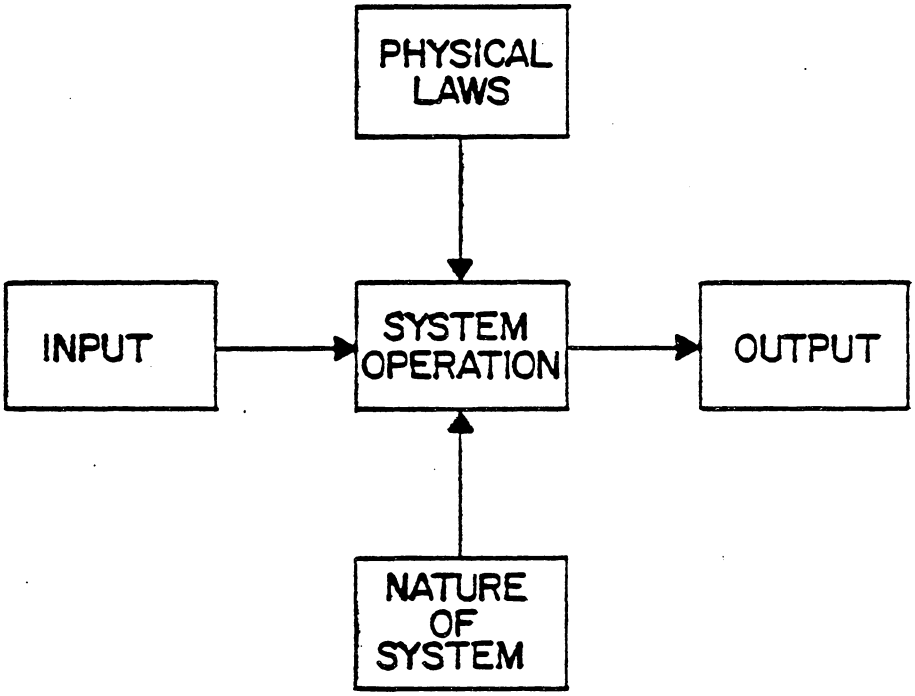
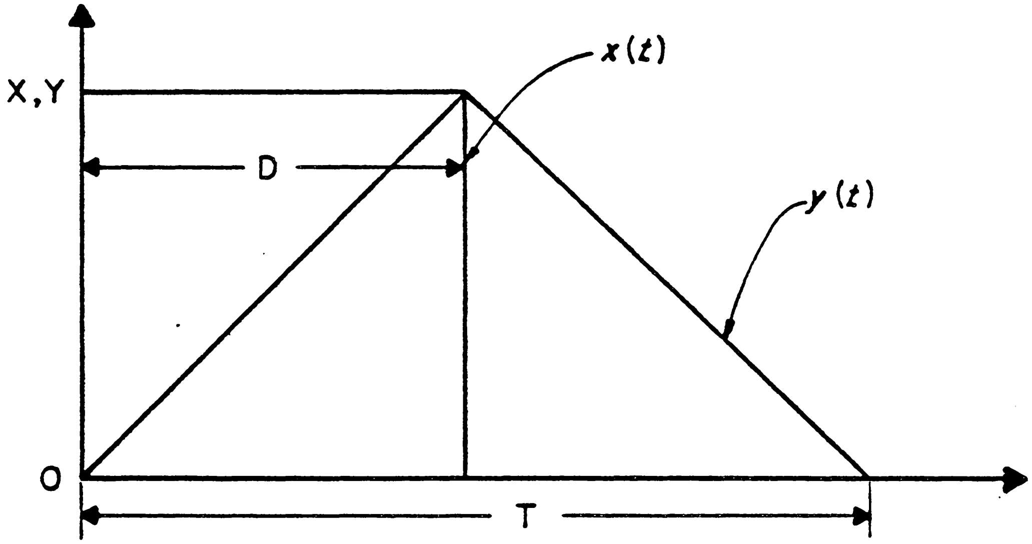
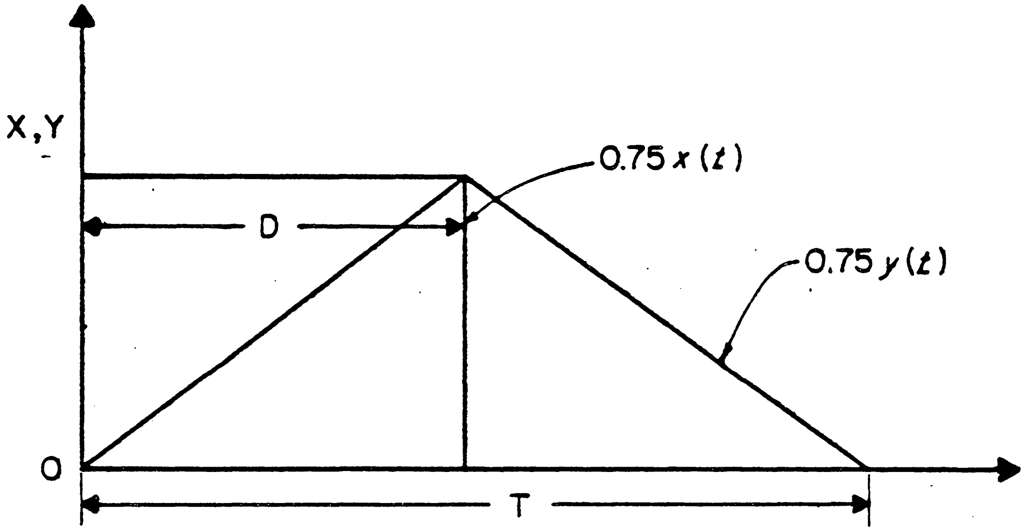


Fig. 2-2. The concept of the systems operation (Dooge, 1973)



(a) input



(b) output

Fig. 2-3. Inputs and outputs in a linear system following the principle of proportionality (Singh, 1980)

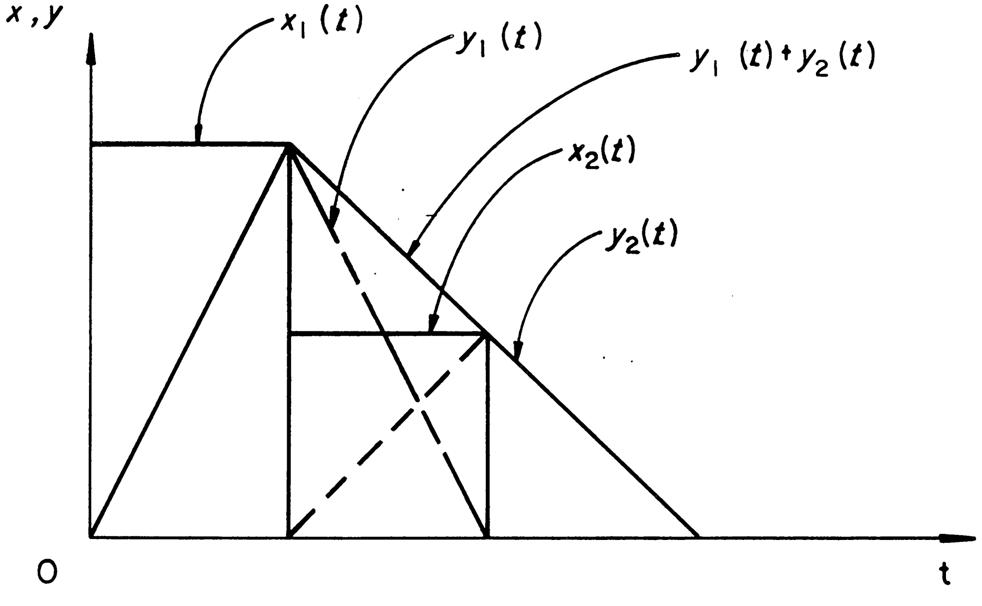


Fig. 2-4. Inputs and outputs in a linear system following the principle of superposition (Singh, 1980)

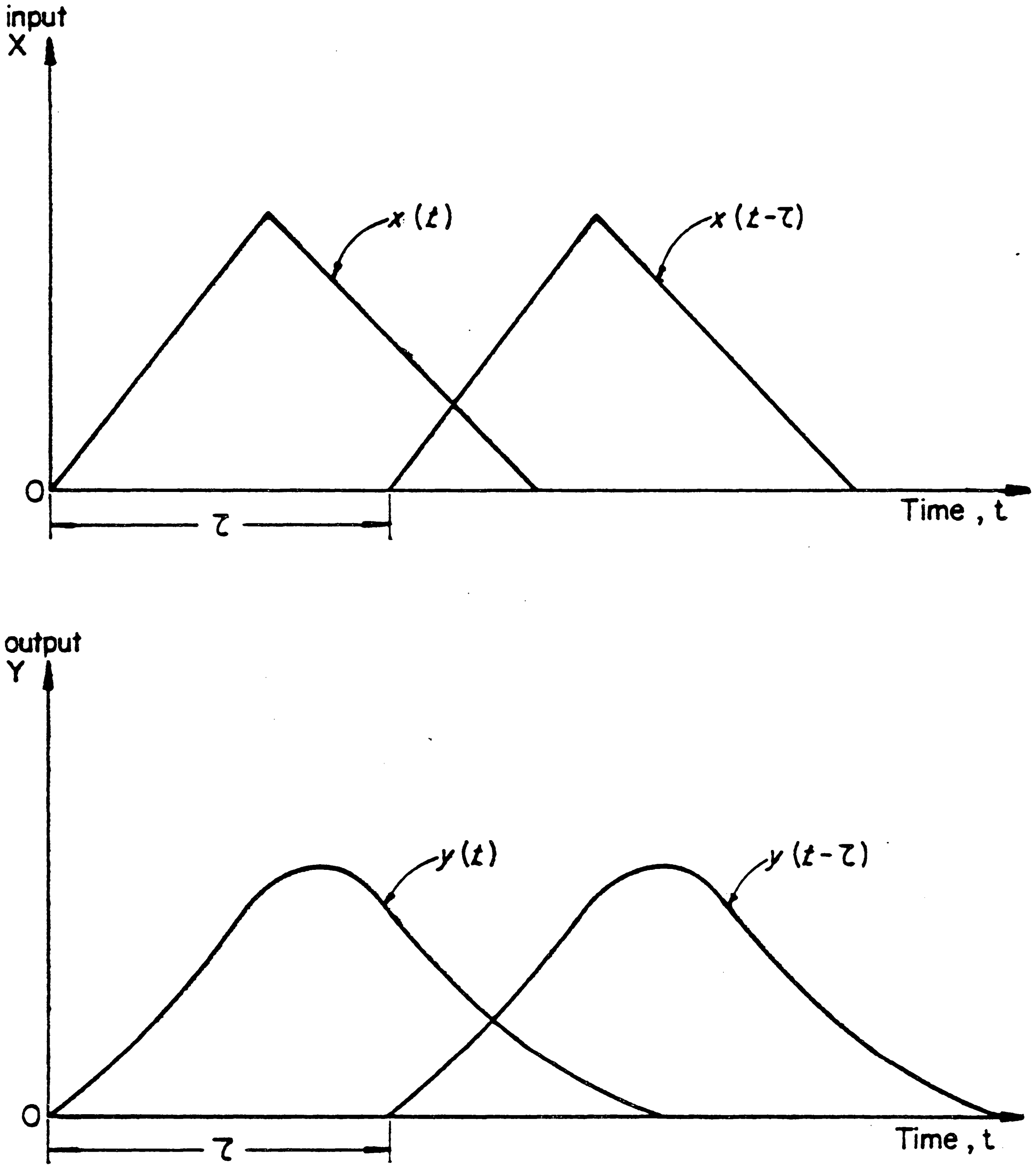


Fig. 2-5. Inputs and outputs in a time-invariant system (Singh, 1980)

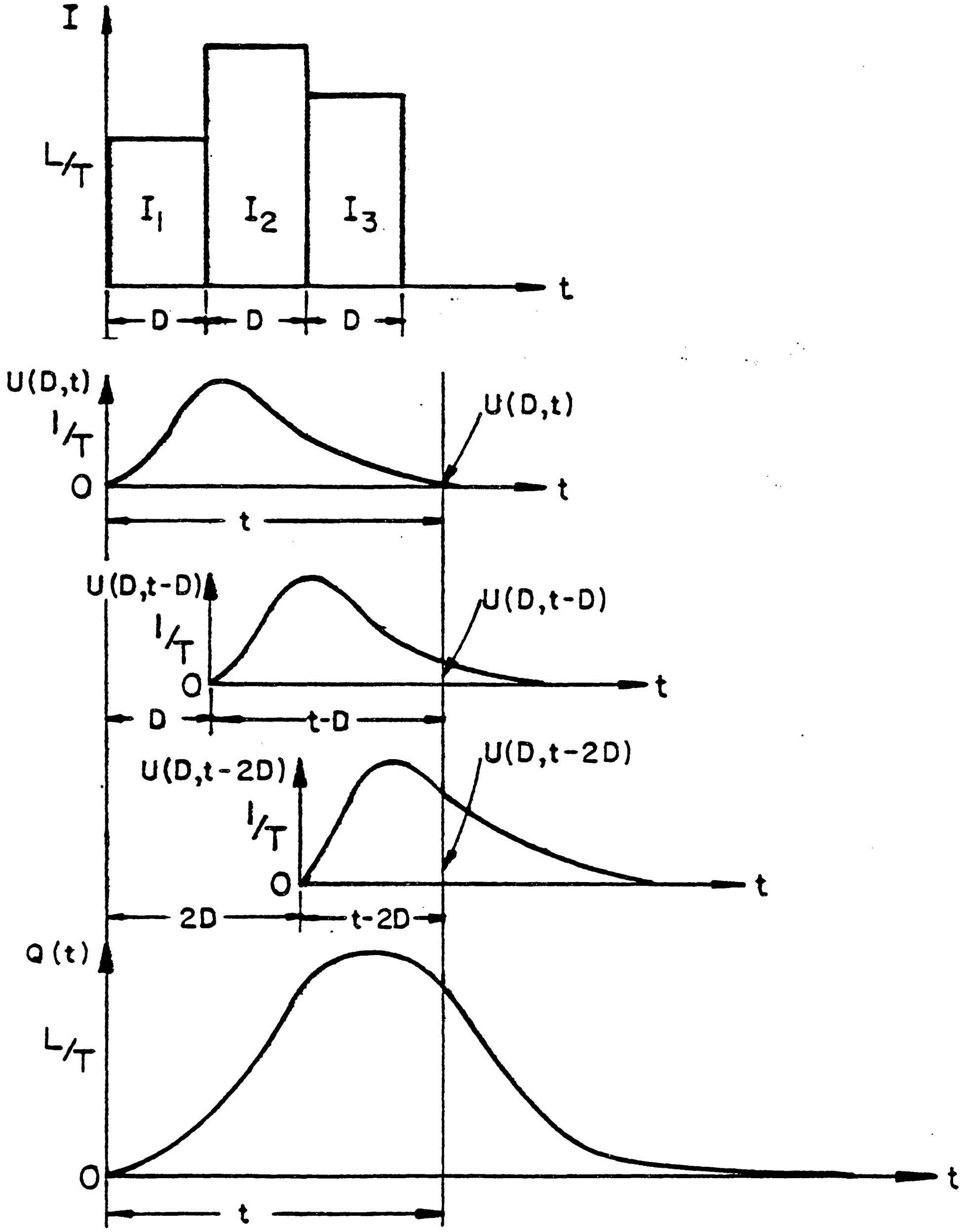


Fig. 2-6. Convolution of uniform rainfall with the unit hydrograph

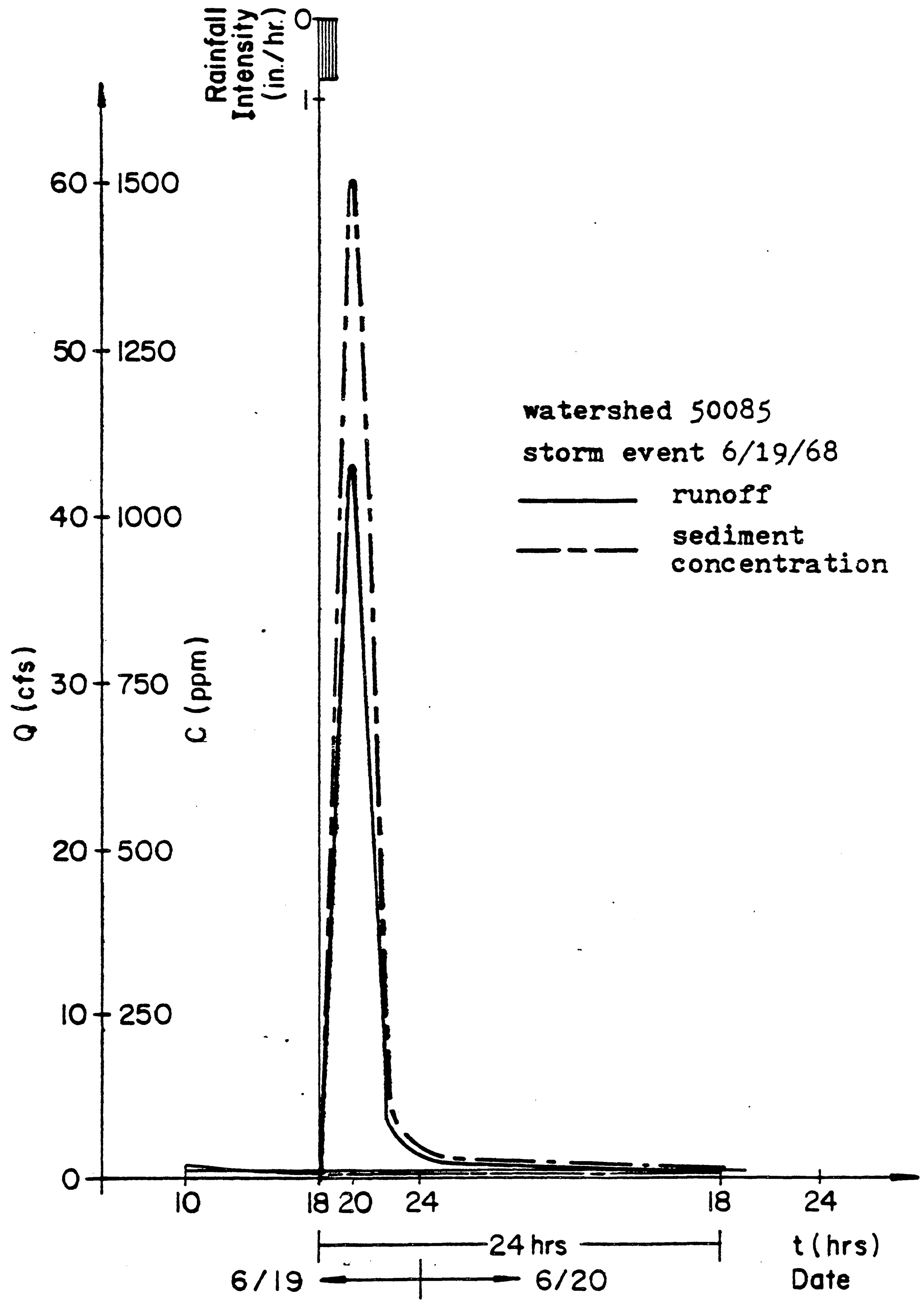


Fig. 3-1. A typical example of baseflow and base sediment concentration separation

