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STUDENT AWARD PAPER

STOCHASTIC PREDICTION OF SEDIMENT YIELDS FROM STRIP MINE SPOILS OF THE ARID SOUTHWEST

by

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ABSTRACT

Mathematical simulation of the erosion process is accomplished by using a time series of hydrologic parameters as inputs into a modified form of the Universal Soil Loss Equation. A parameter to account for antecedent moisture conditions was found to improve the predictive success of the Universal Soil Loss Equation. The simulation predicts sediment yield resulting from a stochastic sequence of precipitation events on an experimental watershed. This sediment model will be used as a component in a larger, more complex hydrologic simulation model which can be used to determine optimum reclamation practices for the strip mined areas of the arid Southwest. Data from regraded strip mine spoils at the Black Mesa of Arizona are used in calibrating the model.

INTRODUCTION

Precise quantification of sediment yield from surface mined areas is essential when the current need for increased domestic energy production is coupled with the ever-present concern for environmental quality. The assessment of environmental impacts of a surface mine requires a knowledge of expected sediment yields from the area when the mine is in operation, and years after the reclamation of the land has been completed. Knowledge of the complex sedimentation process is also required to determine reclamation standards and to develop optimum cost-effective reclamation procedures.

The purpose of this paper is to present a method of predicting sediment yields from surface mined lands for individual precipitation events. The Universal Soil Equation is modified to account for antecedent moisture conditions, which directly affect the quantities of surface runoff and the associated sediment yield for a given event. Limited precipitation data from the Black Mesa is used to derive distributions of rainfall characteristics which were combined to simulate sediment yields for an extended period of time. The simulation gives an indication of expected amounts, probabilities of occurrence and return periods of extreme sediment events.

THE STUDY AREA

Strip mining of coal is taking place on the Black Mesa of northeastern Arizona. Peabody Coal Company operates two mines located on lands held in trust by the federal government for the Navajo and Hopi Indians.

Overburden ranging up to 120 feet in thickness is stripped using furrow techniques to expose the coal seams which range from 5 to 30 feet thick. After the coal has been mined, rows of unconsolidated spoil material are recontoured by reclamation crews to slope gradients averaging 8 to 15 percent and ranging up to 300 meters or more in length.

Sediment losses from the strip mine spoils are accelerated by the high erodibility of the soil due to its lack of structure and the absence of organic matter. Vegetation is sparse on freshly regraded spoils, increasing the potential for rainfall and runoff energies to dislodge soil particles and transport them from the surfaces of the spoils into on-site impoundments or into off-site drainages. The semi-arid climate and overgrazing compound the task of reclamation by severely hindering revegetation attempts on the recontoured spoils.

Experimental watersheds on the regraded mine spoil have been instrumented for nearly 4 years by the School of Renewable Natural Resources, University of Arizona, in cooperation with Peabody Coal Company. These study sites are being monitored for precipitation characteristics, surface runoff, infiltration rates, water quality, erosion rates and sediment yield. A 5.5 acre watershed on the reclaimed area is used for parameter values in the prediction model, and expected sediment yields are simulated for this watershed.

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THE PREDICTION METHOD

The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1965) for midwestern agricultural areas, was used as a basis for the prediction model. An additional parameter accounting for antecedent moisture conditions was incorporated into the USLE to improve its predictive accuracy for the study area. The modified equation is given as:

$$A = R\, I_{am}\, K\, (LS)\, C\, P \qquad (1)$$

in which A = the predicted soil loss (tons per acre); R = the rainfall erosion index (foot-ton-inches per acre-hour); I_{am} = the index of antecedent soil moisture; K = the soil erodibility factor; (LS) = the slope length and gradient factor; C = the cropping-management factor; and P = the erosion control practice factor.

The last four parameters of Equation 1 were assumed to remain constant for a particular area of interest over a relatively short period of time. Numerical values of these factors were obtained from previously published nomographs and tables (Wischmeier, Johnson and Cross, 1971; SCS, 1975). Values obtained for the study watershed are K = 0.35; (LS) = 2.72; C = 0.25; and P = 1.0.

