Runoff and Erosive Storm Occurrence Probabilities

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ABSTRACT

LONG-TERM records of storm magnitude and intensity were used to generate monthly occurrence probabilities of hydrologic events on agricultural lands in mid-Michigan. Based on the SCS curve number method, appropriate combinations of storm magnitude and 5 day antecedent rainfall from 53 years of records were employed to predict the occurrence of overland flow events. Records of excessive rate storms and antecedent rainfall were used to determine the occurrence probability of potentially erosive overland flow events.

INTRODUCTION

Since the passage of the Federal Water Pollution Control Amendments of 1972 (PL 92-500), national efforts to curtail waterborne pollutants from agricultural lands have been steadily increasing. In the Great Lakes drainage basin, fine textured agricultural soils planted to row crops have been identified as the major nonpoint source of sediment and phosphorus per unit area (Pollution from Land Use Activities Reference Group, 1978). Management practices such as conservation tillage and subsurface tiling have been proposed to reduce waterborne discharges from agricultural lands to receiving waters (edge-of-field losses). Several field trials have been undertaken in selected areas of the Great Lakes Basin (Lake and Morrison, 1977; Ellis et al., 1978).

Budget constraints coupled with the immediate information needs of administrators have restricted the length of field evaluations. Many studies evaluating edge-of-field losses range from two to five years. However, Chow (1964) concluded that twenty years of data are necessary to characterize hydrologic events. The dangers of basing management decisions on the results of short or moderate term field studies are best illustrated by the work of Free and Bay (1969).

Since 1895, the National Weather Service (formerly the United States Weather Bureau) has recorded intense rainstorms that meet the classification of an excessive rate storm. Excessive rate storms are defined as storms of depth (mm) equal to or exceeding the quantity (5. + 0.25t) where t is the storm duration in minutes (Schwab et al., 1981). Greer (1971) found that excessive rate storms generated 77% of the soil loss during a 6 year study. Intense storms of relatively small magnitude can produce a significant sediment loss. A 19 mm excessive rate storm in June, 1982 produced the largest storm generated sediment loads monitored during a 2 1/2 year study in mid-Michigan (Gold, 1983). The daily or hourly precipitation records which are utilized in numerous edge-of-field loss models do not have the sensitivity to identify small or moderate magnitude high intensity storms.

Long term records of excessive rate storms and daily precipitation were utilized to identify those periods during the year when runoff or erosion is likely to occur on agricultural lands in the Saginaw Bay drainage basin of Michigan (Fig. 1). The monthly occurrence probabilities of overland flow events were predicted with the SCS curve number method using appropriate combinations of antecedent rainfall and storm magnitude class. Records of excessive rate storms and antecedent rainfall were used to determine the occurrence probabilities of potentially erosive overland flow events. This information can aid in the selection of management practices that provide effective control for conditions most likely to produce the greatest edge-of-field losses.

APPROACH

Occurrence Probability of Overland Runoff Events

The runoff curve number method (Mockus, 1964) coupled with probability estimates of storm magnitude and antecedent precipitation were utilized to predict the monthly probability of overland flow in the study region. The curve number (CN) method predicts runoff whenever the volume of a precipitation event exceeds a

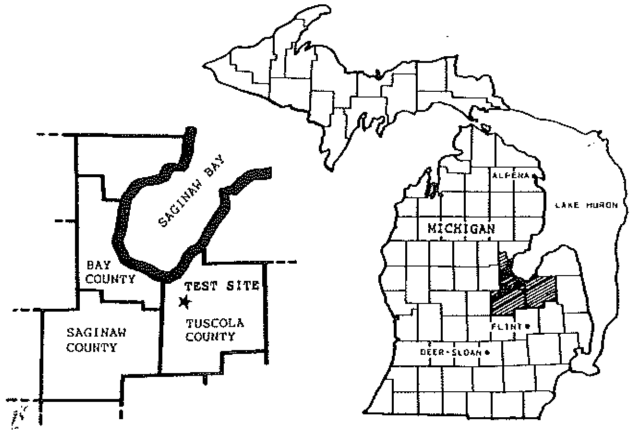

Fig. 1—Location of study region.

