HYDROLOGY AND WATER RESOURCES IN ARIZONA AND THE SOUTHWEST, VOLUME 7, p. 89-102.

Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science, held in Las Vegas, Nevada, April 15-16.

NONPOINT-SOURCE POLLUTANTS TO DETERMINE RUNOFF SOURCE AREAS[1/]

by

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ABSTRACT

Hydrologic information is needed to understand and control water pollution from semiarid rangelands. However, the hydrologic systems under any given conditions must be understood and the effects of various land uses predicted.

Based on the concept of partial area response, a runoff tracer study was conducted on two small watersheds. The watersheds were partitioned into four geomorphic subzones or hydrologic response units. Each of the four zones on both watersheds was treated with about 1 kg/ha of an individual water soluble herbicide. Runoff volumes and sources estimated using the tracers were consistent with results from simulation studies. Also, the principle of corresponding runoff and pollutant discharge rates was used to develop two methods of runoff hydrograph estimation from each of the geomorphic subzones. Method 1 matched the mean total concentration and total runoff volume. Method 2 matched the instantaneous total concentration and the instantaneous runoff rate from the entire watershed. Results from the two methods suggested that, although they may be equivalent with respect to runoff volume, Method 2 may be more consistent with respect to peak discharge.

INTRODUCTION

BACKGROUND

Basic requirements under Public Law 92-500, "The Federal Water Pollution Control Act Amendments of 1972", are "to restore and maintain our water quality." This charge requires two major efforts: 1) to understand the present conditions in order to maintain the present status or to have a base for restoring the quality and 2) to predict the consequences of rehabilitative measures or future land uses. Thus, we must understand the hydrologic systems under any given conditions and be able to predict the effects of various land uses including agricultural practices and conservation measures.

As specified in the legislation, nonpoint pollution sources are characterized by the following: 1) the runoff is not controlled or produced at a single point or source; and 2) runoff, as the transport medium, gathers the pollutants over an area and not from a single point. Thus, one of our research objectives is to provide hydrologic information needed for understanding and controlling water pollution from rangelands.

BASIC CONCEPTS

Partial Area Response (variable source area response) is a term used to designate the response of a watershed when only a portion of the total drainage area is contributing runoff at the watershed outlet or point of interest.

Geomorphic Subzones (or hydrologic response units) are zones within a watershed where specified geomorphic features are relatively homogeneous.

Kinematic Cascade Model is a mathematical model wherein watershed topography is represented by a cascade of planes and channels in a logical flow sequence. Water flow routing is accomplished using the kinematic wave equations as approximations to the full continuity of mass and momentum equations (Kibler and Woolhiser, 1970). Planes and channels in this model are chosen to correspond closely with the geomorphic subzones. Thus, to an extent measured by statistics of goodness-of-fit, the watershed topography (geomorphic character) is preserved in the mathematical model.

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Principle of Corresponding Runoff and Pollutant Discharge Rates states that, for a given geomorphic subzone, if a pollutant is available for transport in surface runoff, then for each runoff rate there is a corresponding pollutant discharge rate.

WATERSHED AND DATA

The Santa Rita Experimental Range is a 200-sq-km range located some 50 km south of Tucson, Arizona. It was established in 1903 and is maintained by the Forest Service, USDA, for studying the interrelationships of organisms, attributes, and processes of semidesert ecosystems (Martin and Cable, 1975). In 1975, eight small experimental watersheds were established and instrumented to investigate the effects of various grazing and vegetation controls on the hydrologic and erosion response of semiarid watersheds.

Generally, surface runoff results from short duration thunderstorms during the summer months. Continuous records of rainfall and runoff are obtained by the recording equipment. Also, water quality/sediment samples are obtained at 3 min intervals throughout the runoff events (Renard, Simanton, and Donica, 1976). Sediment data consist of concentration values throughout the hydrograph. Water quality data consist of the sediment concentration data and concentrations of up to four different herbicides throughout the recorded hydrographs. Infiltrometer data (Dixon and Peterson, 1968) were taken at eight plot sites within the experimental watersheds. Vegetation transects were established at several sites in each watershed (Martin, Morton, and Renard, 1974). Soil samples and plant samples were taken to determine soil concentrations and plant uptake rates of the various herbicides. In a previous experiment, Velvet Mesquite (Prosopis juliflora var. velutina) was killed on Watershed 76.002. Watershed 76.001 was not treated before this experiment.