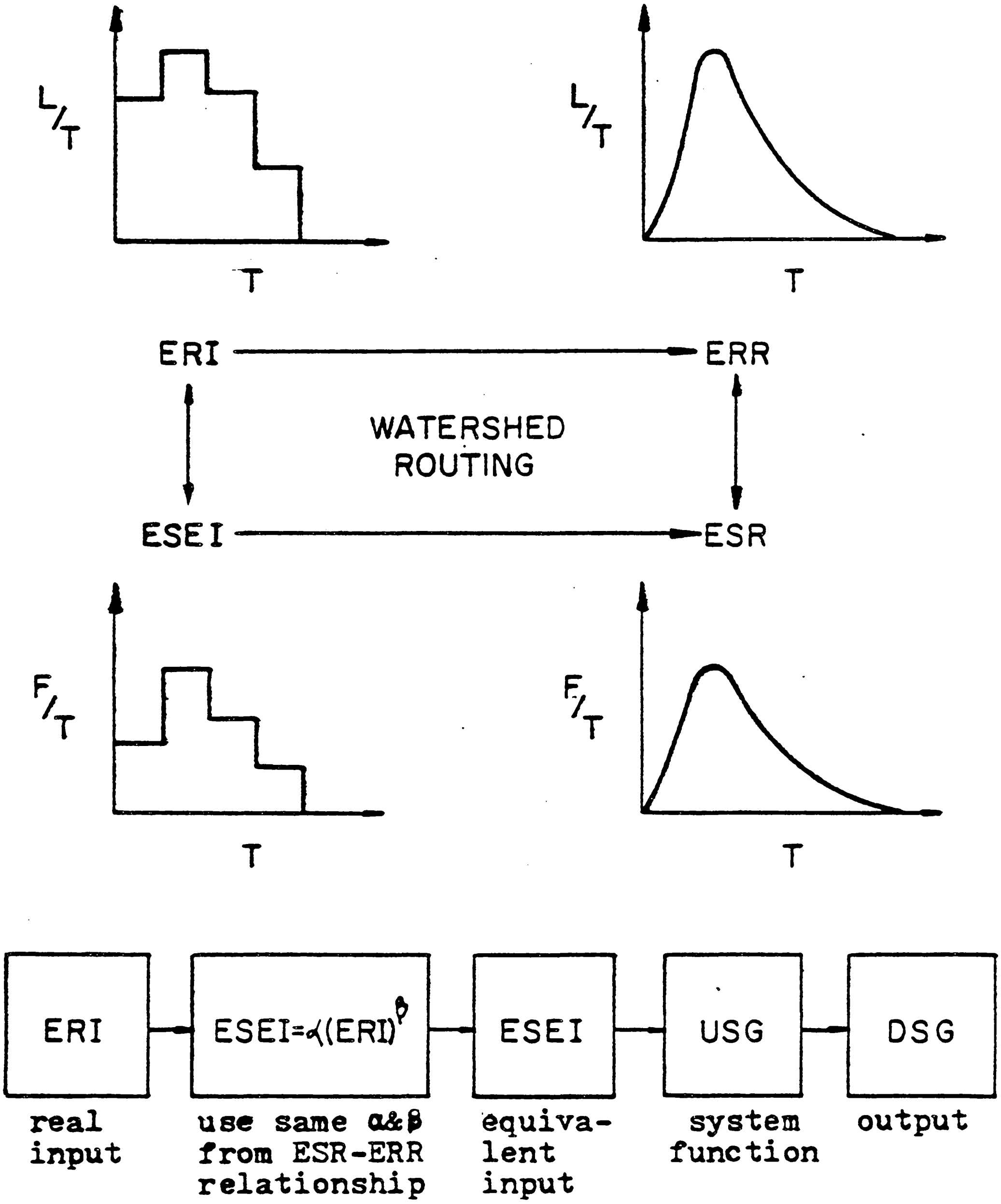
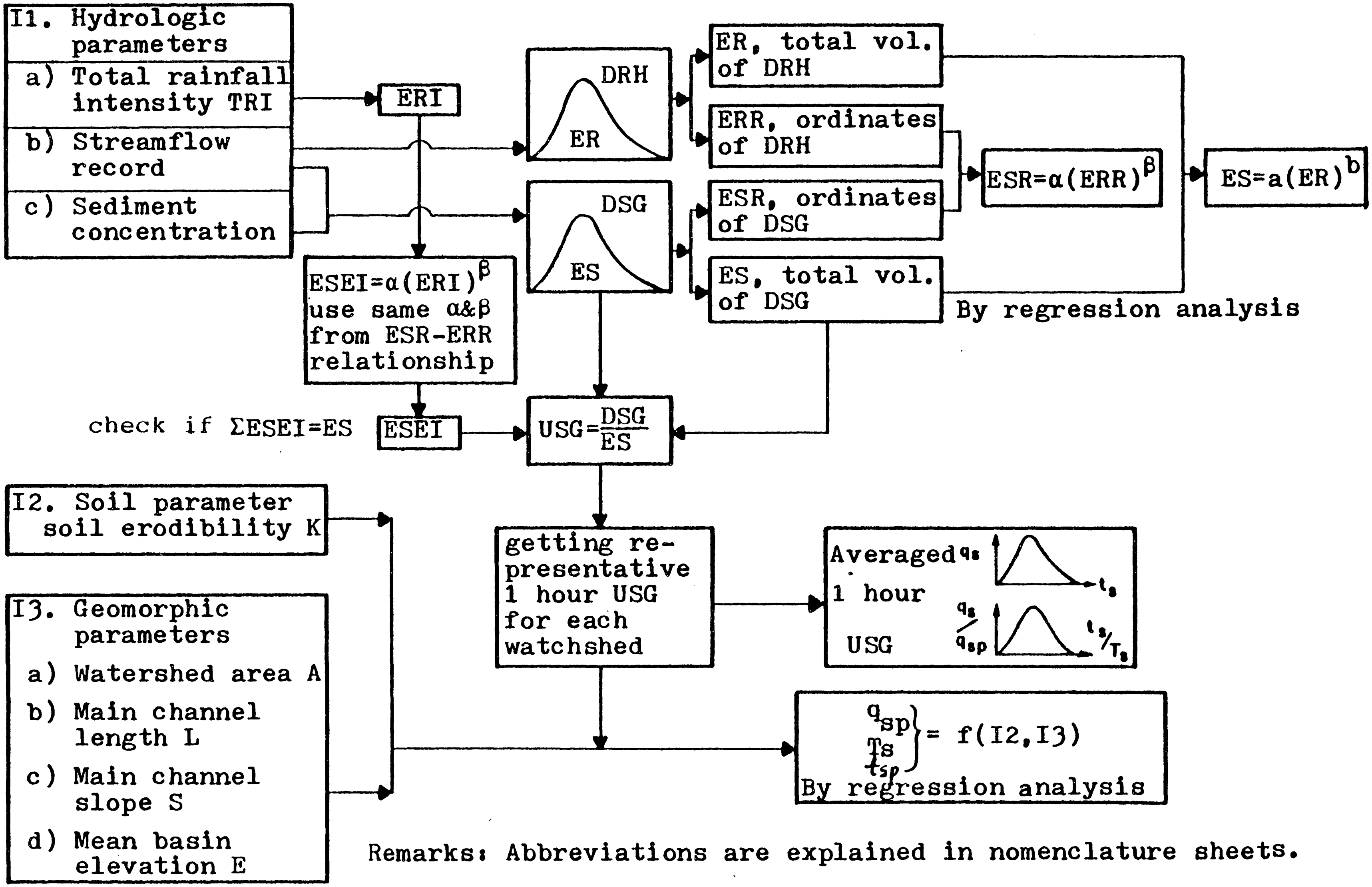


Fig. 3-2. Schematic diagram of model development



Remarks: Abbreviations are explained in nomenclature sheets.

Fig. 3-3. Procedures used in model development

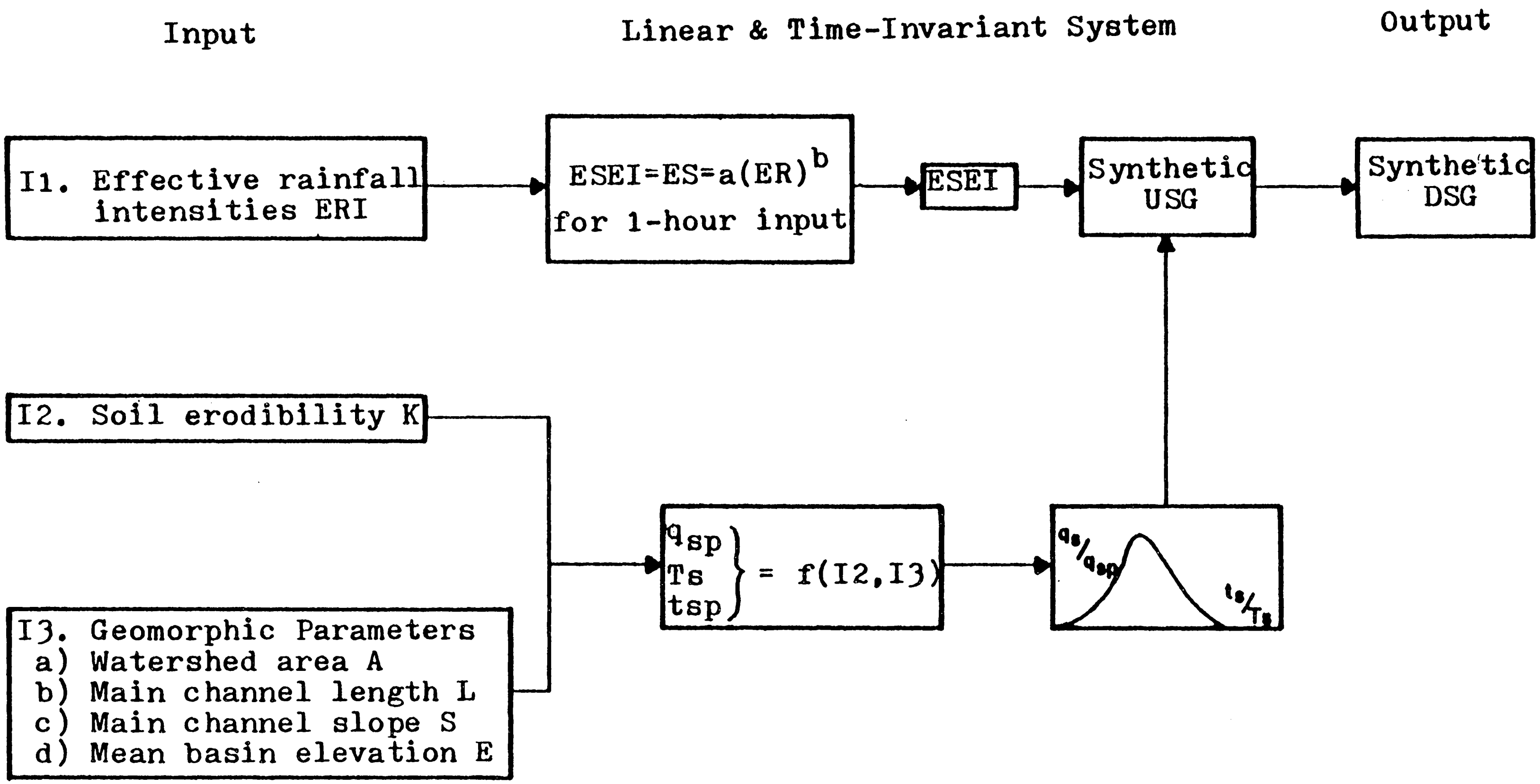


Fig. 3-4. Procedures used in model verification

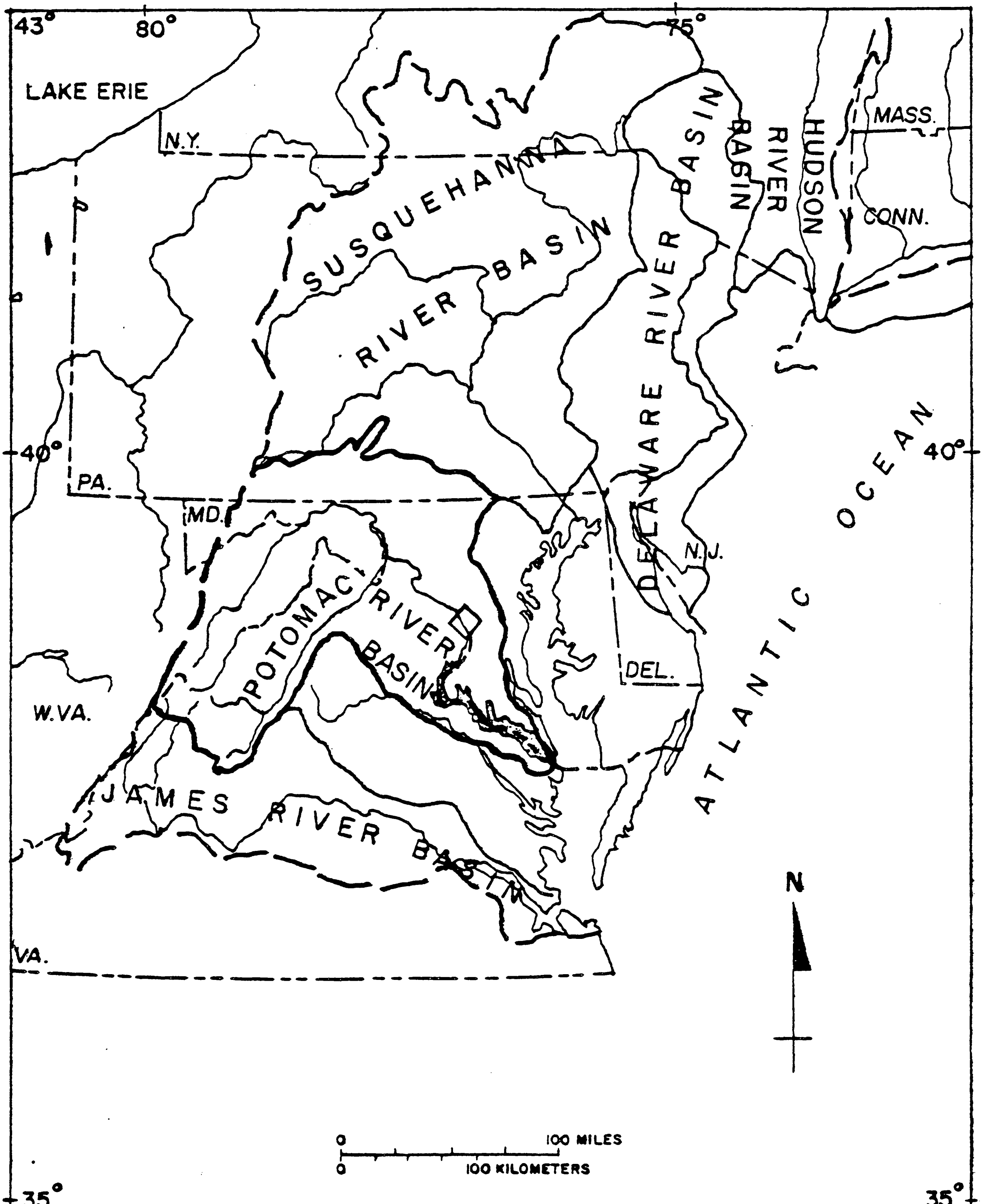


Fig. 4-1. Location map of The Potomac River Basin

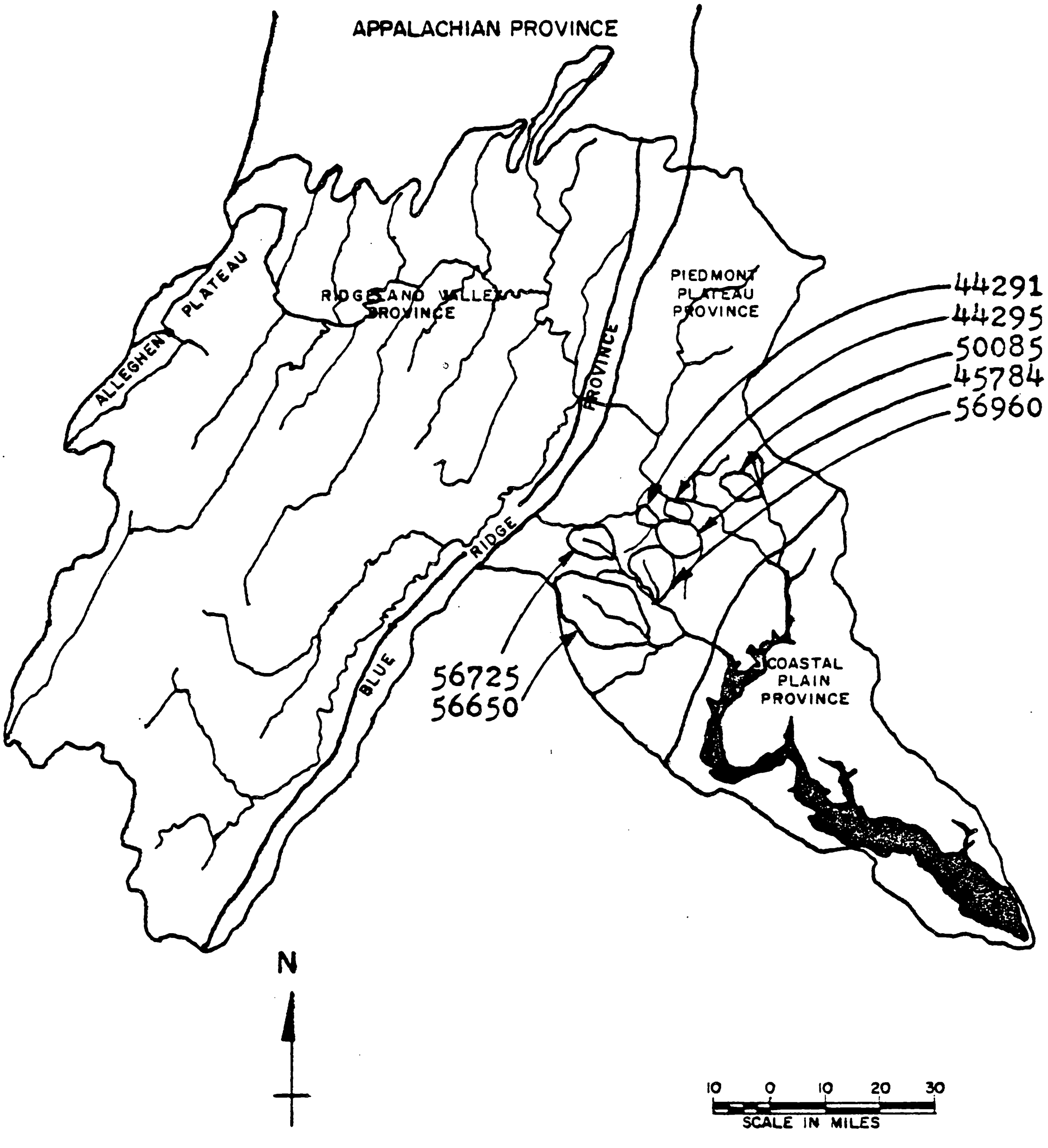


Fig. 4-2. Physiographic provinces and watersheds selected in the lower Potomac River Basin.