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quantity known as the "initial abstraction" (Ia). The initial abstraction represents the hydrologic losses resulting from interception, surface storage, and infiltration prior to runoff. The initial abstraction is based on the SCS runoff curve number for a given site; a function of soil type, antecedent soil moisture condition (AMC class), and retention storage. Specifically, the CN method estimates Ia as the product of 0.2 times S where S (mm) is derived directly from the appropriate curve number. Over an extended period of time the physical characteristics of the site can be expected to remain relatively constant, but the AMC class will change, altering Ia and the minimum magnitude of precipitation required by the CN method to generate overland flow.

The CN method uses the 5 day antecedent precipitation volume to define three AMC classes: drier than annual flood conditions (AMC I), average annual flood conditions (AMC II), and wetter than annual flood conditions (AMC III). For a given site the minimum quantity of five-day antecedent precipitation required for categorization in AMC II or AMC III increases in one discrete step during the growing season. This increase reflects the removal of soil moisture that actively growing plants utilize through transpiration. The method of characterizing AMC class by five day antecedent precipitation was examined in detail by Hawkins (1978).

Based on drainage characteristics, cropping practices, and field monitoring, a curve number of 81 at AMC II was chosen to represent the study region. Table 1 lists the minimum quantity of precipitation that is required to exceed Ia and generate overland flow at each AMC class.

When precipitation is greater than the depths listed in Table 1, overland flow is predicted. To exclude trace volumes of overland runoff from the probability analysis, precipitation depths were used which would result in at least 2 to 3 mm of runoff for each AMC level (Table 2).

For discussion purposes storms capable of generating overland flow at AMC III will be referred to as small storms (SS). Moderate storms (SM) are designated as those events which can cause runoff at either AMC III or AMC II. Storms which will result in overland flow regardless of soil antecedent moisture (i.e. AMC I, II or III) are classified as large storms (SL). Magnitudes of each storm class are given in Table 3.

The occurrence probability of each runoff scenario is the intersection of the probability of a storm of a given magnitude class P[S(i)] with the occurrence probability

TABLE 1. MINIMUM PRECIPITATION PREDICTED TO GENERATE OVERLAND FLOW AT STUDY SITE

AMC	CN	Precipitation, mm
I	64	28.5
II	81	12.0
III	92	4.5

TABLE 2. MINIMUM PRECIPITATION DEPTHS USED IN OVERLAND FLOW ANALYSIS

AMC	Precipitation, mm	Predicted runoff, mm
I	51.0	3.0
II	25.5	2.5
III	13.0	2.5

TABLE 3. COMBINATIONS OF STORM MAGNITUDES AND AMC CLASSES EXPECTED TO GENERATE RUNOFF

Storm class	Magnitude, mm	AMC class
SL	> 51.0	I, II, III (AMC≥I)
SM	25.5-51.0	II, III (AMC≥II)
SS	13.0-25.5	III

of the set of AMC classes P[AMC(j)] that is expected to promote runoff from a storm of magnitude S(i). If the occurrence of each AMC class is assumed to be independent of the occurrence or magnitude of a storm event, the runoff occurrence probability is obtained directly from

$$P[RO(i,j)] = P[S(i) \cap AMC(j)] \quad \ldots\ldots [1]$$

where RO(i,j) is a runoff event resulting from one of the three combinations of storm magnitude (i) and the set of AMC classes (j) listed in Table 3.

Daily rainfall events may compose a portion of longer continuous storm events. In these situations AMC class may be influenced by the conditions which generate a storm. Since independence of AMC class and storm events cannot be assumed, conditional AMC probabilities must be utilized to compute runoff occurrence probabilities. Employing standard probability relations (Bhattacharyya and Johnson, 1977), the intersection of a given storm event and an AMC condition is found from

$$P[S(i) \cap AMC(j)] = P[S(i)] \cap P[AMC(j) \mid S(i)] \quad \ldots\ldots [2]$$

when AMC class is not considered to be independent of a storm event. P[AMC(j) | S(i)] is the conditional probability of the occurrence of a given set of AMC conditions (j) when a given storm class (i) occurs.

Since storm runoff is expected to occur as a result of any of the three combinations of storm magnitude and AMC class in Table 1, the occurrence probability for any storm runoff event can be expressed as

$$P(RO) = P(SL \cap AMC \geq I) + P(SM \cap AMC \geq II) + P(SS \cap AMC\ III) \quad \ldots\ldots [3]$$

The data base used in this analysis consisted of 53 years of daily precipitation values (1928-1980) recorded to the nearest 0.25 mm (0.01 in.) at a NOAA weather station located at Caro, MI (U.S. Dept. Comm., 1928-1980). Analysis was restricted to the monthly occurrence probability of storm runoff from April 1 to October 31 to avoid situations for which the CN method is not intended, such as snowmelt runoff and frozen soils.