PROCEDURE AND EXPERIMENTAL DESIGN

Two watersheds were divided into four geomorphic zones as shown in Figs. 1 and 2 (Lane and Wallace, 1976). Watershed 76.001 has a drainage area of 1.64 ha, whereas Watershed 76.002 drains 1.77 ha. Water soluble herbicides were applied to the zones at about 1 kg/ha (Table 1) on July 9, 1976 in anticipation of minimizing the time between application and the start of the runoff season. In actual brush control programs, the herbicides would be applied earlier to minimize, rather than maximize, the likelihood of their transport in runoff. Soil surface herbicide concentration data through time are shown in Table 2 for Watershed 76.001 and Table 3 for Watershed 76.002. Smooth curves were fitted to means of these data as shown in Figure 3. These curves were then used to show qualitative trends in the concentrations of herbicides available for transport throughout the runoff season. For comparison, data from White, et al. (1976) are shown in Figure 3. Since precision in the soil concentration data was poor, they were not used to normalize concentration in the water samples.

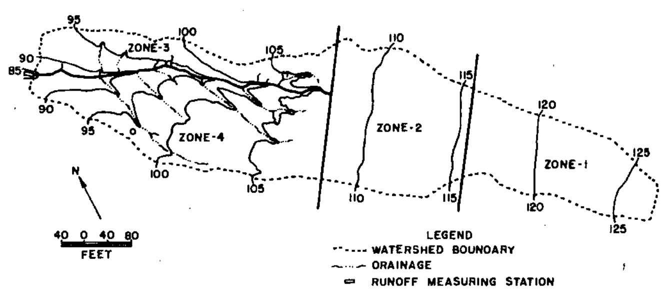

Figure - 1. Map of Watershed 76.001 showing drainage pattern and division of the watershed into geomorphic zones.

Herbicide concentrations in the water and soil samples were determined using a gas-chromatograph technique (Merkle, M. G. et al. 1966). Any herbicides that may have traveled with the sediment were extracted and combined with the water samples. Water and soil samples were refrigerated after collection until analysis to minimize herbicide degradation. Concentration and runoff data were combined to determine sediment and herbicide yield rates from all zones in each watershed.

RESULTS

OBSERVED DATA

Runoff and corresponding herbicide yield data are summarized in Table 4 for storms in 1976.

Essentially, there was no difference in runoff yield between the two watersheds (Watershed 76.001 had more small storms), but Watershed 76.002 had nearly 3 times as much herbicide yield in the runoff. Although the reasons for this difference were not determined, our speculation is that part of the differences may be due to differences in watershed topography (Figs. 1 and 2) and to differences in vegetation due to previous experiments.

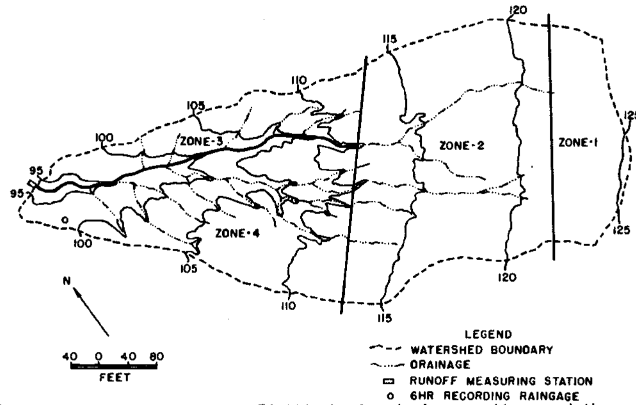

Figure - 2. Map of Watershed 76.002 showing drainage pattern and the division of the watershed into geomorphic zones.

TABLE 1.

Amount of herbicides applied to each zone in Watersheds 76.001 and 76.002 for the 1976 tracer study.