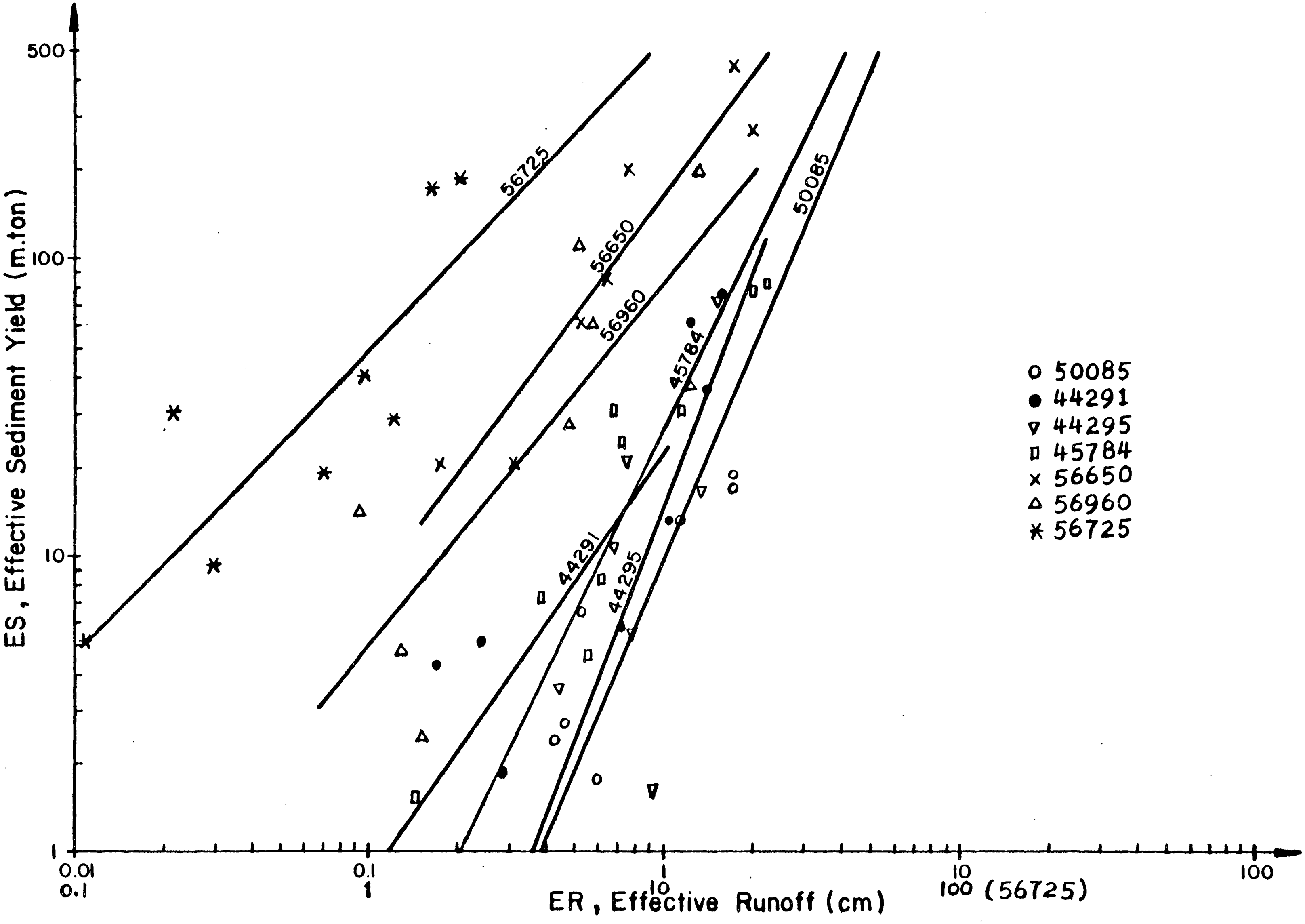


Fig. 4-3, Log-transformed ES-ER relationship

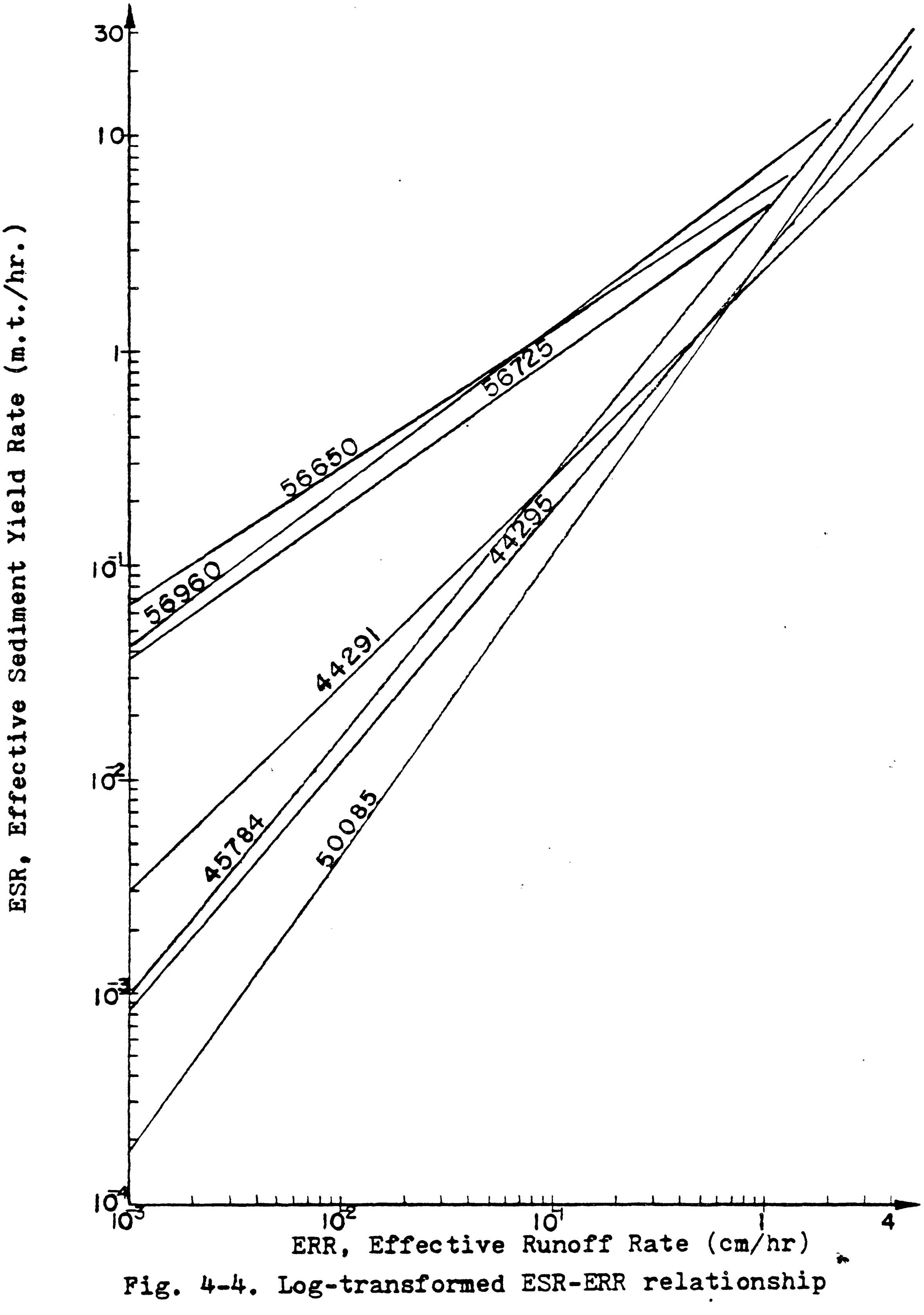


Fig. 4-4. Log-transformed ESR-ERR relationship

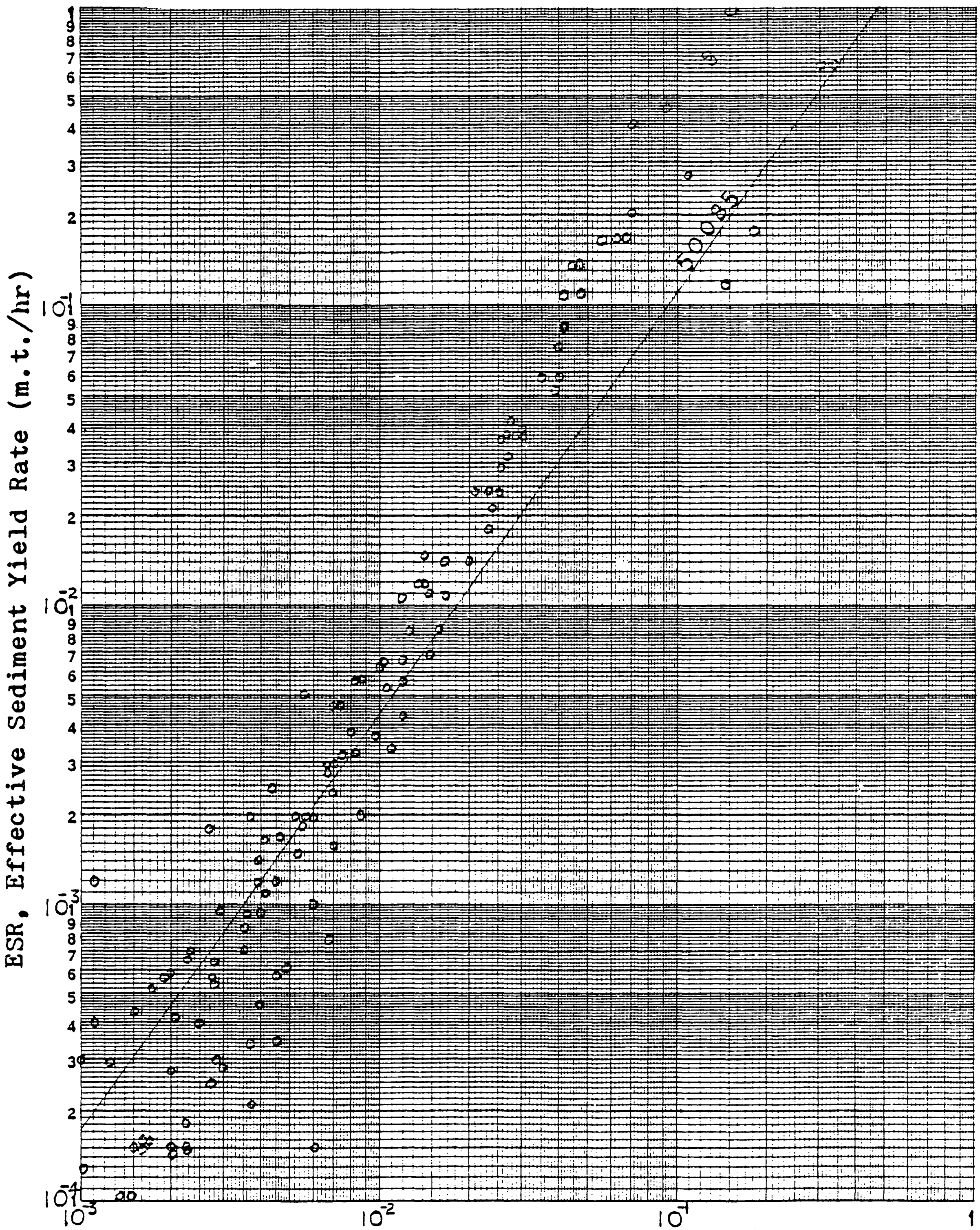


Fig. 4-5. Log-transformed ESR-ERR relationship (watershed 50085)

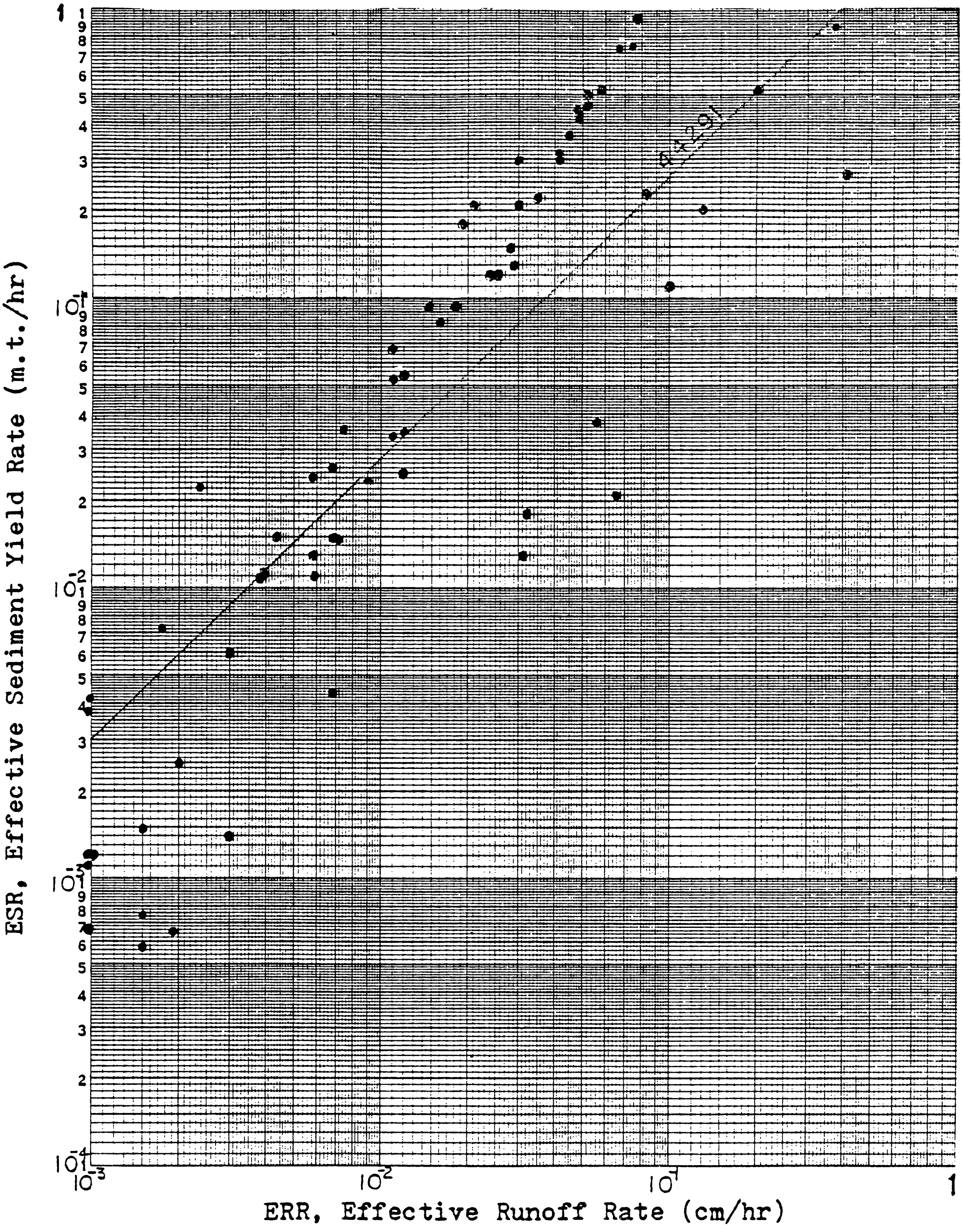


Fig.4-6. Log-transformed ESR-ERR relationship (watershed 44291)

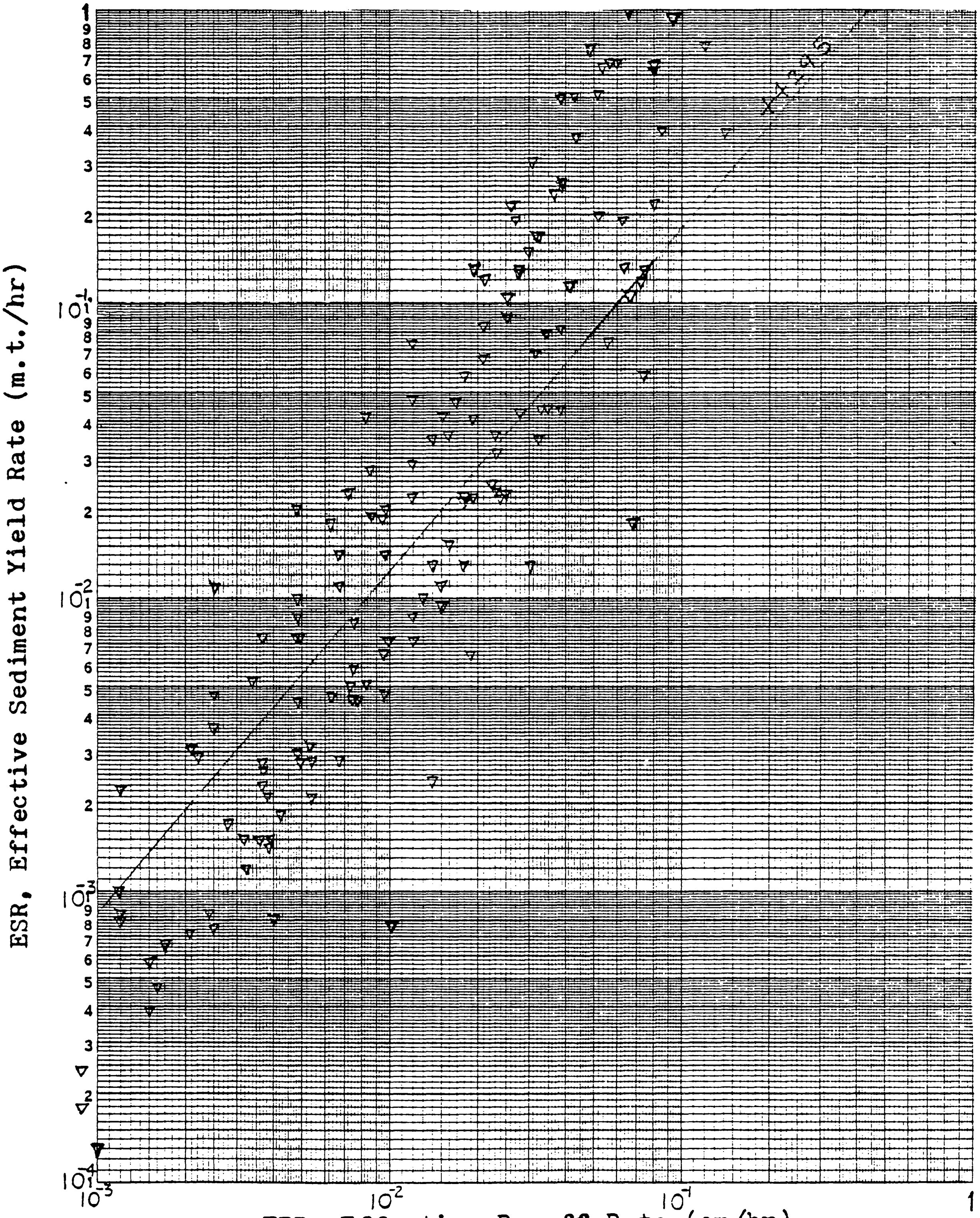


Fig.4-7. Log-transformed ESR-ERR relationship (watershed 44295)