Corn is planted approximately May 7 in the study region. Its growing season was defined to be from June 1 to September 30. The division between dormant and growing season was based on when evapotranspiration might begin to accelerate due to the growing crop. In accordance with the curve number method different magnitudes of antecedent precipitation were used to define each AMC class during the growing and the dormant seasons.

Determining P[AMC(j) | S(i)]

Monthly estimates were derived for the conditional probability of each AMC class occurring with each storm class. A running total was kept of the five-day antecedent precipitation permitting daily classification of the AMC status. Whenever one of the three storm classes of interest occurred, the AMC class of the previous 5 days was identified and tabulated. The total number of occurrences of S(i) in each month for each AMC class was then divided by the total number of storm events of class (i) in the month for the period on record to determine the monthly conditional probability.

Determining P[S(i)]

The occurrence probability of storms of each magnitude class of interest was determined by the extreme value method (Chow, 1964). For a given month, the extreme value series was obtained by selecting the maximum daily precipitation event from each year of record. Pearson's Goodness of Fit test was used to evaluate the suitability of lognormal, normal, and Type I Fisher and Tippett distributions to characterize the annual and monthly series of interest (Meyer, 1970). The lognormal distribution was accepted for each series. The two other distributions were rejected P(0.95) for at least two of the tested series and where accepted did not improve the fit for the data. A lognormal distribution was therefore used to obtain the monthly probability of each storm class (Chow, 1964). The predicted values were adjusted to compensate for the difference between observational day data, (i.e. midnight to midnight), and the values expected if precipitation records based on any consecutive 24 h period were utilized (Hershfield, 1961).

As indicated in Table 4, the predictions for 2, 5 and 10 year annual storms derived from the data set compare quite well with the estimates obtained from the Rainfall Frequency Atlas of the United States (Hershfield, 1961).

OCCURRENCE PROBABILITIES OF POTENTIALLY EROSIVE RUNOFF EVENTS

A high intensity storm that causes soil detachment will not generate edge-of-field losses unless overland runoff occurs. To obtain the monthly probabilities of potentially erosive events in the study region, the magnitude and frequency of excessive rate storms were coupled with records of antecedent precipitation. These runoff events can only be considered as potentially erosive, since sediment detachment and transport will depend on crop cover and surface condition as well as rainfall intensity.

Excessive rate storms that occur before a crop canopy is established can generate considerable soil detachment and transport from a field. After July, in the study region, the crop canopy will dissipate most of the energy in a high intensity storm, reducing the likelihood of an erosive event. Runoff monitored from a 50 year excessive rate storm on standing corn in September, 1981, generated low sediment movement although its rainfall erosion index (EI) was 70 (Gold, 1983); nearly equal the annual average of 75 (Wischmeier and Smith, 1978). Occurrence probabilities of potentially erosive runoff events were therefore computed only for the periods from April 1 through July 31.

Mockus (1964) does not consider storm intensity in the curve number method. In this analysis, the same minimum precipitation volumes selected to generate runoff for each AMC class were used regardless of storm intensity (Table 2). Excessive rate storms of large, moderate or small magnitude class (Table 3) are denoted as XL, XM, and XS, respectively. The occurrence probability of potentially erosive runoff events (PERO) can be expressed as

$$P(PERO) = P(XL \cap AMC \geqslant I) + P(XM \cap AMC \geqslant II) + P(XS \cap AMC\ III) \quad [4]$$

The intersection of each excessive rate storm class and the appropriate AMC conditions was found using the occurrence probability of each excessive rate storm class and the conditional AMC probabilities P[AMC(j) | X(i)], where X(i) is the ith excessive rate storm class.

Data on excessive rate storms were not recorded in the immediate vicinity of the study region. Within the mid-Michigan region, the most extensive records of excessive rate storms were found to be the Deer-Sloan rain gauge network. This network is located near E. Lansing, MI, 140 km SSW of the study site (MDA/DC)*. Twenty-five years of data from five of the 22 gauges were manually sorted to delineate the average monthly occurrence of excessive rate storms of each magnitude class. To check the applicability of the data set obtained from the Deer-Sloan network to the study region, the data were compared graphically to the limited data available for Flint, MI (70 km south of the study region) and to data from Alpena, MI (130 km north of the study site). During the years 1958-1972, records of excessive rate storms were kept at all three stations permitting a comparison based on 15 years of data (U.S. Dept. of Commerce, 1958-1972). A similar distribution pattern of excessive rate storms occurred at all three locations (Fig. 2).