ZONE	AREA (ha)	AMOUNT OF HERBICIDES APPLIED (g) Design	Actual	ACTUAL APPLICATION RATE (kg/ha)
		Watershed 76.001		
1 (2, 4-D)	0.38	426.	393.	1.03
2 (2,4,5-T)	0.45	504.	483.	1.07
3 (Picloram)	0.26	291.	272.	1.05
4 (Dicamba)	0.55	616.	605.	1.10
TOTAL	1.64	1837.	1753.	
		Watershed 76.002		
1 (2, 4-D)	0.21	235.	181.	0.86
2 (2,4,5-T)	0.78	874.	914.	1.17
3 (Picloram)	0.24	269.	242.	1.01
4 (Dicamba)	0.54	605.	544.	1.01
TOTAL	1.77	1983.	1881.	

RELATION BETWEEN RUNOFF AND HERBICIDE YIELDS

Although the data were limited, they suggested that there is no simple relation between runoff volume and herbicide yield for individual events (Figs. 4(A) and 5(A)). Points labeled 7/17/76 are for the first runoff event after treatment and the points labeled 7/27/76 are for the largest event observed during 1976. These figures illustrate the importance of storm sequencing and size. For Watershed 76.001, the first storm (7/17/76) produced the greatest herbicide yield while on Watershed 76.002, the largest storm (7/27/76) produced the greatest herbicide yield. For Watershed 76.001, about 0.21% of the applied herbicide was washed off with the summer runoff. About 0.56% of the applied herbicide was washed off in runoff from Watershed 76.002. Figures 4(B) and 5(B) show the cumulative runoff and herbicide yields. Data from White et al. (1976) are shown for comparison in Figures 4 and 5. Their data produced nearly 2% of the applied herbicides in runoff from simulated rainfall for a time period of 35 days for herbicides applied at the rate of 0.56 kg/ha (White et al. 1976, Table 2, p. 489).

RELATIONS BETWEEN RUNOFF RATES AND CONCENTRATION

Relations between runoff rate and sediment concentration for two storms on Watershed 76.001 are shown in Figures 6(A) and 7(A). Apparently, there may be a relationship for the data from the storm on 7/17/76, but not from the storm on 7/27/76. Similar data for herbicide concentrations are shown in Figures 6(B) and 7(B). The linear relationships between concentrations and runoff rate for the first

TABLE 2.

Summary of herbicide concentrations in the surface soil, Watershed 76.001.

Type and Time of Samples	Zone-1 2, 4-D	Zone-2 2, 4, 5-T	Zone-3 Picloram	Zone-4 Dicamba	Mean of All Zones
	Herbicide Concentrations in μg/g				
7/9/76[1]					
GLC[2]	1.78	1.56	.51	.96	1.2
BIO[3]	- - -	- - -	- - -	- - -	- - -
7/15/76					
GLC	.20	.66	.04	.73	.41
BIO	.04	.12	≥.01	≥1.0	≥.29
7/22/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.006	.08	≥.01	.14	≥.06
8/6/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	1.37	.004	≥.01	.14	≥.38
9/2/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.09	.004	≥.01	.78	≥.22

1. Date of application.
2. Gas liquid chromatograph.
3. Bio-assay

TABLE 3.

Summary of herbicide concentrations in the surface soil, Watershed 76.002.

Type and Time of Samples	Zone-1 2, 4-D	Zone-2 2, 4, 5-T	Zone-3 Picloram	Zone-4 Dicamba	Mean of All Zones
	Herbicide Concentrations in μg/g				
7/9/76[1]					
GLC[2]	.39	.51	.22	.89	.50
BIO[3]	- - -	- - -	- - -	- - -	- - -
7/15/76					
GLC	.44	.68	.06	.19	.34
BIO	.04	1.08	≥.01	≥1.	≥.53
7/22/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	≥2.	.004	≥.01	.14	≥.53
8/6/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	≥2.	.06	≥.01	.14	≥.55
9/2/76					
GLC	- - -	- - -	- - -	- - -	- - -
BIO	.0001	.001	≥.01	.007	≥.005