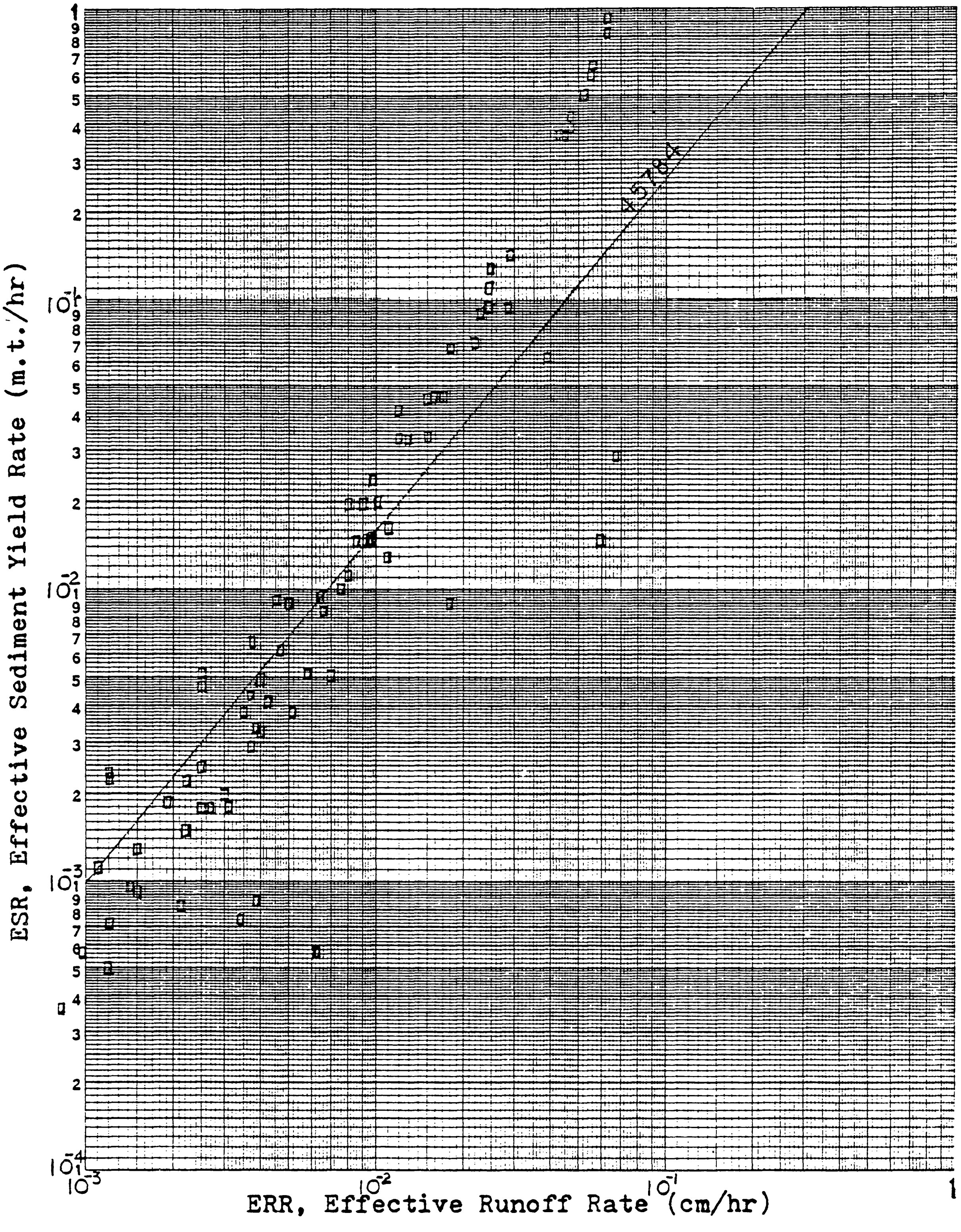


Fig.4-8. Log-transformed ESR-ERR relationship (watershed 45784)

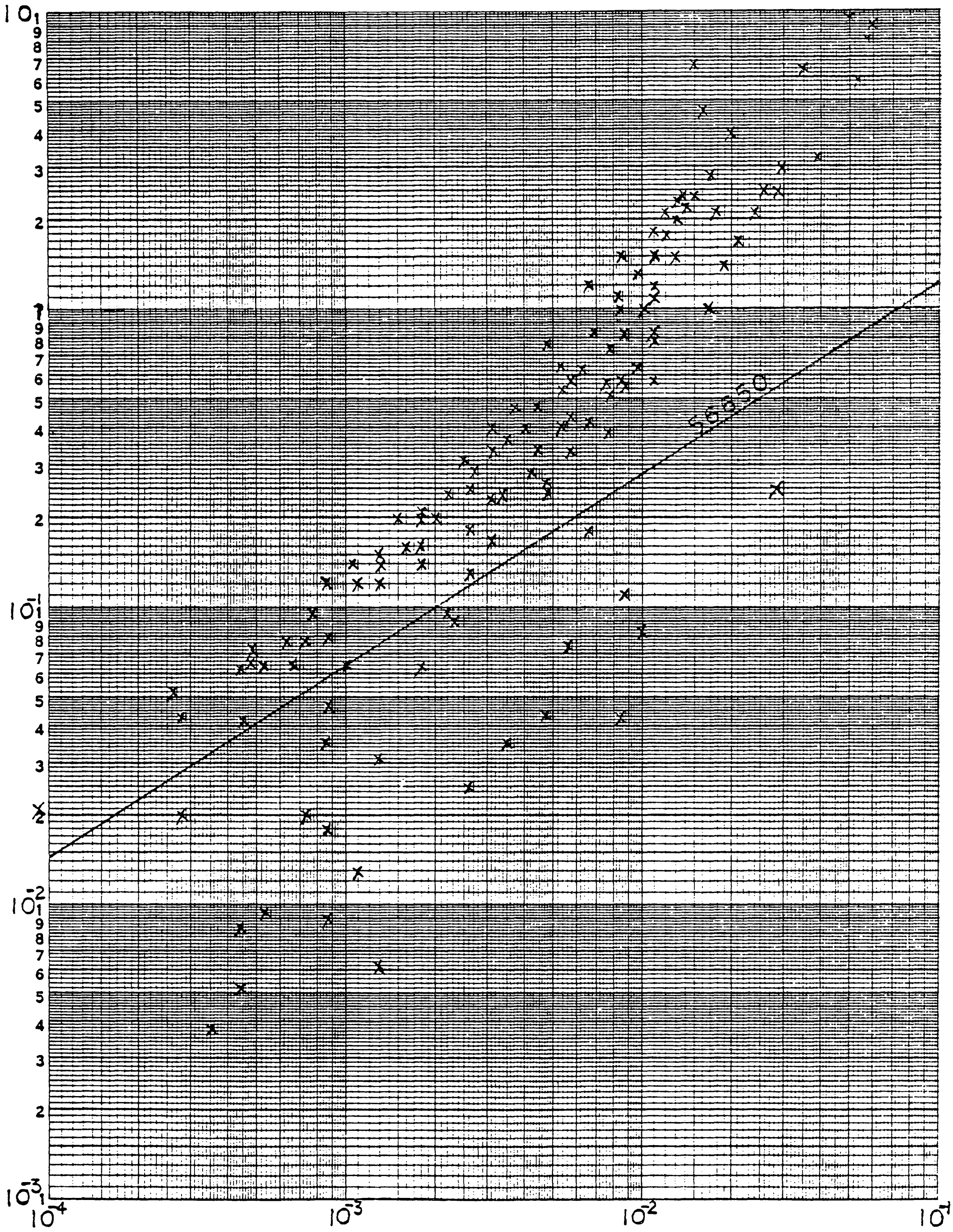


Fig.4-9. Log-transformed ESR-ERR relationship (watershed 56650)

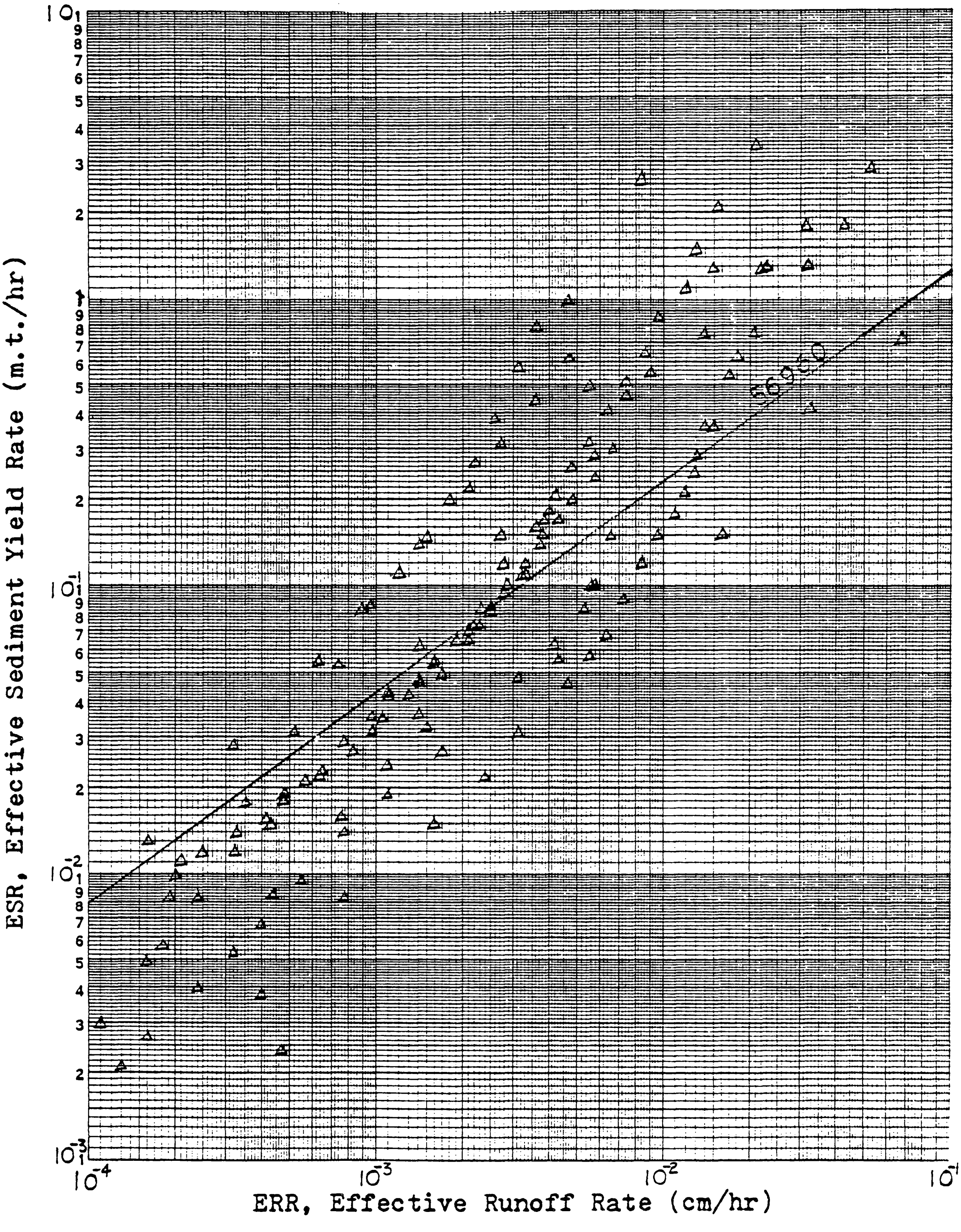


Fig.4-10. Log-transformed ESR-ERR relationship (watershed 56960)

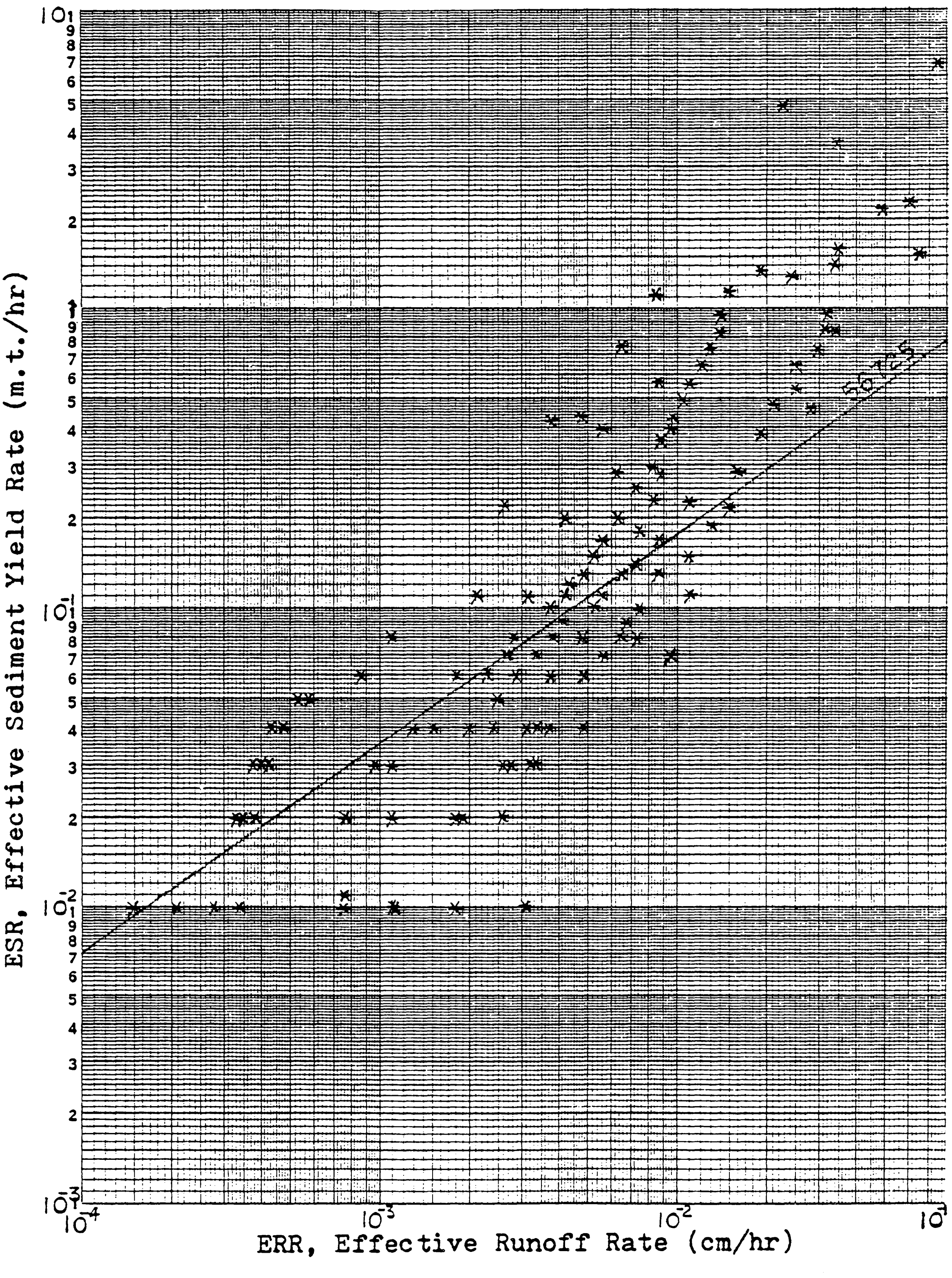


Fig.4-11. Log-transformed ESR-ERR relationship (watershed 56725)

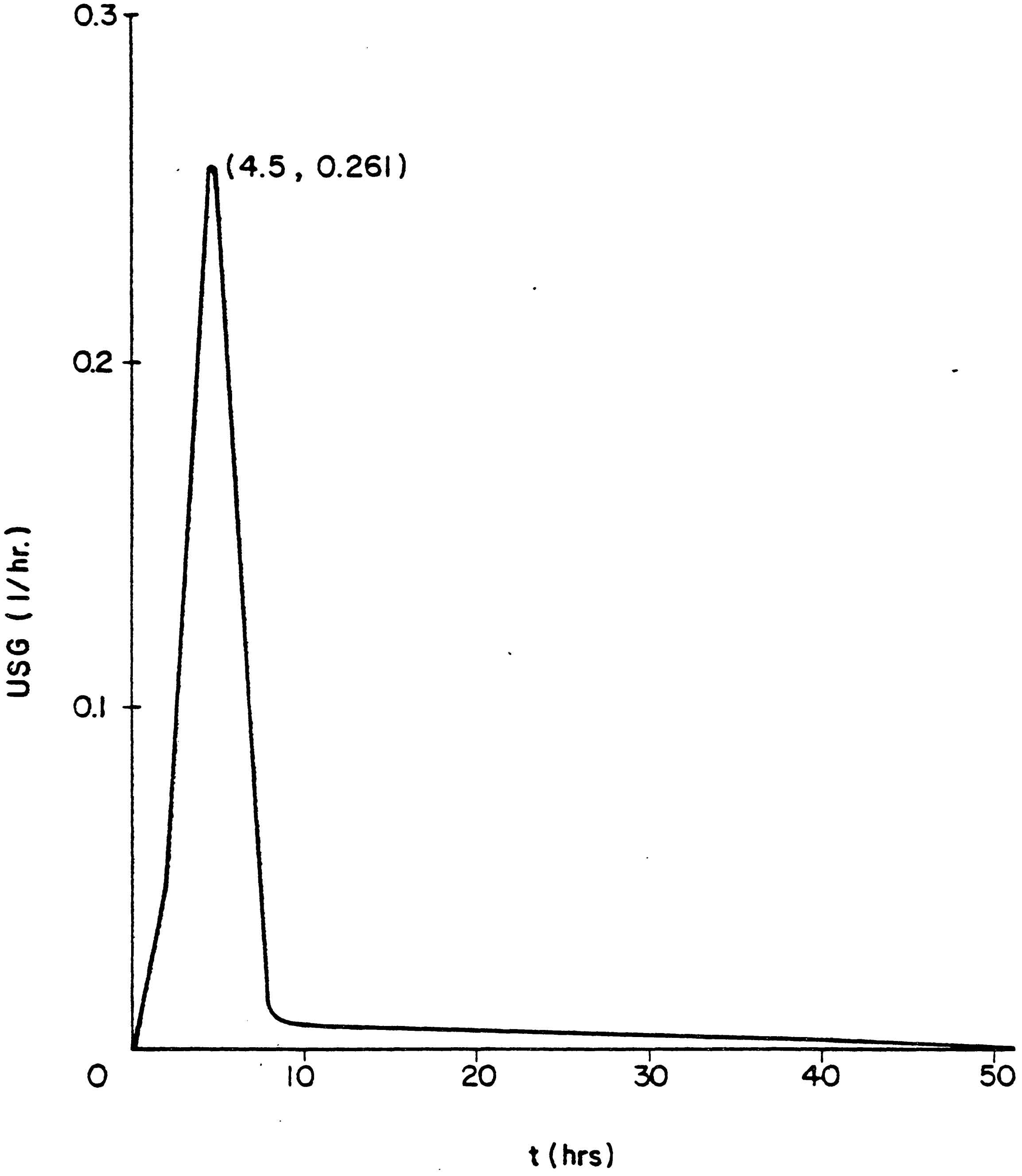


Fig. 5-1. Averaged dimensional USG based on data from 6 watersheds (50085 excluded)

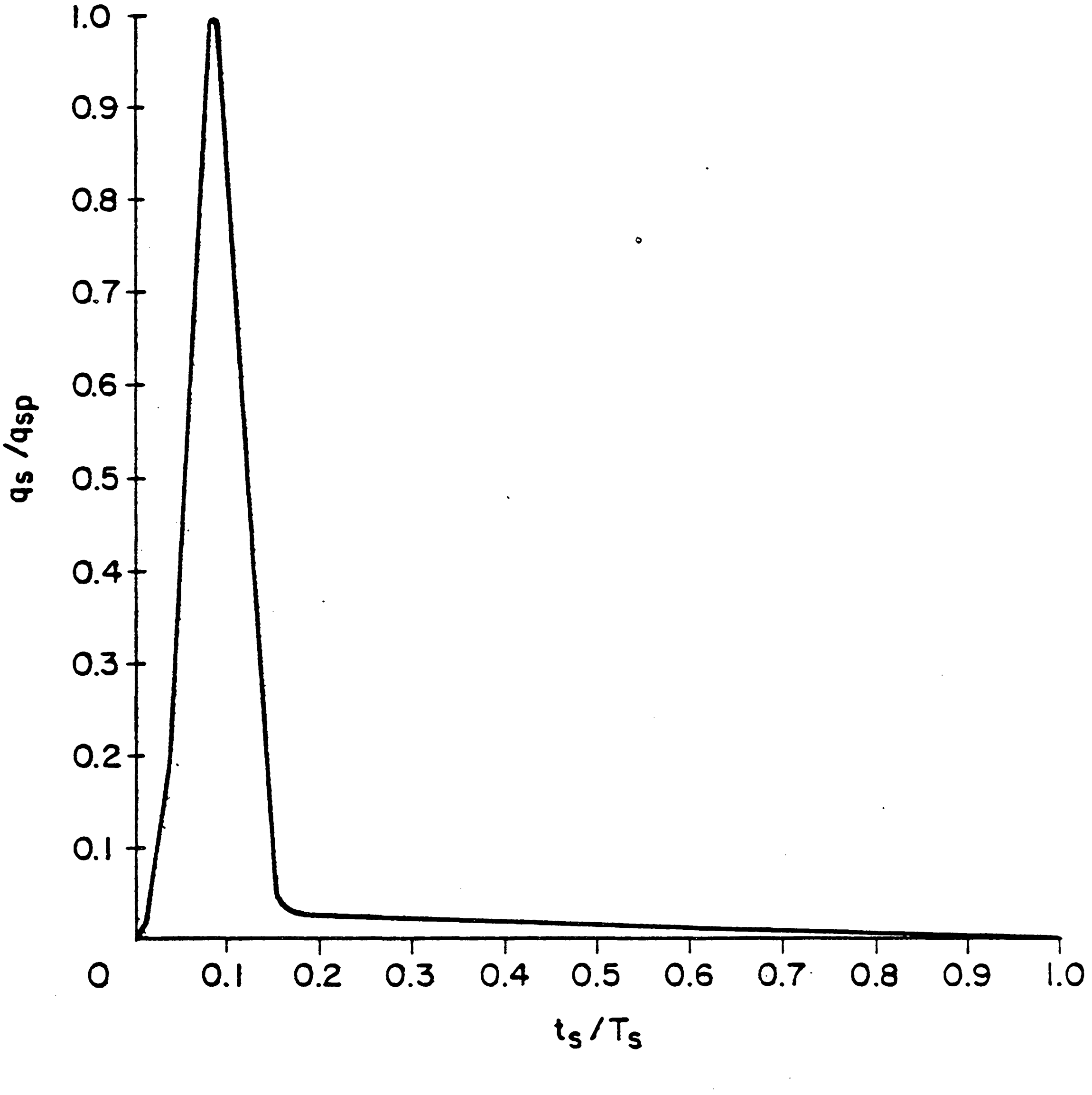


Fig. 5-2. Averaged dimensionless USG based on data from 6 watersheds (50085 excluded)