The USLE has been most popularly used to predict annual soil loss using an average annual R factor. However, more recently, R values for each event have been used to predict sediment losses for individual storms to obtain greater accuracy (Williams, 1975; Fogel, Hekman and Duckstein, 1976). Renard, Simanton and Osborn (1974) found that a single event on the Walnut Gulch Experimental Watershed in southeastern Arizona accounted for as much as 55 percent of the total annual sediment yield. Therefore, since a few large storms can produce most of the annual sediment yield, it is important to be accurate in predicting the individual storm sediment yields.

Prediction by event also allows for the inclusion of an index of antecedent moisture. Obviously soil moisture directly affects the initiation time and total volume of surface runoff. It is therefore also apparent that the increased energy of larger runoff volumes would yield greater volumes of sediment. A form of a relation proposed by Chow (1964) was used to describe antecedent soil moisture, and is illustrated in Equation 2.

$$I_{am} = 15 \sum_{t=1}^{10} K^t P_t \qquad (2)$$

K is a constant assumed to be equal to 0.85; P is the precipitation amount for a single event in inches; and t is the length of time in days between the day in question, and the day on which the antecedent precipitation occurred. Another assumption made, is that the effect of rain occurring more than 10 days previous to the day in question is negligible. Calculated values of I_{am} for three different events are shown in Table 1.

Table 1. Calculated values for the rainfall factor, R and the antecedent moisture index, I_{am} for 3 individual events

	Date of Event		
	8/11/75	7/26/76	7/30/76
R	1.08	0.92	5.60
I_{am}	1.70	1.01	4.50

The rainfall factor, R is defined to be 1 percent of the erosion-index (EI) units in a single storm or in a year's rainfall. The EI units are a product of the total kinetic energy of a storm and its maximum 30-minute intensity in inches per hour. Equation 3 shows the relationship of Y, the kinetic energy of the rainfall in foot-tons per acre, to X, the rainfall intensity in inches per hour (Wischmeier and Smith, 1958).

$$Y = 916 + 331 \log X \qquad (3)$$

Calculated values of R for the three test events are illustrated in Table 1.

Average values of soil loss per event were obtained from 4 runoff plots on the experimental watershed. Due to the sporadic and infrequent occurrence of rainfall on the Black Mesa, soil loss data was obtained for only 3 events. The modified soil loss equation was applied using the parameters listed in Table 1, and the USLE was also applied using the R factors from Table 1. The values of the four constant parameters mentioned earlier were identical for both equations. Observed soil loss and the predictions of each equation are compared in Figure 1. Note the success of the modified equation for the second and third events. The antecedent moisture factor did not change the near-accurate prediction of the USLE for the second event. However, the prediction of soil loss for the third event by the modified equation was considerably higher than the prediction of the USLE and nearly equal to the observed volume. The prediction of the modified equation for the first storm was quite low, but still an improvement over the USLE.

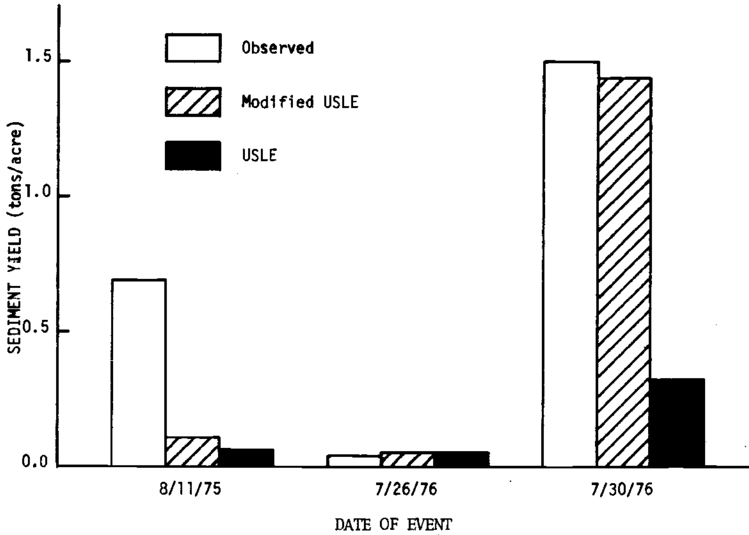

Figure 1. Comparison of observed soil loss to predictions by the modified soil loss equation and the Universal Soil Loss Equation

DEVELOPMENT OF SIMULATION TECHNIQUES

A severe limitation to applying either of the two equations to ungaged watersheds is the difficulty in obtaining the erosion-index units for a storm. Rainfall intensities are needed to calculate values of erosion-index, and it is nearly impossible to estimate intensities without a recording raingage. Attempts have been made to relate readily available precipitation data to the erosion-index units of a given storm. This would eliminate the need for tediously extracting the rainfall intensities from raingage charts, and enable the extrapolation of long-term historical data from one station to a nearby ungaged area.