1. Date of application.
2. Gas liquid chromatograph.
3. Bio assay.

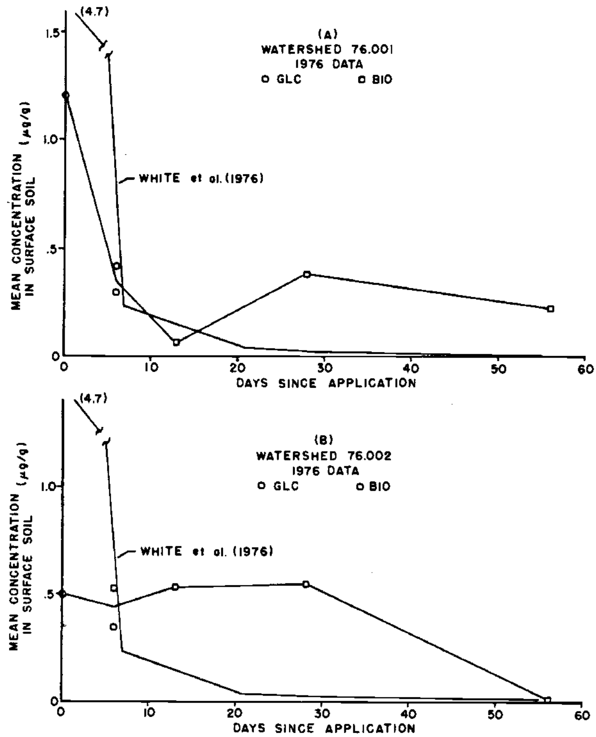

Figure - 3. Herbicide concentrations in surface soil. Initial application rate of 1.0 kg/ha. GLC represents concentrations by gas chromotography and BIO is the bia-assay method.

TABLE 4.

Summary of runoff and herbicide yields from Watershed 76.001 and 76.002 during the 1976 study.

DATE OF EVENT	DAYS SINCE TREATMENT	VOLUME OF RUNOFF (liters x 10^4)		YIELD OF HERBICIDES (g)[1/]	
		EVENT	CUMULATIVE	EVENT	CUMULATIVE
		Watershed 76.001			
7/17/76	8	1.99	1.99	2.04	2.04
7/21/76	12	.65	2.64	.13	2.17
7/27/76	18	7.06	9.70	.69	2.86
7/28/76	19	.07	9.77	.01	2.87
8/10/76	32	.42	10.19	.06	2.93
8/26/76	48	3.19	13.38	.19	3.12
9/1/76	54	.61	13.99	.05	3.17
9/22/76	75	.07	14.06	.01	3.18
9/25/76	78	2.81	16.87	.46	3.64
		Watershed 76.002			
7/17/76	8	.69	.69	.95	.95
7/21/76	12	.03	.72	.05	1.00
7/27/76	18	7.36	8.08	8.41	9.41
8/26/76	48	5.49	13.57	.53	9.94
9/25/76	78	2.40	15.97	.64	10.58

1. No 2, 4-D from Zone 1 was found in any of the water quality samples.

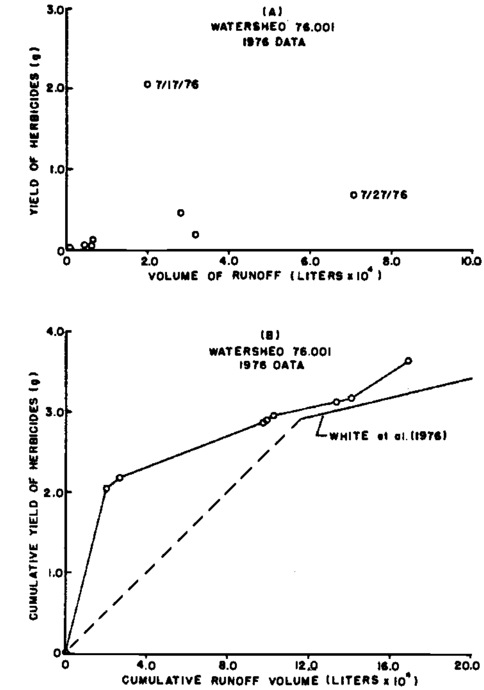

Figure - 4. Relation between runoff volume and herbicide yields.