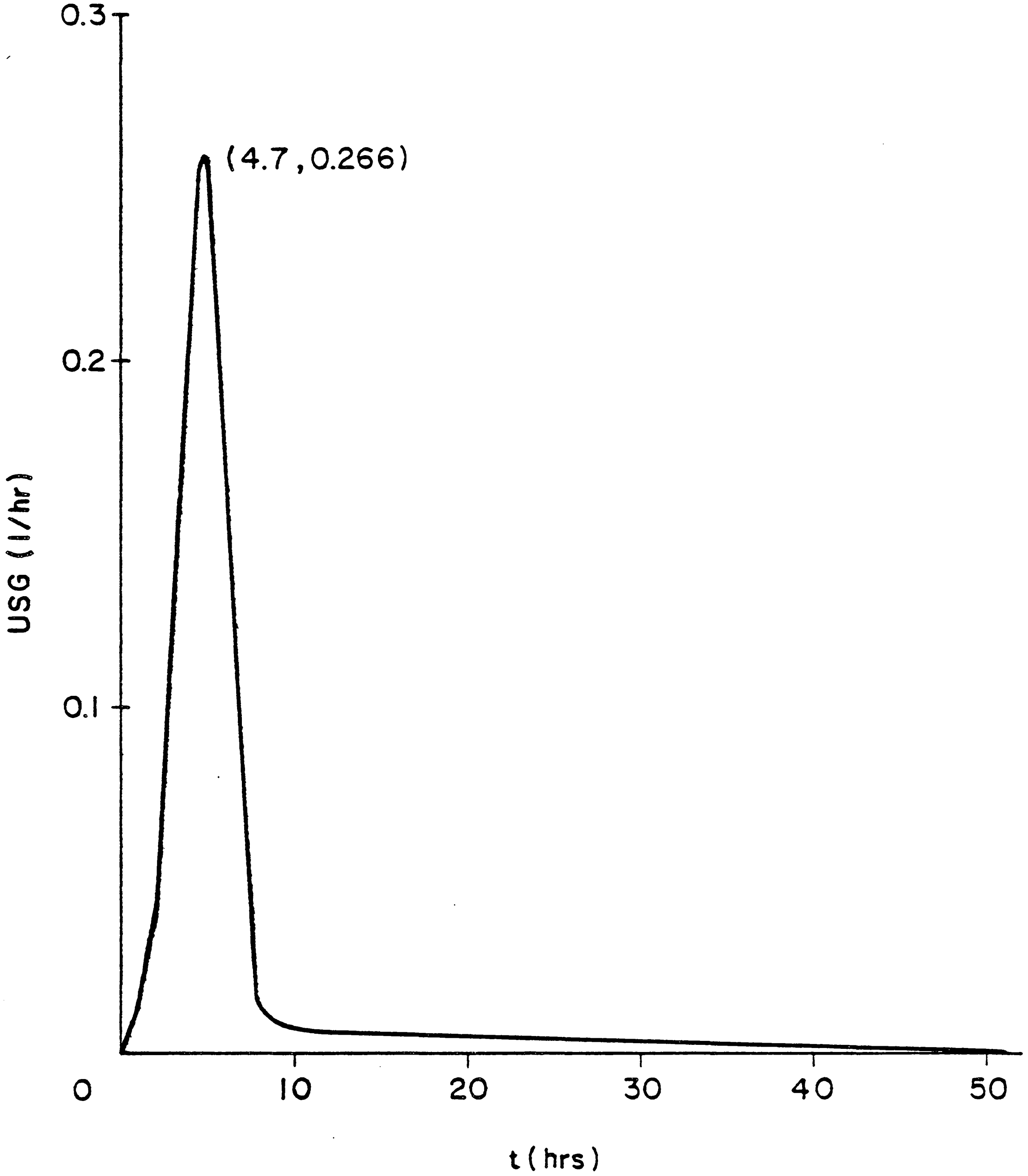


Fig. 5-3. Averaged dimensional USG based on data from 6 watersheds (44295 excluded)

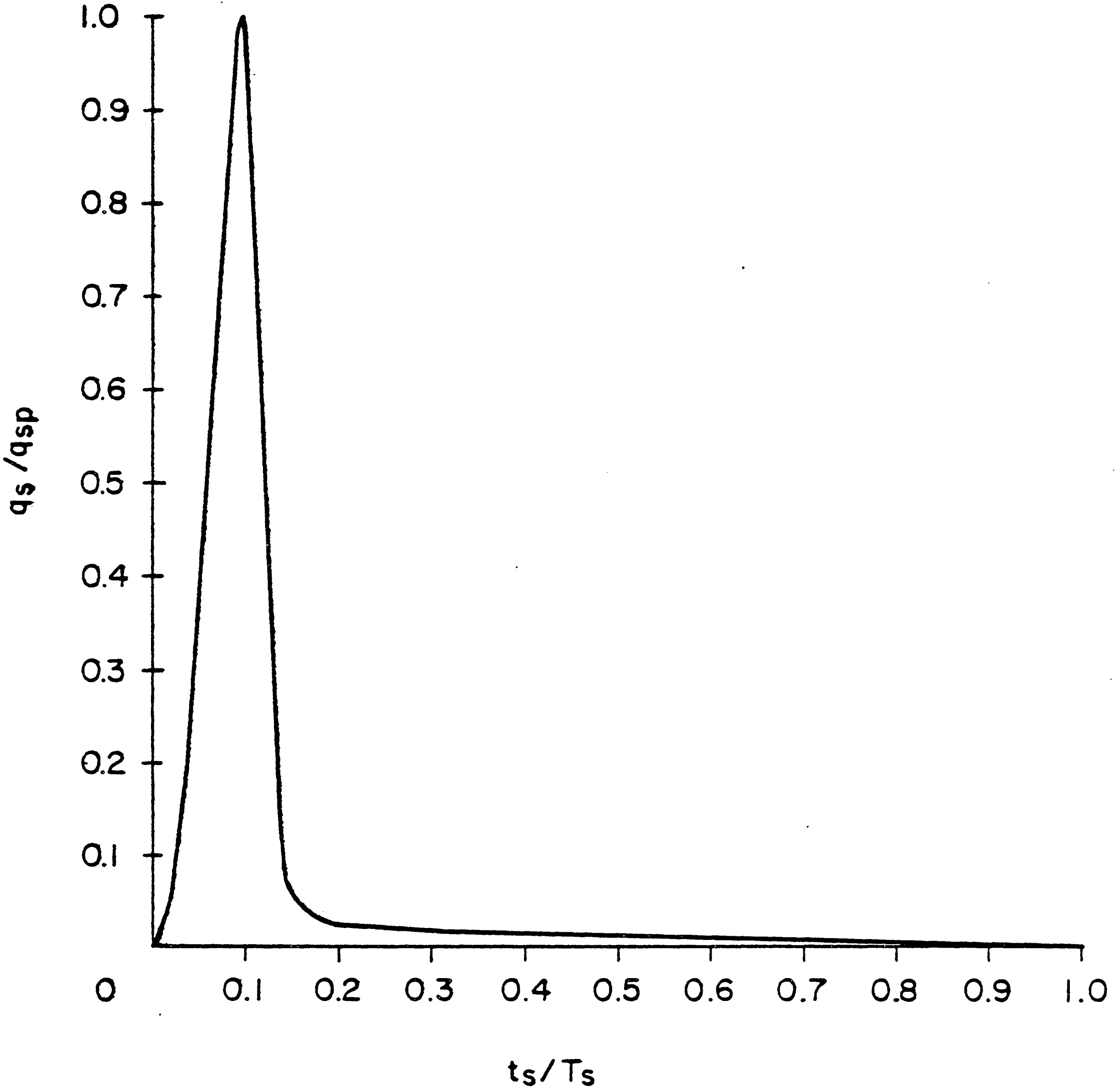


Fig. 5-4. Averaged dimensionless USG based on data from 6 watersheds (44295 excluded)

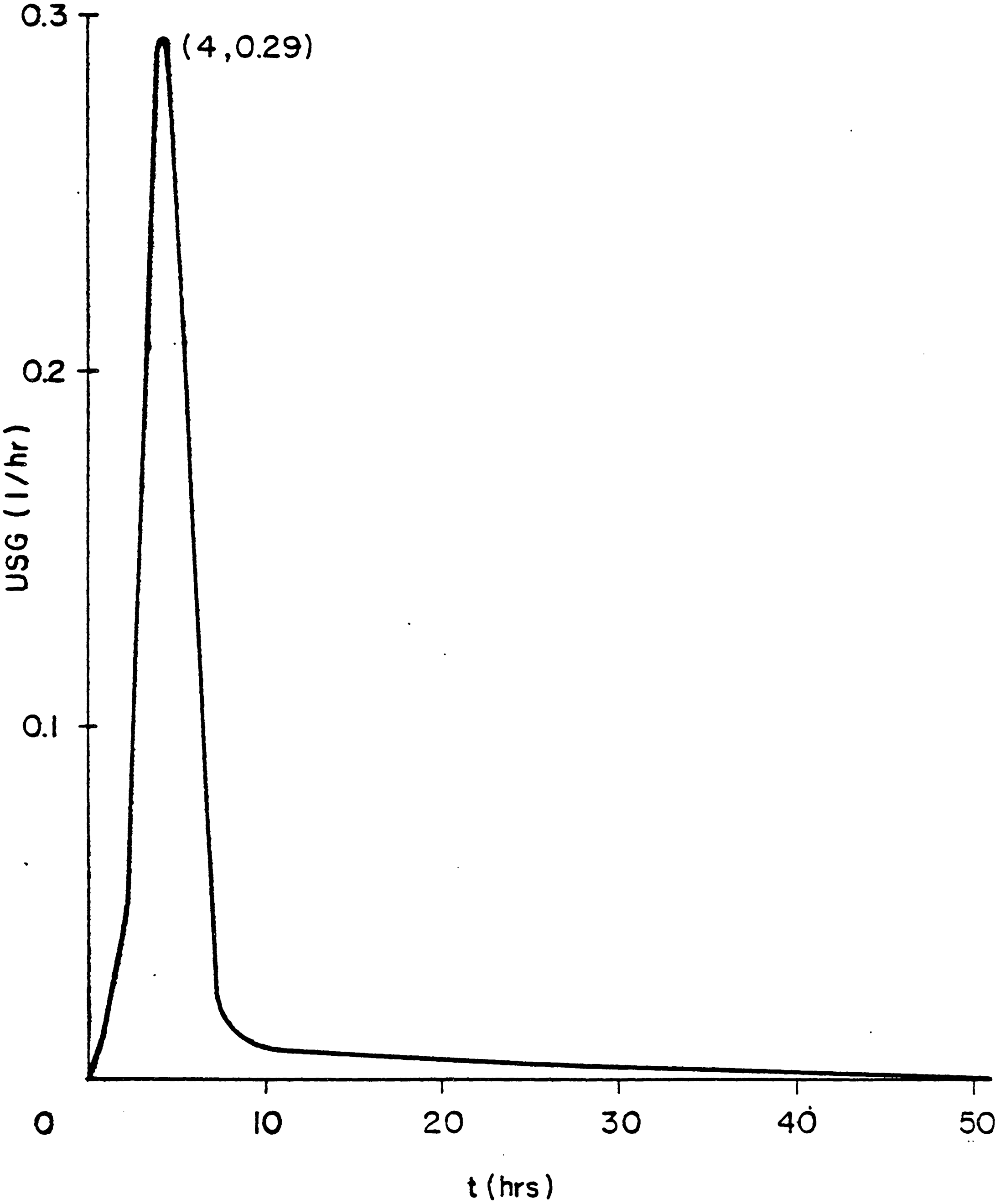


Fig. 5-5. Averaged dimensional USG based on data from 7 watersheds (no exclusion)

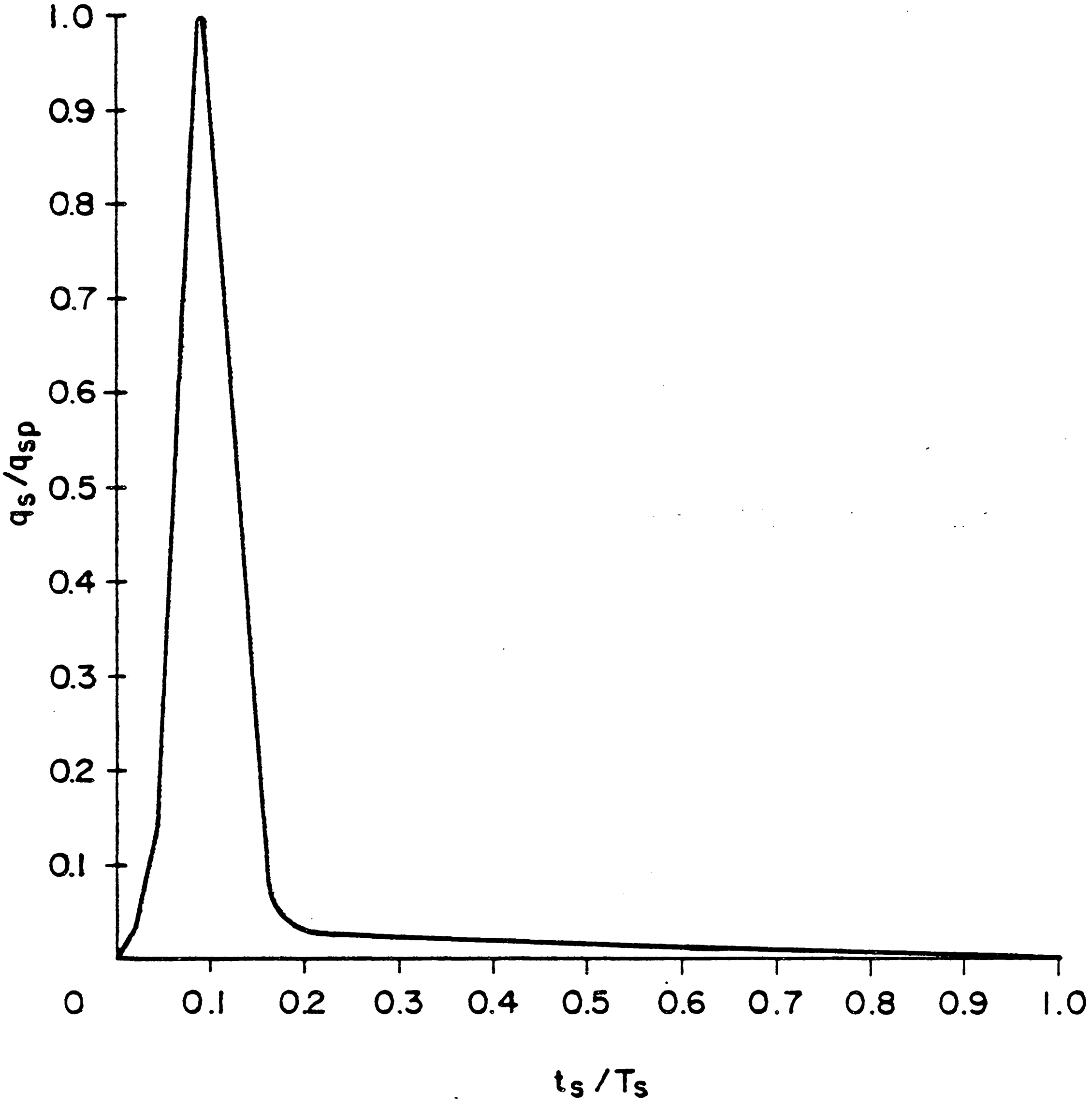


Fig. 5-6. Averaged dimensionless USG based on data from 7 watersheds (no exclusion)

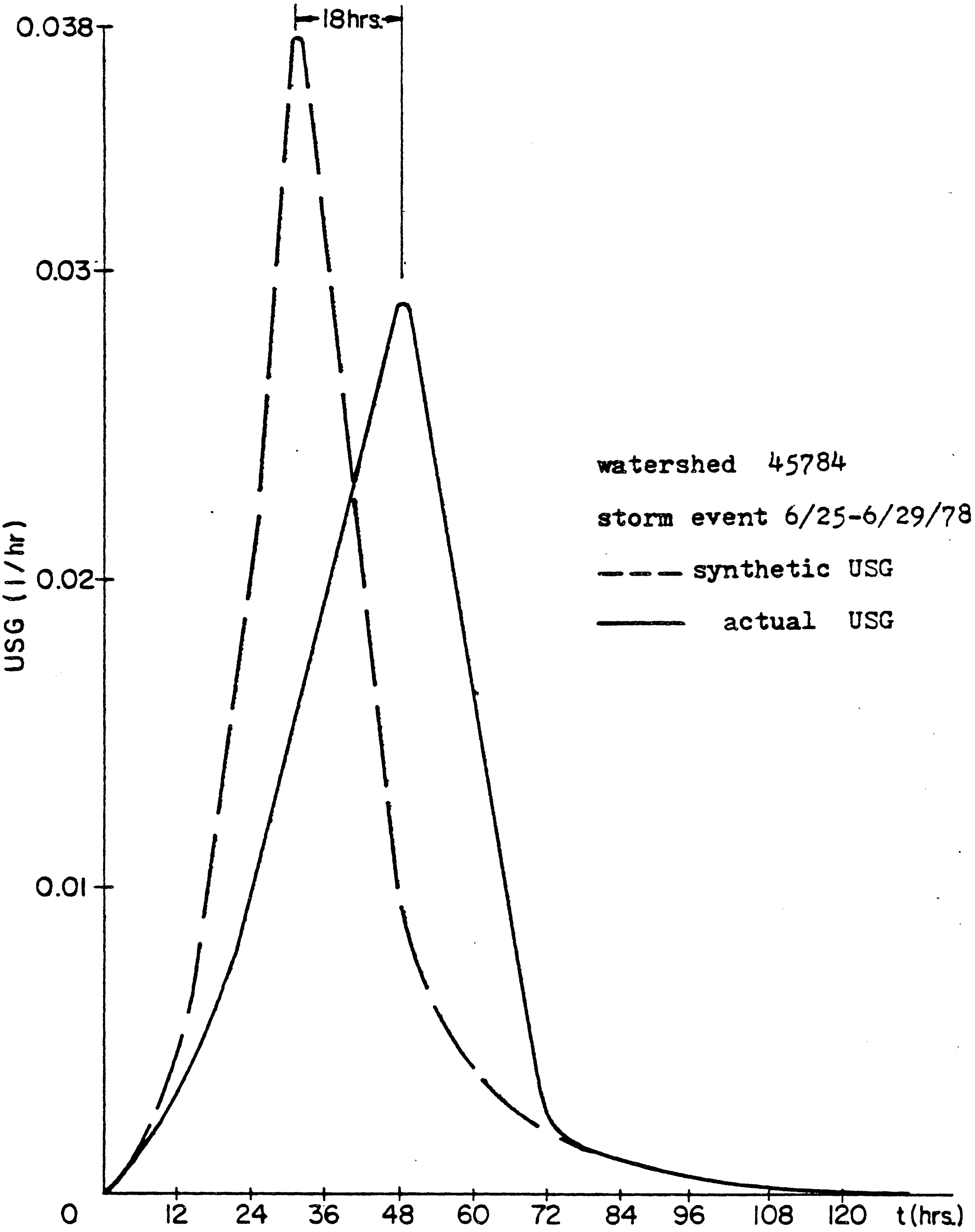


Fig. 5-7. An example of a storm event on a daily basis showing peak time error between the synthetic USG and actual USG