Ateshian (1974) derived several equations which related the erosion-index of a storm to its precipitation amount and the duration of the event. One equation was found to accurately predict erosion-index units for precipitation characteristics that are representative of Hawaii, Alaska, and the coastal side of the Sierra Nevada and Cascade Mountains in California, Oregon, and Washington. The second equation was said to be representative of the rest of the United States, Puerto Rico, and the Virgin Islands. Upon comparing these equations to precipitation data from the Black Mesa, it was found that the first equation, for the Pacific coast fit the study data significantly better than the second equation. The equation used is:

$$EI = \frac{180\ P^{2.2}}{T_{min}^{\ 0.6065}} \qquad (4)$$

where EI = the erosion-index units; P = the precipitation amount per storm in inches; and T_{min} = the duration of the event in minutes. Figure 2 shows a comparison of Black Mesa data to Ateshian's Type I equation.

Using hypothesized distributions of precipitation characteristics and equation 4, a distribution of EI units and subsequent distributions of sediment yield were simulated. Data from 3 years of climatic records taken at the study site were used to derive distributions for precipitation per event, event duration, and event interarrival time. Fogel, Hekman and Duckstein (1976) found that precipitation amount and storm duration are interrelated for summer events. To satisfy this relationship for simulation purposes, a separate distribution of duration was developed for each of 3 precipitation classes (0.0 inch to 0.09 inch; 0.1 inch to 0.25 inch; and greater than 0.25 inch). All five of the characteristics were hypothesized to be exponentially distributed as shown in Figures 3 and 4. Comparison of the observed data to the hypothesized distributions was made using the Kohmogorov-Smirnov goodness-of-fit test. At the significance level, $\alpha = 0.10$, none of the hypothesized distributions could be rejected.

In addition to assuming that the precipitation characteristics were distributed exponentially for the simulation model, it was also assumed that all of the annual sediment yield was produced in the summer. This was defined to be the period from April 1 to October 31 when the likelihood for high-intensity convective storms is greatest.

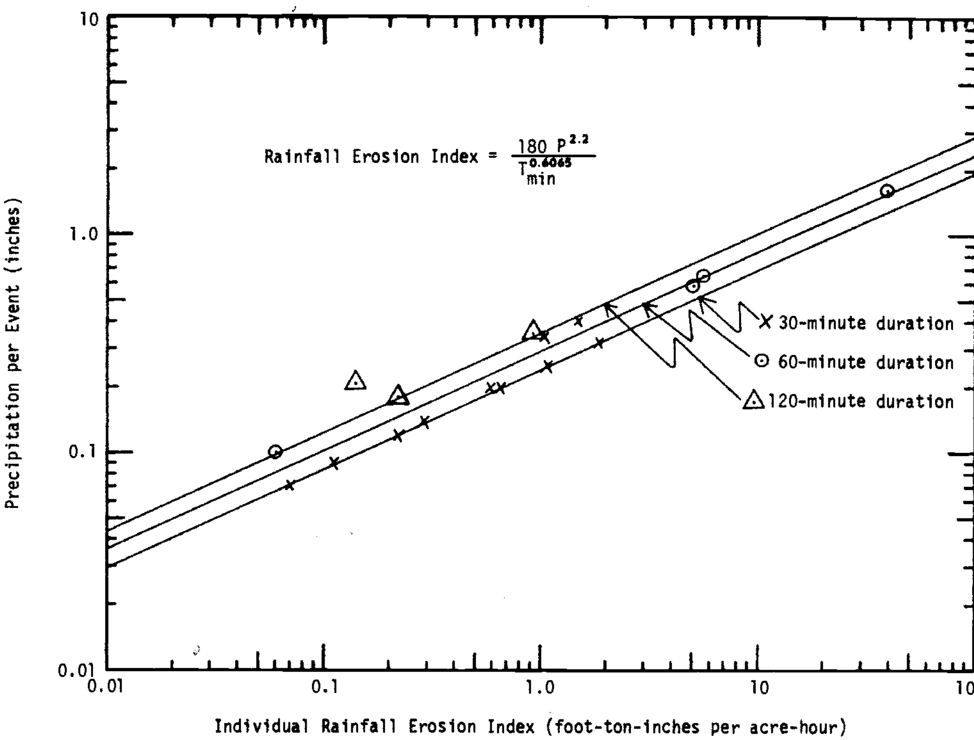

Figure 2. Comparison of Black Mesa data to Ateshian's Type I Equation for determining erosion-index units from durations and precipitation amounts