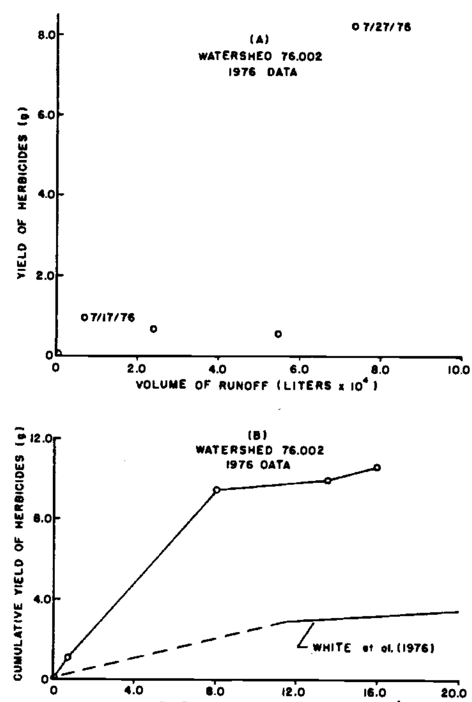

Figure - 5. Relation between runoff volume and herbicide yields.

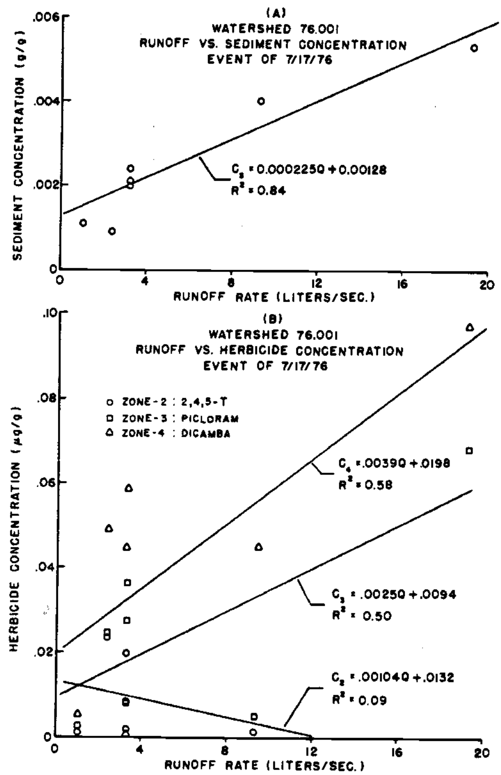

Figure - 6. Relations between runoff rate and concentration.

storm (7/17/76) can be partly explained from the time distributions of the water quality samples. Relations between runoff rate, sediment concentration and time for the two storms are shown in Figure 8. For the event of 7/17/76, both runoff and concentration decreased with time, although no sample was collected on the hydrograph rise. This was not true for the second event (Fig. 8(B)). Therefore, the existence of a linear relationship between concentration and runoff rate was due to the simple hydrograph shape and the small number of samples for the event on 7/17/76. Similar results are seen in plots of herbicide concentration (Fig. 9) where there appeared to be no linear relation between runoff rate and herbicide concentration.

APPLICATION: A TRACER STUDY

PARTIAL AREA CONCEPT

The partial area concept (variable runoff source area concept) was developed in humid regions (e.g., Hewlett, 1961, and Dunne and Black, 1970). An exception, developed for semiarid watersheds, is the average loss rate procedure of Arteaga and Rantz (1973). Lane et al. (1976) developed four analytical procedures to simulate partial area response on small semiarid watersheds. From these studies and observations, we concluded that the mechanism for surface runoff generation on small semiarid watersheds, like those discussed here, is generation of overland flow on portions of the watersheds. The four analytic procedures used suggested that for the 1.64 ha watershed, 40 to 100% of the total area was contributing runoff. These results are from analysis and not observation. Therefore, a tracer study was conducted for field testing the simulation results.

GEOMORPHIC SUBZONES

Watersheds 76.001 and 76.002 were both divided into four zones (Figures 1 and 2) These zones were selected to be relatively homogeneous within each zone with respect to average slope, drainage density, and mean length of first order streams. These criteria were more nearly met in Watershed 76.001 than in Watershed 76.002. Figure 10 shows a simplified kinematic cascade model corresponding to the four zones on Watershed 76.001. Each of the four zones is modeled as a plane and the channel network is modeled as a single channel corresponding to the main channel of the watershed.