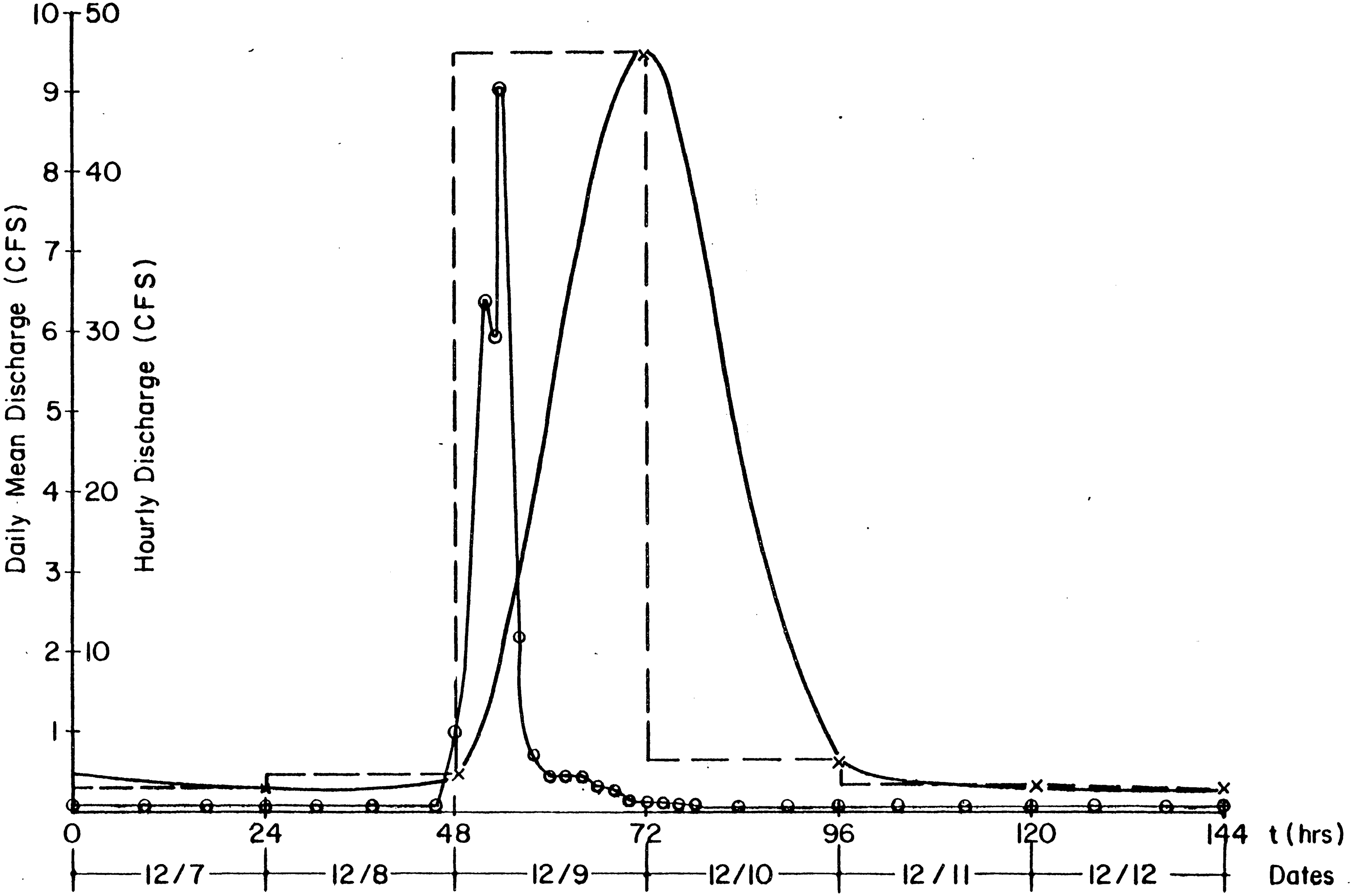


Fig. 5-8. A typical example showing the difference between hourly hydrograph and daily hydrograph (event 12/7-12/12/1974, watershed 45784)

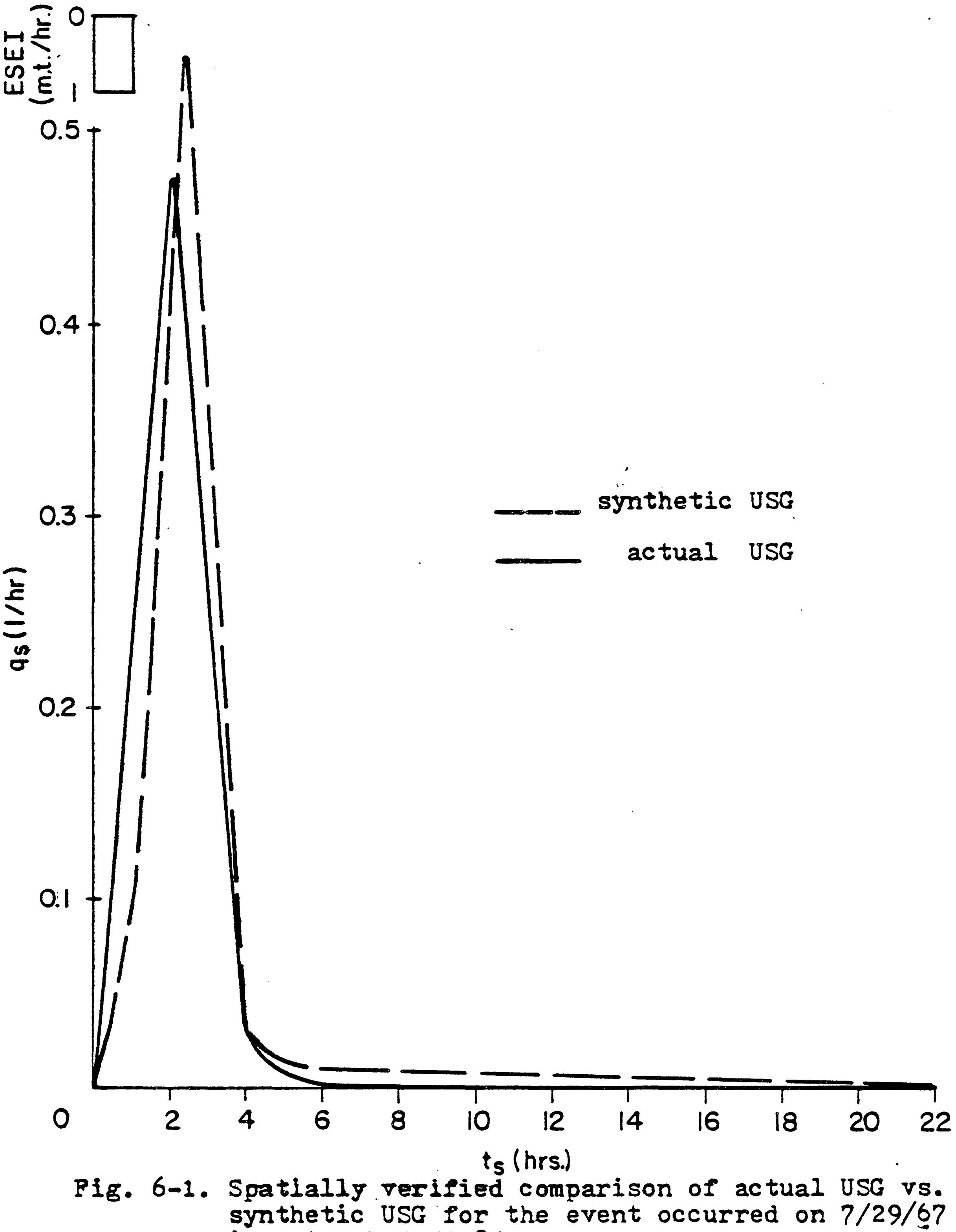


Fig. 6-1. Spatially verified comparison of actual USG vs. synthetic USG for the event occurred on 7/29/67 in watershed 50085

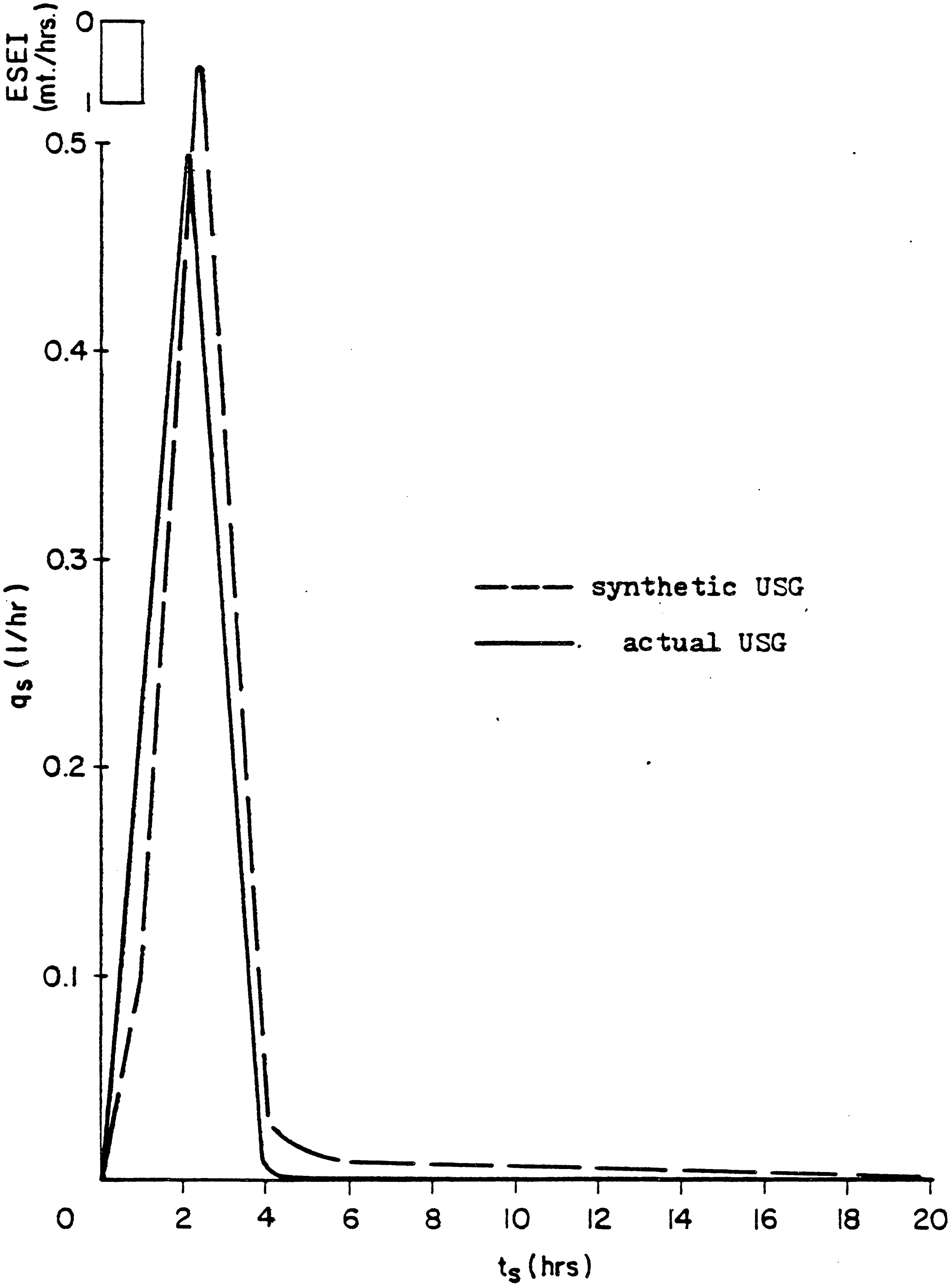


Fig. 6-2. Spatially verified comparison of actual USG vs. synthetic USG for the event occurred on 6/19/68 in watershed 50085

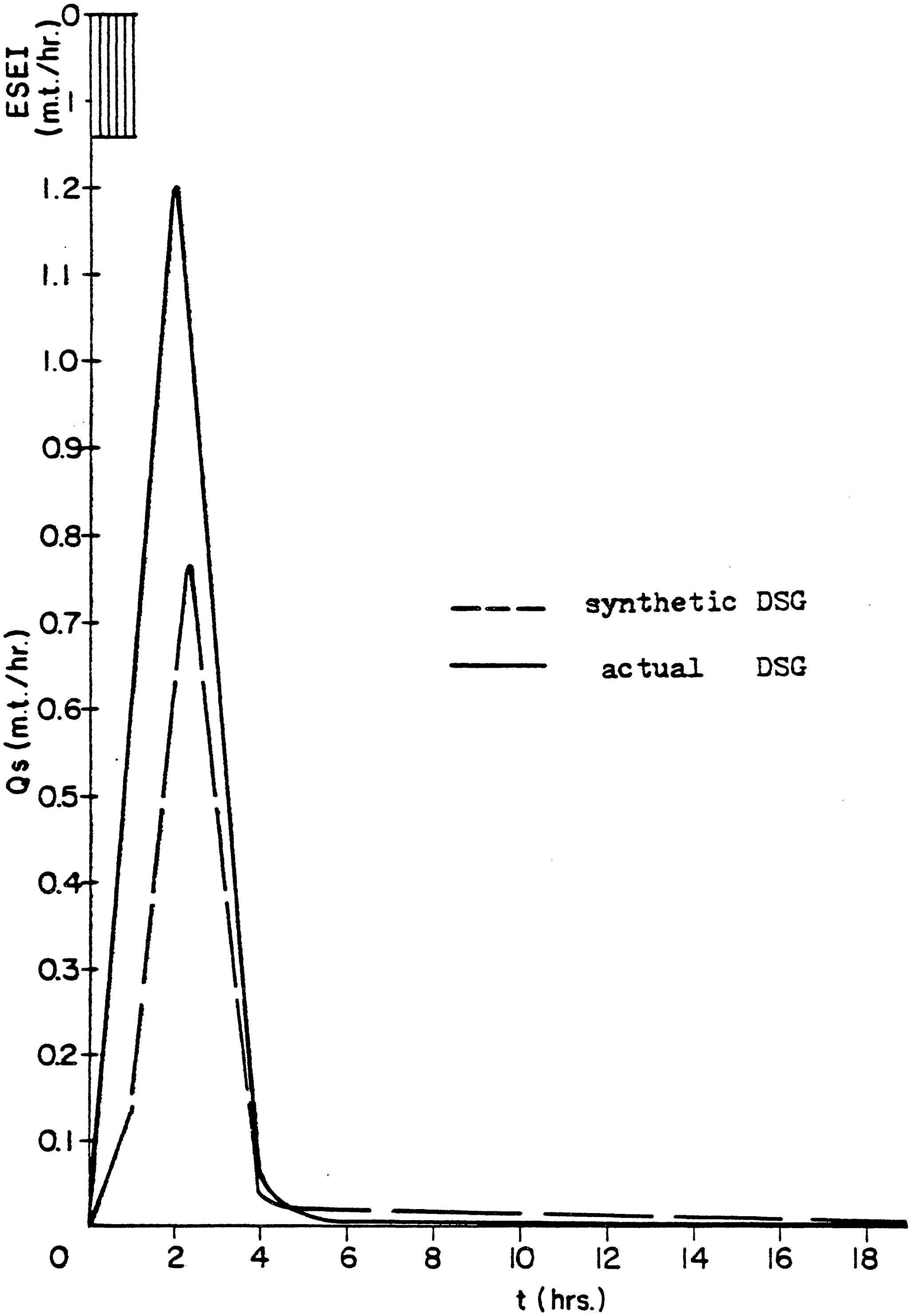


Fig. 6-3. Spatially verified comparison of actual DSG vs. synthetic DSG for the event occurred on 7/29/67 in watershed 50085

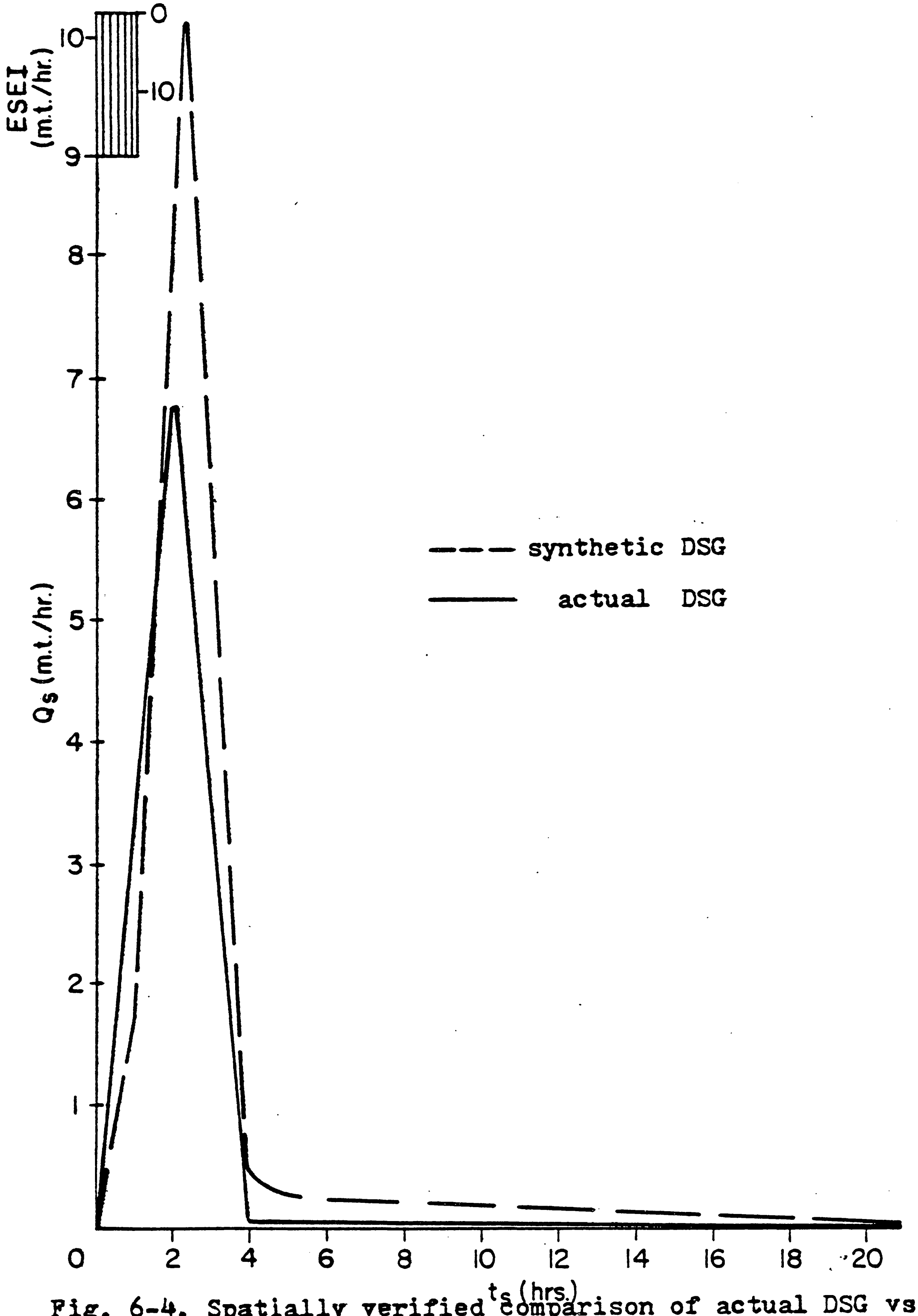


Fig. 6-4. Spatially verified comparison of actual DSG vs. synthetic DSG for the event occurred on 6/19/68 in watershed 50085