The monthly occurrence probability of an excessive rate storm was computed as

$$P[X(i)] = P[S(i)] \cap P[X(i) \mid S(i)] \quad [5]$$

where P[S(i)] is the occurrence probability of a given storm class and P[X(i) | S(i)] is the conditional probability of an excessive rate storm. The monthly conditional occurrence probability of each excessive rate storm class was computed for the period of record as

$$P[X(i) \mid S(i)] = [\text{Total number of excessive storms for class (i)}]/[\text{Total number of storms of class (i)}] \quad i = S, L\ M. \quad [6]$$

TABLE 4. COMPARISON OF ESTIMATES OF 2, 5 AND 10 YEAR STORM VOLUMES

Return period, yrs	Adjusted lognormal estimates, mm	Hershfield (1961) estimates, mm
2	56.0	56.0
5	67.5	70.0
10	78.0	81.0

*MDA/DC. (Michigan Dept. of Agriculture/Div. of Climatology). 1957-1981. Unpublished Data. E. Lansing, MI 48824.

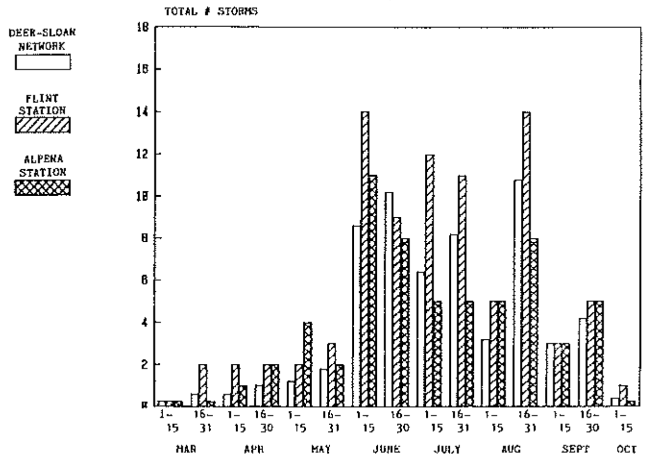

Fig. 2—Number of excessive rate storms ⩾ 13.0 mm, 1958-1972.

Daily precipitation records were manually reviewed to establish the AMC class of each excessive rate storm. The conditional AMC class probability was computed as

$$P[AMC(j) \mid X(i)] = [\text{Number of occurrences of } AMC(j) \text{ given } X(i)]/[\text{Total number of } X(i)] \quad [7]$$

RESULTS AND DISCUSSION

Table 5 lists the monthly occurrence probabilities of overland runoff events in the study region. Overland flow events were predicted to be irregular occurrences. The highest probabilities for overland runoff events are found to coincide with planting and emergence for corn (May). Numerous researchers have found that runoff events following planting often carry high concentrations of nutrients and pesticides (Wauchope, 1978; Baker, 1980). Most of the post-planting runoff events predicted in the study region result from small or moderate magnitude storms with high antecedent moisture conditions.

Table 6 gives the occurrence probability for any excessive rate storm greater than 13.0 mm in the study region. Few high intensity storms occur during the fallow periods (October through May), when the soil is most susceptible to sediment detachment. June through August was found to be the period with the greatest likelihood for high intensity storms. For sediment loss to occur, however, surface cover and edge-of-field runoff probability must be considered.

TABLE 6. OCCURRENCE PROBABILITY OF EXCESSIVE RATE STORMS

Month	P(S)	P(X|S)	P(X)	T(yr)
April	0.70	0.19	0.13	7.7
May	0.85	0.13	0.11	9.1
June	0.95	0.54	0.51	2.0
July	0.86	0.43	0.37	2.7
August	0.88	0.42	0.37	2.7
September	0.84	0.21	0.18	5.6
October	0.75	0.02	0.02	50.0

P(S) based on 53 years of record at Caro, MI

P(X|S) based on 25 years of record for the selected stations of the Deer-Sloan network, near E. Lansing, MI

$P(X) = P(S) \cap P(X|S)$ - equation [5]

The probability of runoff events generated by excessive rate storms is listed in Table 7. The analysis shows that virtually all of the overland flow events that occur during May are the result of low intensity storms and little sediment movement should be expected from any management practice. During April, the occurrence of overland flow from excessive rate storms is expected to have a 14 year return interval. June was found to have the greatest likelihood for generating erosion and sediment loss. Cultural practices which reduce erosion should be in place during June to reduce annual sediment losses.