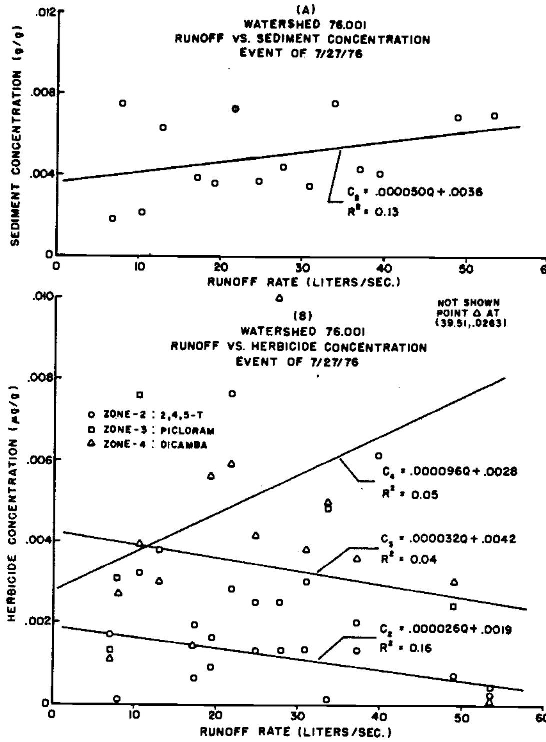

Figure - 7. Relations between runoff rate and concentration.

Using the kinematic cascade model described above and the SCS (1971) curve number procedure, runoff rates and amounts were estimated for each zone for various storm sizes. These estimates were used to determine the amounts of herbicide to be applied to each zone so that detectable and safe concentrations of herbicides could be sampled (Table 1).

EXPERIMENTAL DESIGN FOR TRACER STUDY

Infiltrometer data (Dixon, 1976) suggested a variation of infiltration rates in the ratio 2:1 between the upper and lower zones on Watershed 76.001. The optimal curve number in the SCS runoff estimation procedure (SCS, 1971) for the entire watershed is 89. Therefore, zones 1 and 2 were assigned a value of 84, and zones 3 and 4 were assigned a value of 94. With these values, a rainfall depth of 3 mm (0.12 in) would cause runoff on zones 3 and 4. A rainfall depth of 8.9 mm (0.35 in) would produce runoff on zones 1 and 2. From these values of rainfall and runoff, it was determined that rainfall depths of 8.9 mm (0.35 in) or more would produce runoff and detectable concentrations of the herbicides, if they were applied at the rate of 1 kg/ha.

PROCEDURES FOR DETERMINING RUNOFF FROM EACH ZONE

Total runoff and concentration data were used with the principle of corresponding runoff and pollutant discharge rates to estimate runoff rates and amounts for each zone. The technique involving matching runoff volumes is Method -1 and that based on matching rates is Method -2.

RUNOFF VOLUMES

Let Q_i be the volume of runoff from zone i during a particular runoff event. Let Q_T be the total volume of runoff from the entire watershed. Thus

$$Q_T = \sum_{i=1}^{N} Q_i \quad (1)$$

where N is the number of zones. Let Y_i be the total yield of herbicide i from zone i, and Y_T be the total yield of herbicides from all zones so that

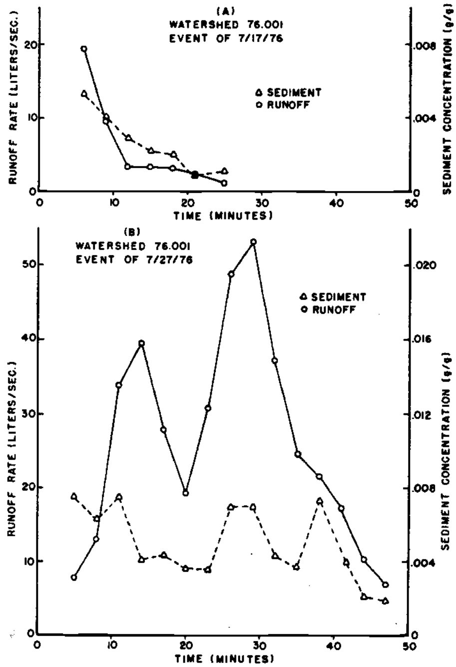

Figure - 8. Relation between runoff rate and sediment concentration.