A computer model was developed to simulate 700 years of hypothetical sediment data using equations 1, 2, and 4. The probability mass functions (PMF) of sediment yield per event and annual sediment yield are shown in Figure 5. As yet, the model does not determine the lag time between the beginning of a rainfall event and the time when surface runoff is initiated. Minute amounts of sediment yield are therefore recorded for very low rainfall amounts that would not actually produce surface runoff. To account for this, the smallest class (0.00 to 0.05 tons/acre) was ignored when calculating the PMF of sediment yield per event. The mean volume of sediment produced in 1352 events was 0.19 ton per acre. A yield of less than 0.1 ton per acre occurred for more than 50 percent of the runoff events. The extreme event in 700 years of simulated data was 5.9 tons per acre from the experimental watershed. A mean annual volume of 0.53 ton per acre was predicted by the model.

CONCLUSIONS

Limited data has shown that the Universal Soil Loss Equation, modified to account for antecedent soil moisture may be used for predicting soil loss from reclaimed mine spoils on the Black Mesa. Additional instrumentation has been installed to measure sediment yield, and the results will be used to further validate and improve the existing model. An advantage of the proposed method is that estimation of the rainfall factor has been extremely simplified by using the relation developed by Ateshian (1974). This allows for use of the model where available rainfall data is limited.

The event-based approach enables simulation techniques to be applied to the modeling procedure. Simulations can provide planners and managers with probable volumes of sediment resulting from various mine reclamation practices and different surface treatments. The expected lifetime of water-holding installations on the reclaimed areas can also be more accurately evaluated using this method.

Incorporation of the sediment model as a separate routine in a comprehensive model to evaluate the hydrologic processes on the regraded mine spoils is being planned. With this model as a decision-making tool, optimum reclamation methods can be determined that will minimize the high cost of reclaiming the land and at the same time, minimize the impact of the mining operation on the surrounding area.