Evapotranspiration from the developing corn is an important factor in minimizing real and predicted runoff losses during June. Field beans, the other major crop in the study region, are planted approximately June 1, (3 weeks later than corn) and have a lower rate of evapotranspiration during June. Classification of AMC during June would more appropriately be based on dormant season criteria, potentially resulting in greater likelihood for runoff and erosive events when compared to the actively growing corn crop.

CONCLUSIONS

Long term records of precipitation magnitude and intensity can be used to predict occurrence probabilities of overland flow and potentially erosive flow events. In the mid-Michigan region the highest occurrence probabilities for overland flow events coincided with spring planting and crop emergence. Runoff during May was generated by low intensity storms, while June events had the greatest likelihood for generating edge-of-field sediment loss.

TABLE 5. MONTHLY OCCURRENCE PROBABILITIES OF OVERLAND RUNOFF EVENTS, P(RO), CARO, MI

	Small storms			Moderate storms			Large storms	Runoff	
Month	P(SS)	P(AMC III|SS)	P(SS∩ AMC III)*	P(SM)	P(AMC ⩾ II|SM)	P(SM∩ AMC ⩾ II)†	P(SL)‡	P(RO)§	Return period T(yr)
April	0.30	0.18	0.054	0.36	0.14	0.050	0.04	0.144	6.9
May	0.42	0.18	0.076	0.38	0.29	0.110	0.05	0.236	4.2
June	0.38	0.03	0.011	0.47	0.19	0.089	0.10	0.199	5.0
July	0.37	0.02	0.007	0.35	0.24	0.084	0.14	0.231	4.3
August	0.36	0.01	0.004	0.39	0.04	0.016	0.13	0.150	6.7
September	0.33	0.02	0.007	0.33	0.09	0.030	0.18	0.217	4.6
October	0.35	0.11	0.004	0.34	0.40	0.136	0.06	0.200	5.0

*Probability of runoff being produced by a small storm. equation [2]
†Probability of runoff being produced by a moderate storm. equation [2]
‡Probability of runoff being produced by a large storm. equation [2]
§Probability of runoff being produced by any combination of storm size and AMC. equation [3]

TABLE 7. MONTHLY OCCURRENCE PROBABILITIES OF POTENTIALLY EROSIVE RUNOFF EVENTS (PERO), CARO, MI

Month	Small storms				Moderate storms				Large storms			
	P(XS|SS)	P(XS)*	P(AMC III|XS)†	P(XS ∩ AMC III)	P(XM|SM)	P(XM)*	P(AMC≥II|XM)†	P(XM ∩ AMC≥II)	P(XL|LS)	P(XL)*	P (PERO)‡	T(yr)
April	0.148	0.044	0.375	0.016	0.143	0.051	0.330	0.017	1.000	0.040	0.073	13.6
May	0.107	0.045	0.091	0.004	0.176	0.067	NR§	NR	NR	NR	<0.010	>100.0
June	0.430	0.163	0.083	0.014	0.673	0.316	0.300	0.095	0.286	0.028	0.137	7.3
July	0.356	0.132	NR	NR	0.604	0.211	0.330	0.070	0.200	0.028	0.098	10.2

*P[X(i)] = probability of an excessive rate storm, equation [5]; P[S(i)] from Table 5.
†Computed from Deer-Sloan network data.
‡P(PERO) = Occurrence probability of potentially erosive runoff events, equation [4].
§NR = No record of occurrence in 25 years.

DEFINITIONS

The following symbols are used in this paper:

P( )	The probability of the parameter within ( ) occurring.
P[AMC(j)|S(i)]	The conditional probability of an AMC class occurring given the occurrence of a specific size storm, S(i).
P[S(i)∩AMC(j)]	The probability of the intersection of a given storm class and a given AMC class.
P[AMC(j)|X(i)]	The conditional probability of an AMC class occurring given the occurrence of a specific excessive rate storm, X(i).
(P[X(i)∩AMC(j)]	The probability of the intersection of a given excessive rate storm class and a given AMC class.

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