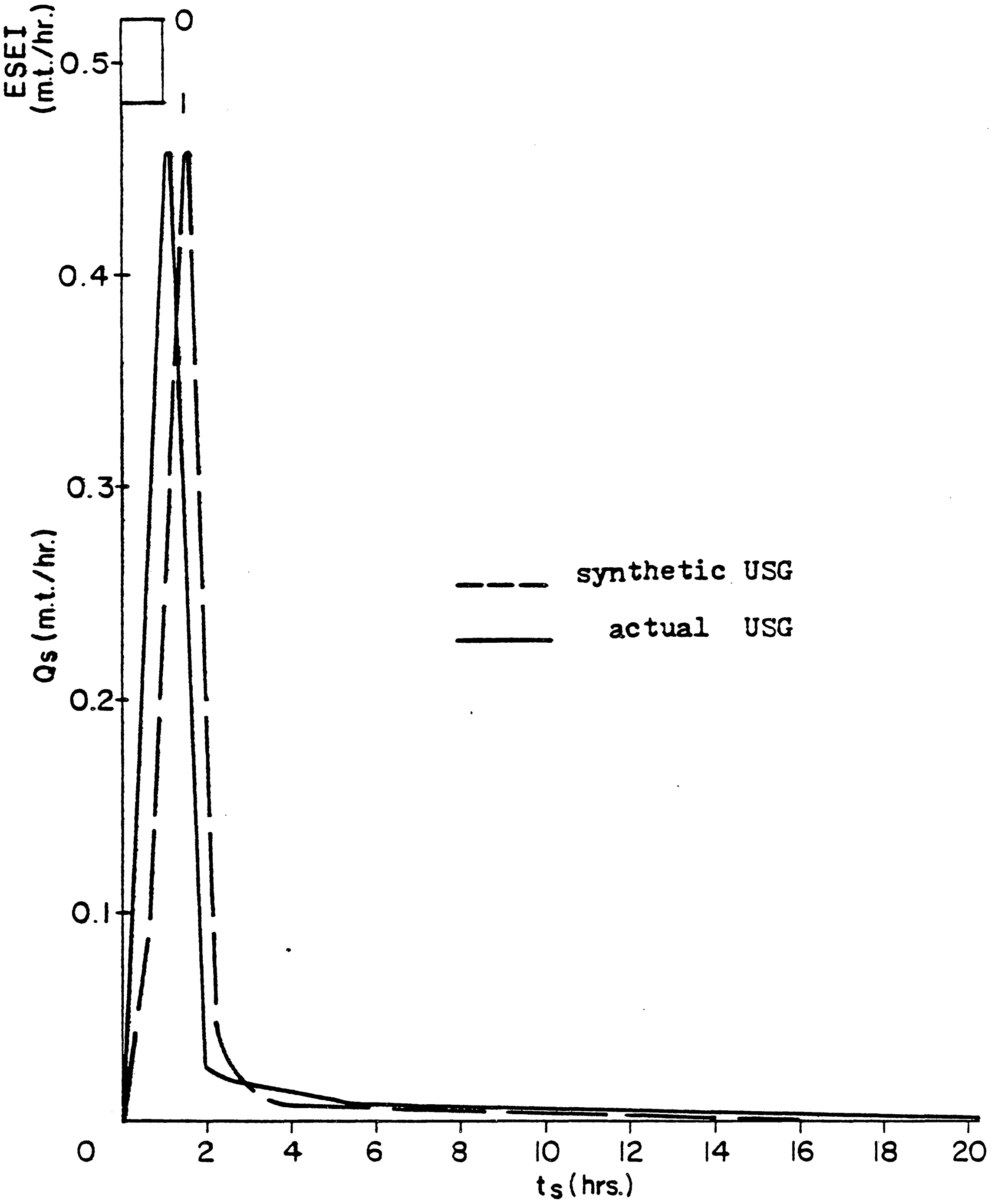


Fig. 6-5. Spatially verified comparison of actual USG vs. synthetic USG for the event occurred on 5/12/74 in watershed 44295

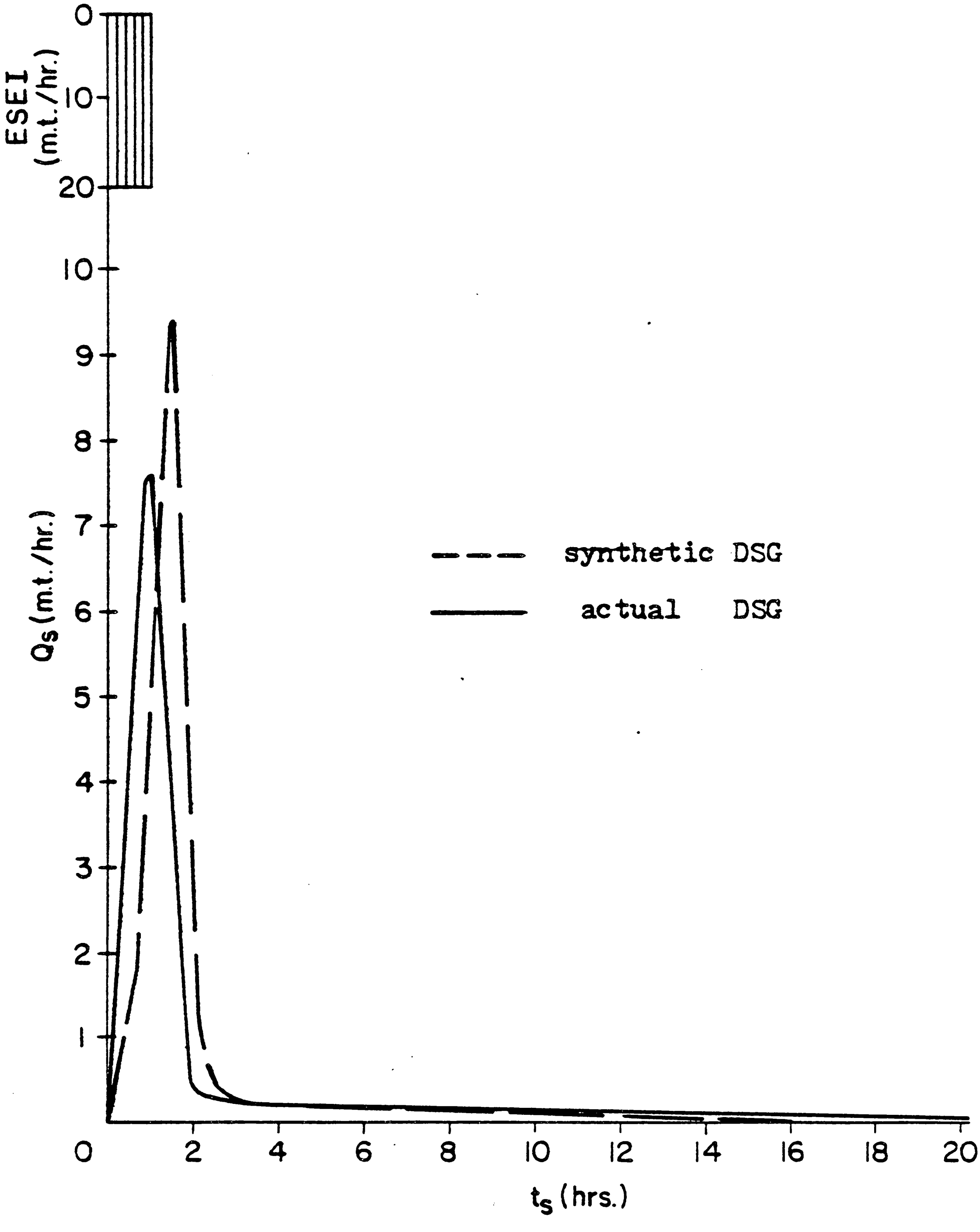


Fig. 6-6. Spatially verified comparison of actual DSG vs. synthetic DSG for the event occurred on 5/12/74 in watershed 44295

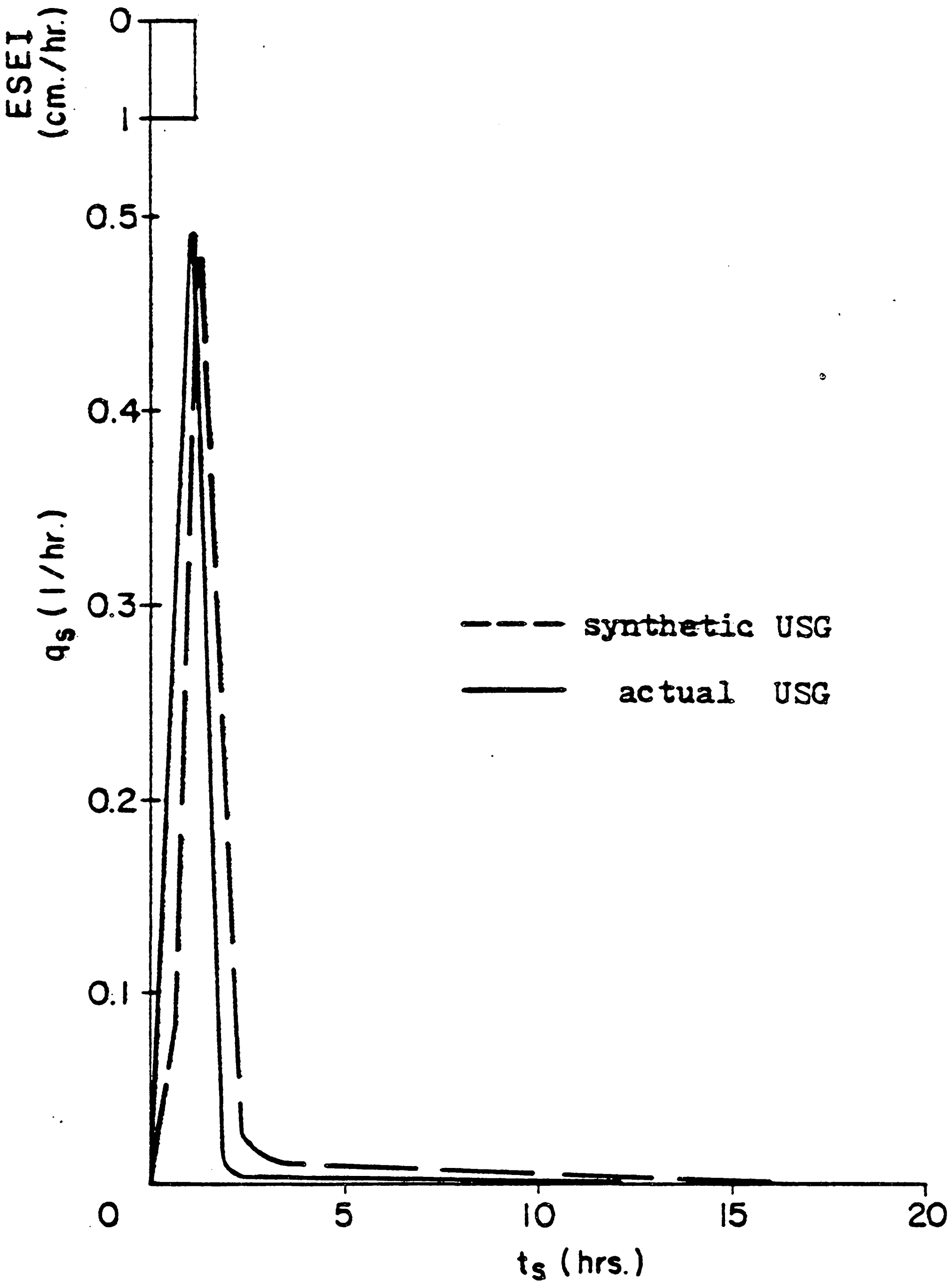


Fig. 6-7. Temporally verified comparison of actual USG vs. synthetic USG for the event occurred on 6/27/78 in watershed 45784

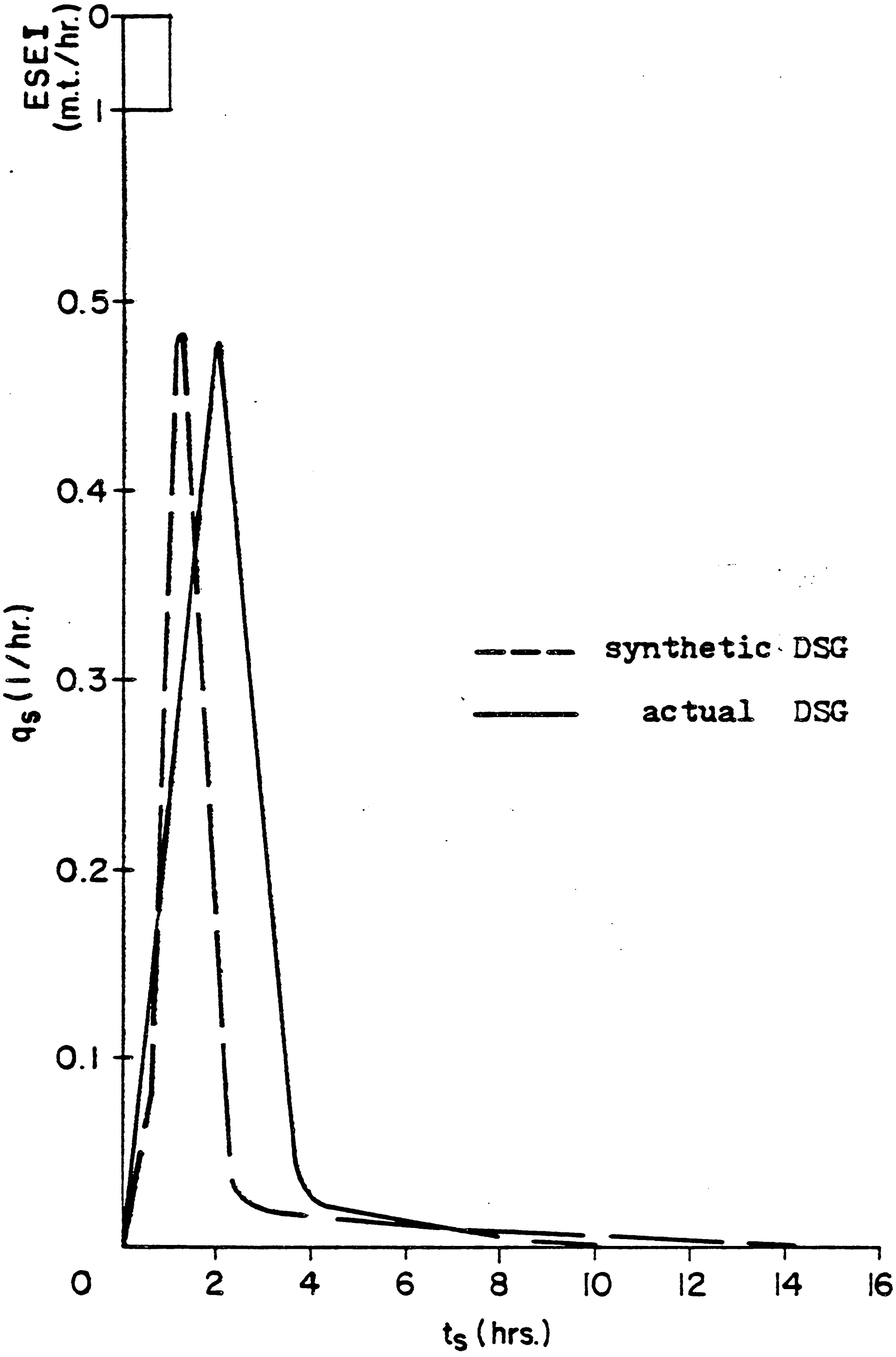


Fig. 6-8. Temporally verified comparison of actual USG vs. synthetic USG for the event occurred on 6/21/78 in watershed 45784

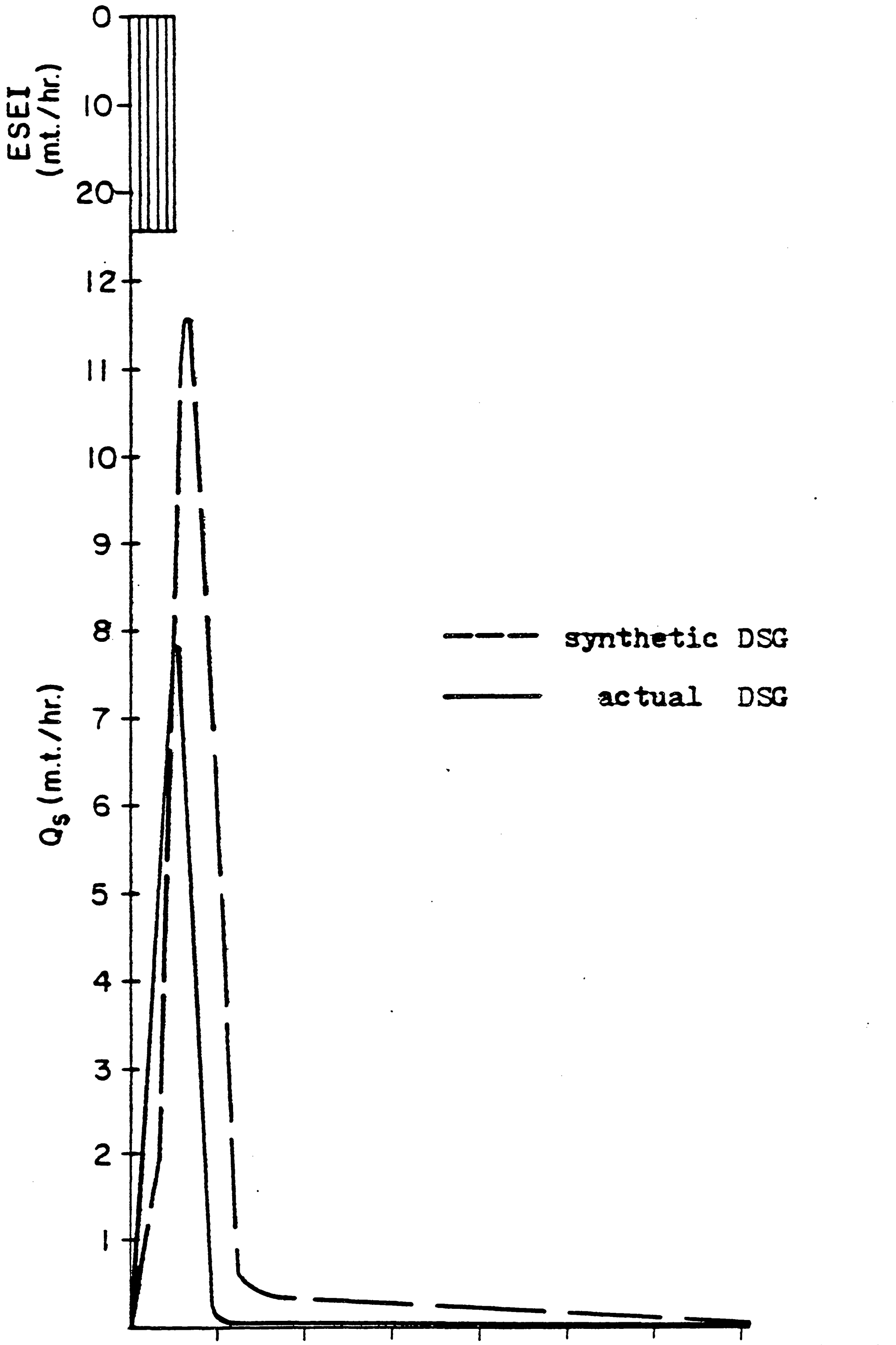


Fig. 6-9. Temporally verified comparison of actual DSG vs. synthetic DSG for the event occurred on 6/27/78 in watershed 45784