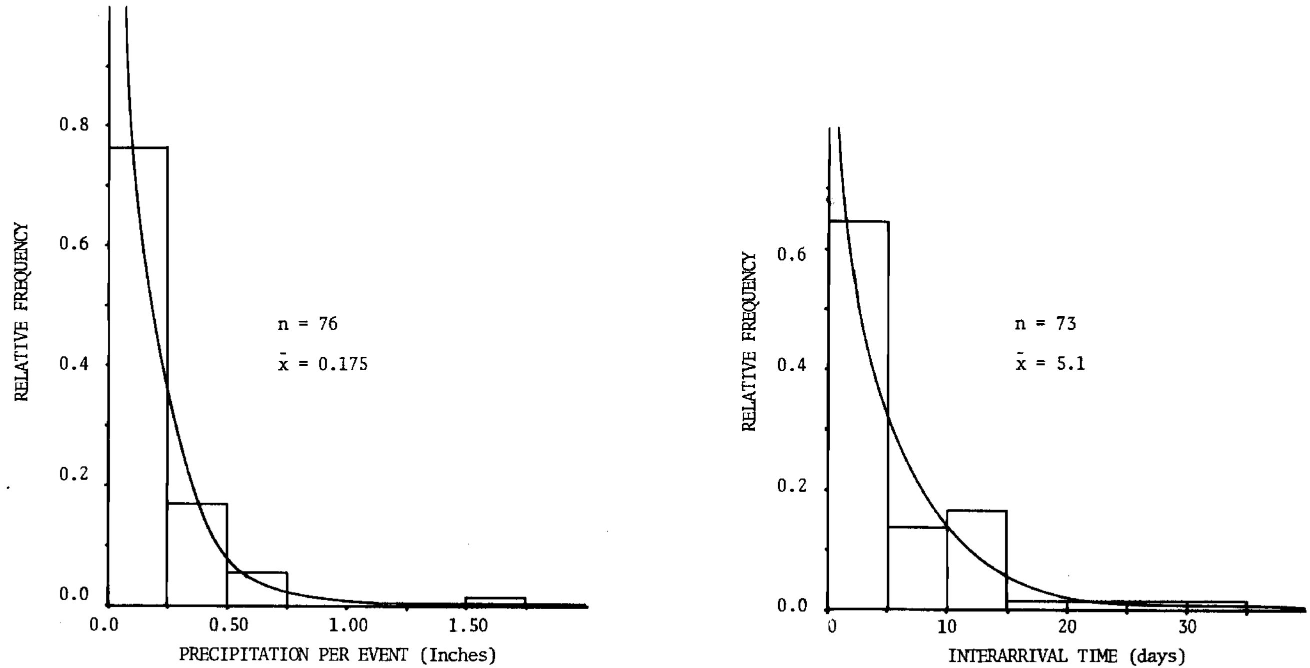

Figure 3. Illustrations of hypothesized exponential distributions compared to probability mass functions of the observed data for precipitation per event and event interarrival time

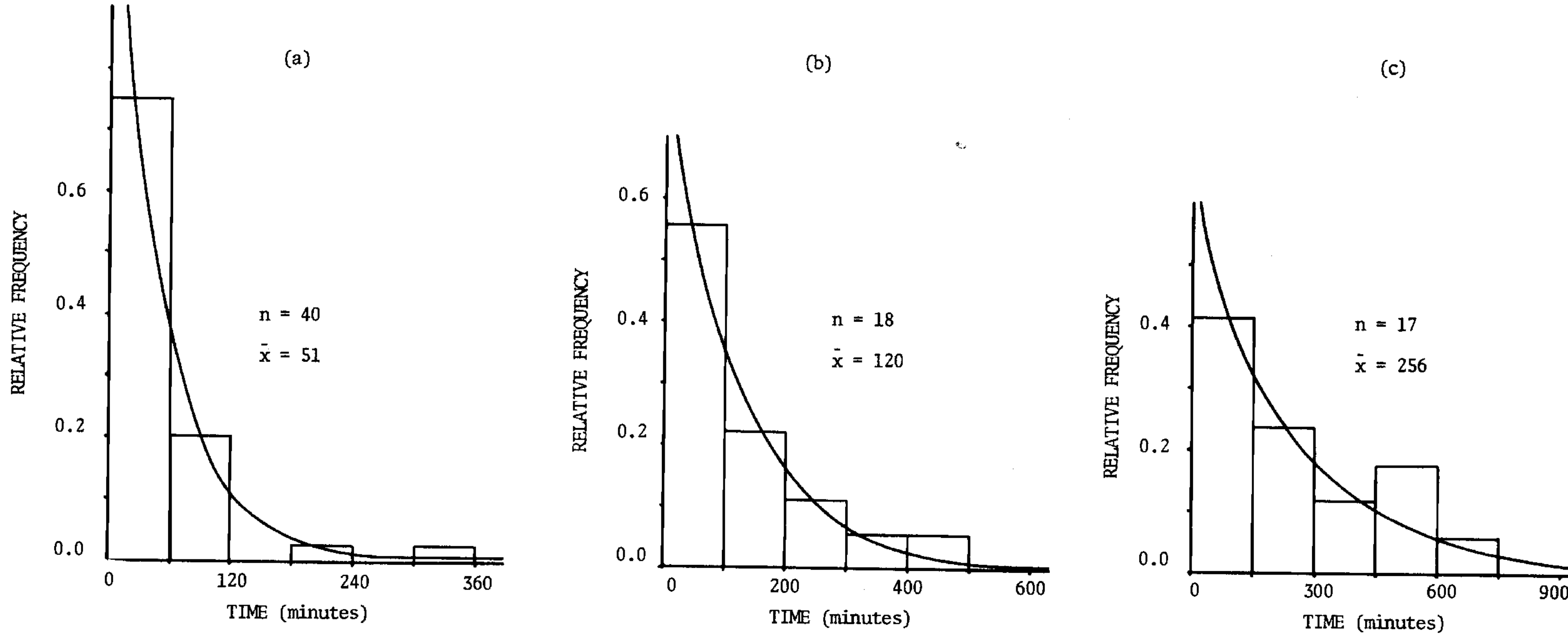

Figure 4. Illustrations comparing hypothesized exponential distributions of event duration to probability mass functions of the observed durations for precipitation events (a) between 0.00" and 0.09"; (b) between 0.10" and 0.25"; and (c) greater than 0.25"

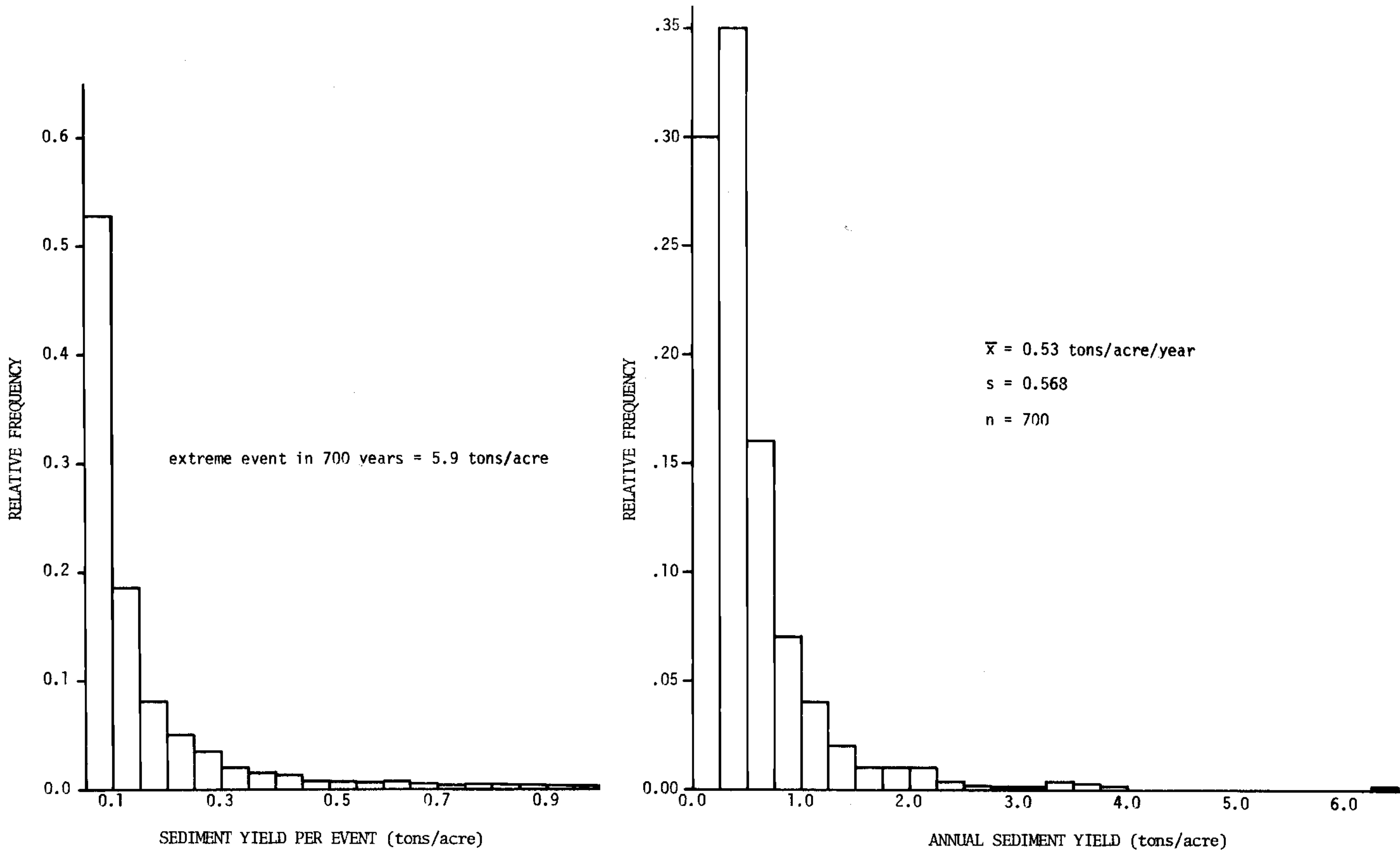

Figure 5. Probability mass functions of sediment yield per event and annual sediment volumes from 700 years of hypothetical data simulated by the model

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