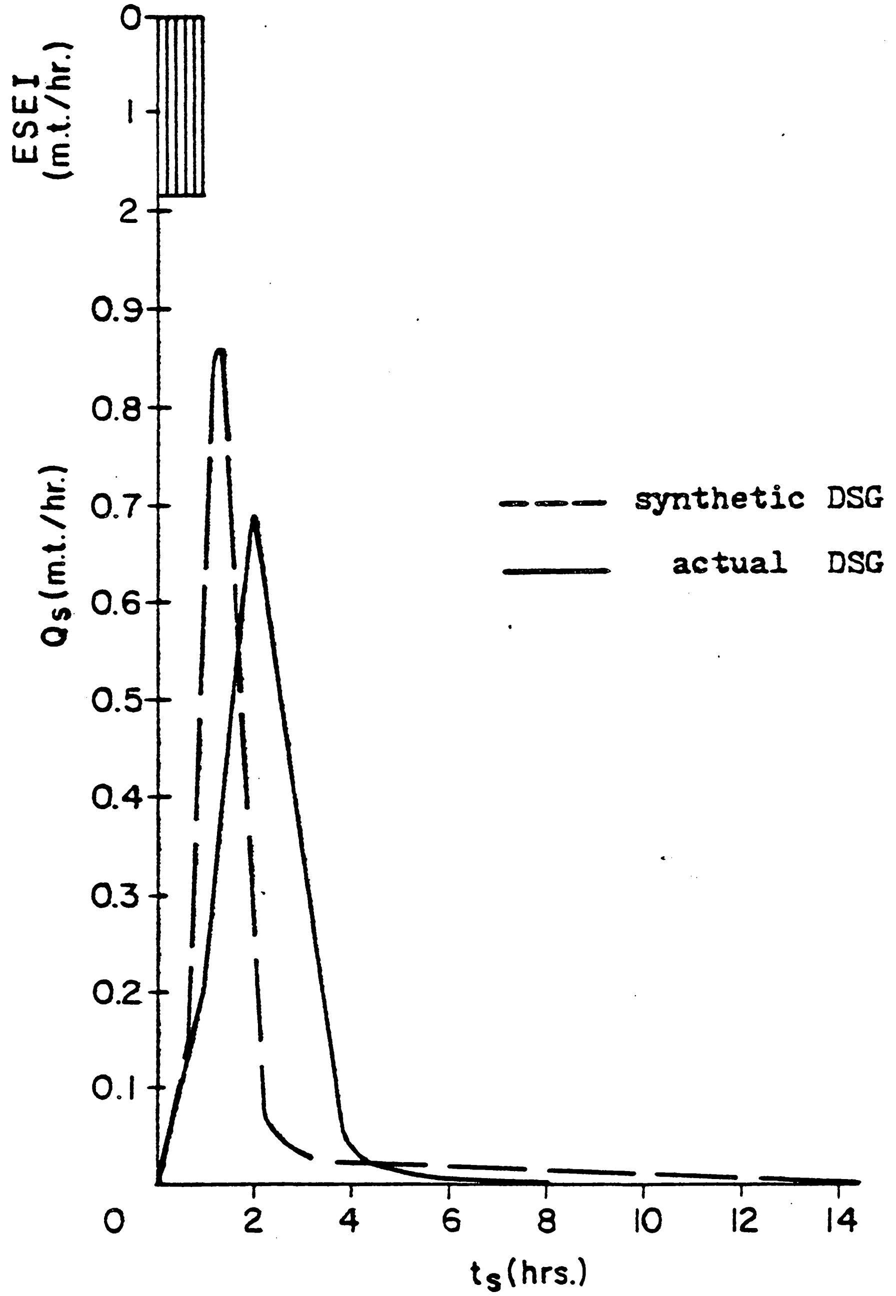


Fig. 6-10. Temporally verified comparison of actual DSG vs. synthetic DSG for the event occurred on 6/21/78 in watershed 45784

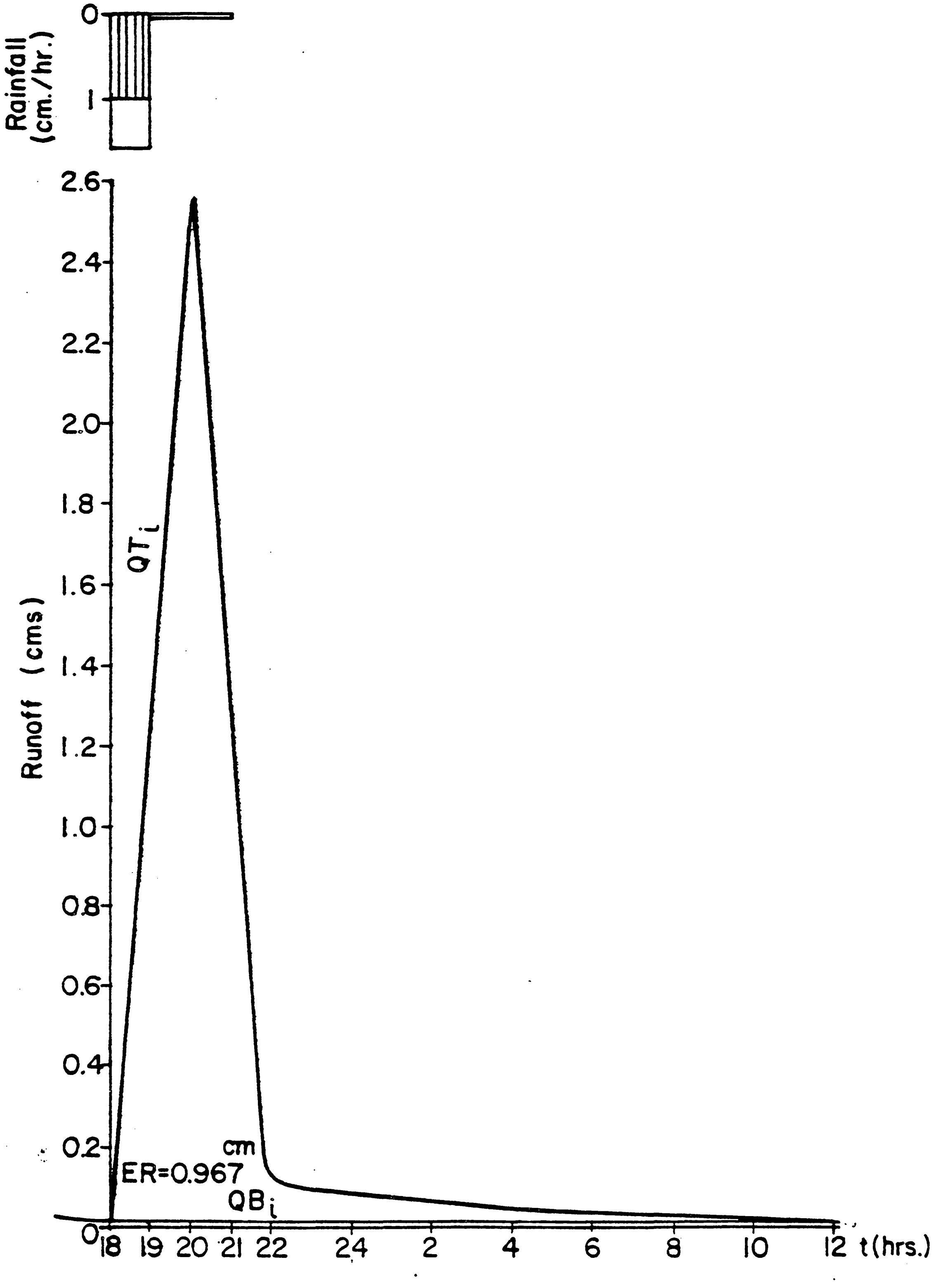


Fig. A. Separation of baseflow from total runoff

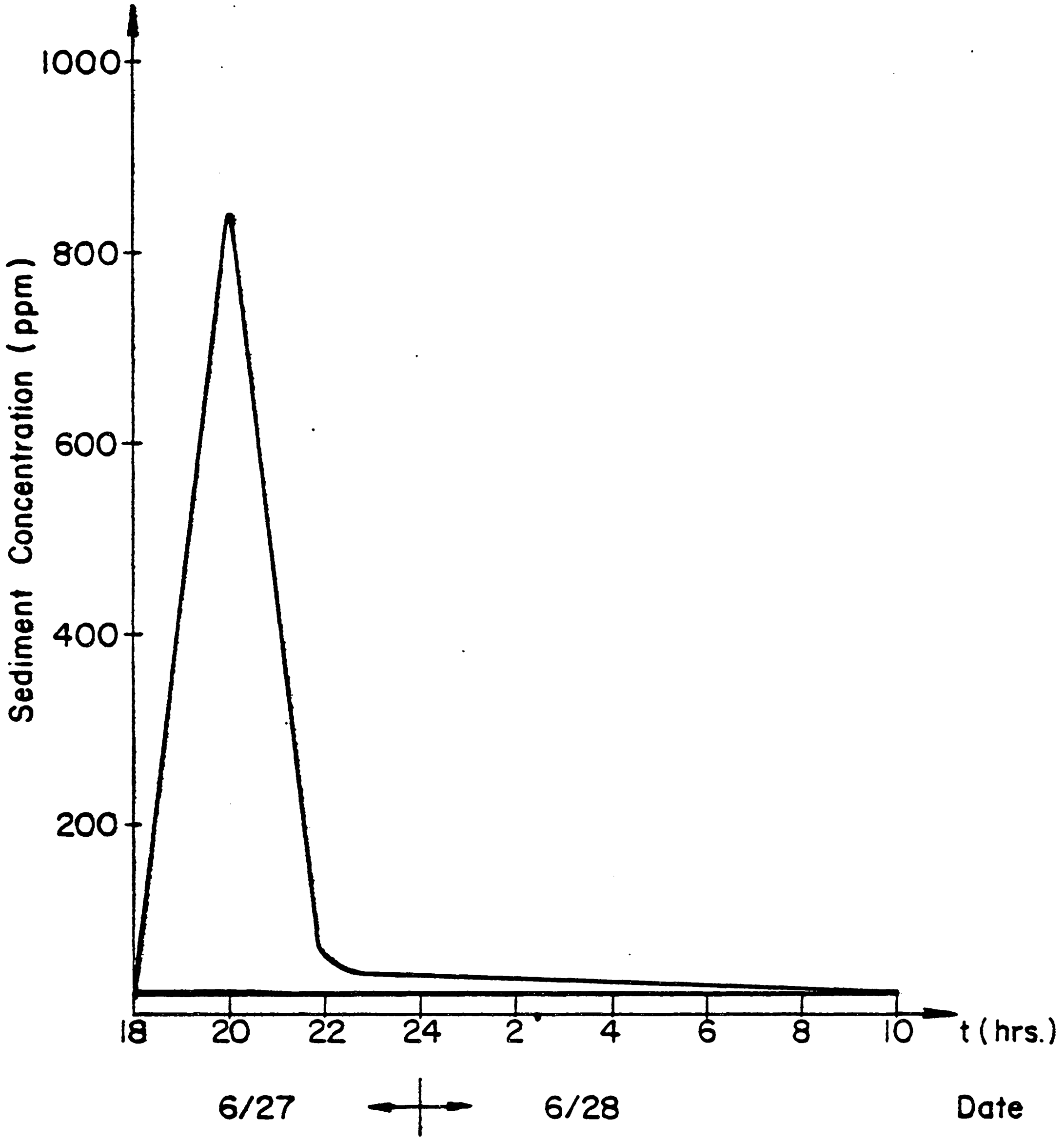


Fig. B. Separation of baseflow sediment concentration from total sediment concentration

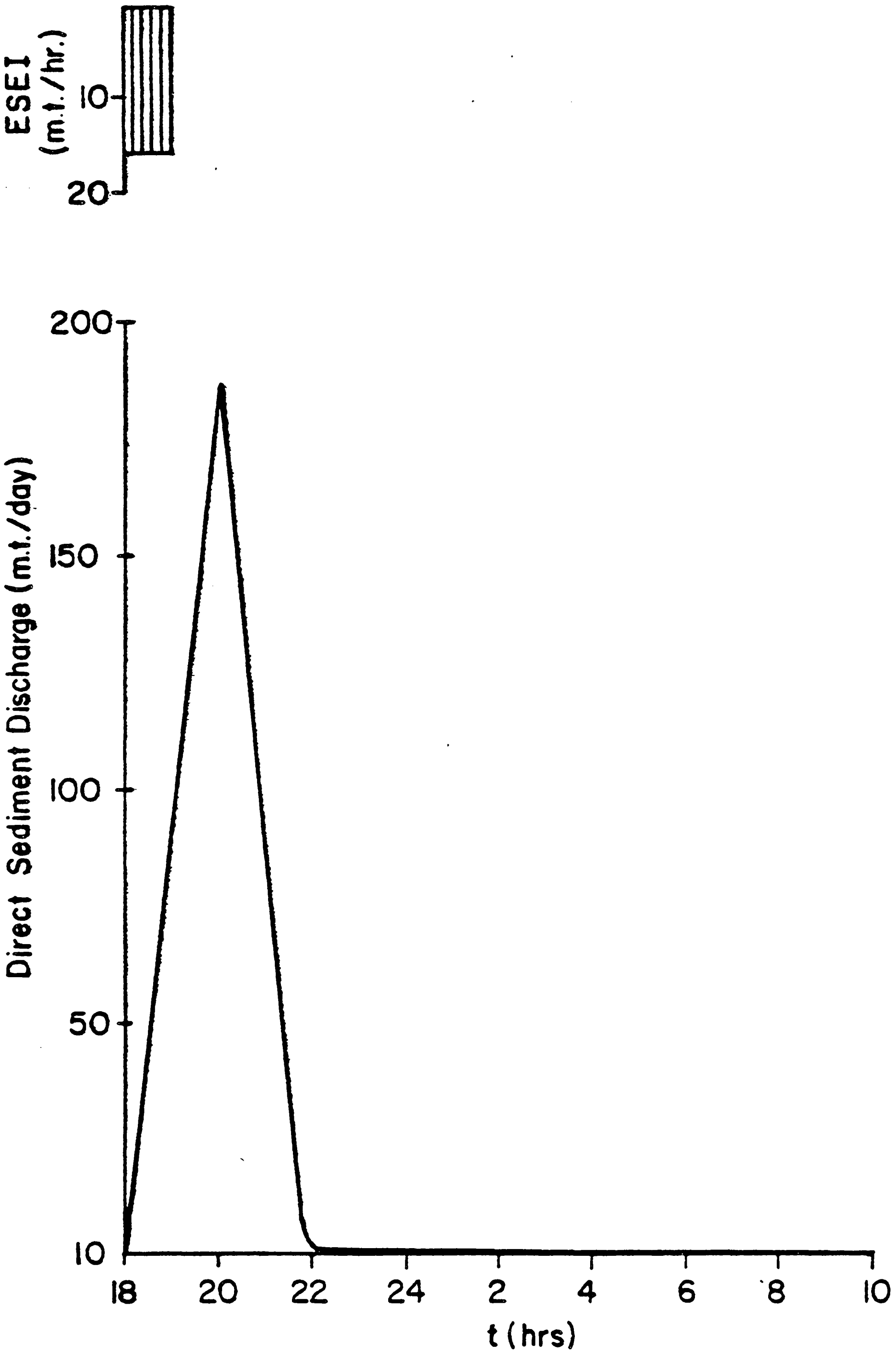


Fig. C. Direct sedimentgraph after separation

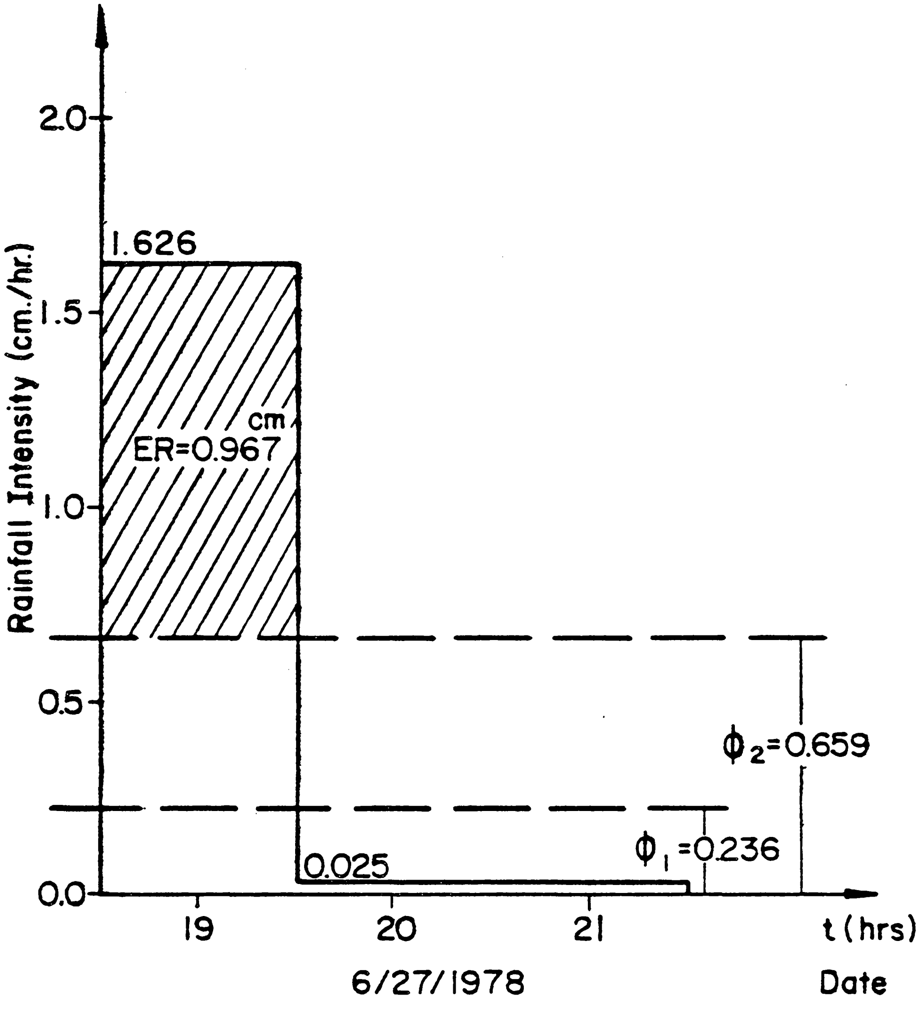


Fig. D. Evaluation of ∅-index

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