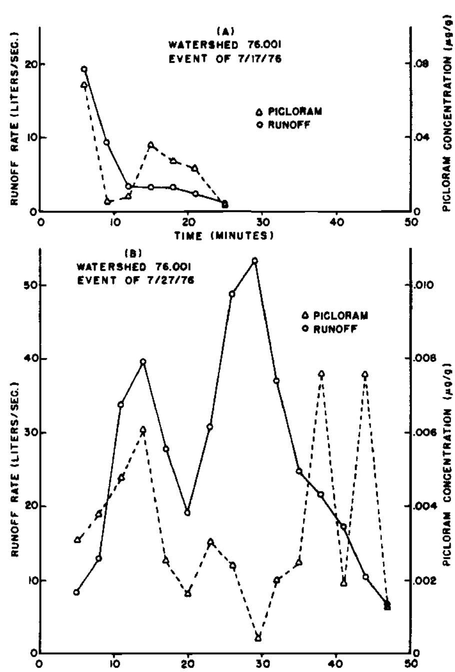

Figure - 9. Relation between runoff rate and herbicide concentration.

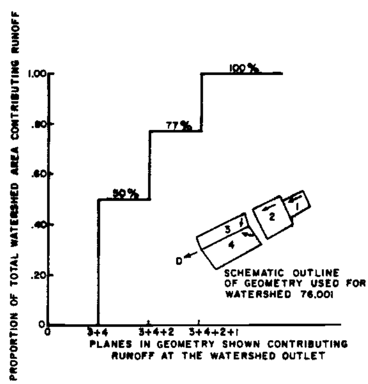

Figure - 10. Relation between number of planes and proportion of watershed area contributing runoff.

$$Y_T = \sum_{i=1}^{N} Y_i \tag{2}$$

as in Eq. 1. If the volumes of runoff are proportional to the mass yields of corresponding herbicides,

$$\frac{Q_i}{Q_T} = \frac{Y_i}{Y_T} \tag{3}$$

which can be solved for Q_i as

$$Q_i = \frac{Q_T}{Y_T} Y_i \tag{4}$$

where the variables are as described above. Equation 4 is used to estimate the volumes of runoff from each zone.

RUNOFF RATES

As in Eq. 4, if $q_i(t)$ is the runoff rate from zone i, $q_T(t)$ is the runoff rate from the entire watershed; $y_i(t)$ is the yield rate of herbicide i from zone i, and $Y_T(t)$ is the total yield of all herbicides, then

$$q_i(t) = \frac{Q_T}{Y_T} y_i(t) \tag{5}$$

is a means to estimate the runoff rate from zone i. This procedure was called Method -1. Following the form of Eq. 5, but in terms of rates (following a similar suggestion by E. D. Shirley), the second method of estimating the runoff rate is

$$q_i(t) = \frac{q_T(t)}{y_T(t)} y_i(t) \tag{6}$$

called Method -2. The sum of runoff volumes from Eq. 4 equals the total observed runoff volume since summing both sides of Eq. 4 produces

$$\sum_{i=1}^{N} Q_i = \frac{Q_T}{Y_T} \sum_{i=1}^{N} Y_i \tag{7}$$

which simplifies to $Q_T = Q_T$. With this, Eq. 4 matches the observed runoff flow volume. If both sides of Eq. 5 are integrated up to time T, the duration of flow,

$$\int_0^T q_i(t) = \frac{Q_T}{Y_T} \int_0^T y_i(t)\, dt \tag{8}$$

and,

$$Q_i = \frac{Q_T}{Y_T} Y_i \tag{9}$$

which is the same as Eq. 4. Therefore, Method -1 also matches the observed runoff volume. With the same logic, if both sides of Eq. 6 are summed,

$$\sum_{i=1}^{N} q_i(t) = \frac{q_T(t)}{y_T(t)} \sum_{i=1}^{N} y_i(t) \tag{10}$$

which becomes $q_T(t) = q_T(t)$ since

$$\sum_{i=1}^{N} q_i(t) = q_T(t) \tag{11}$$

and

$$\sum_{i=1}^{N} y_i(t) = y_T(t) \tag{12}$$

by definition. Also

$$\int_0^T q_T(t)\, dt = Q_T \tag{13}$$

so that Eq. 6 matches total rate and total volume of runoff.

Examples of runoff predictions by Method -1 and Method -2 are shown in Figures 11 and 12. There was no herbicide detected from Zone -1, and Method -2 exactly matches the total runoff hydrograph from the entire watershed. Also, Method -2 seemed less prone to overestimate peak discharge rates.

Volumes of runoff from each zone, as estimated by the two methods, are shown in Figure 13. There is nearly a one-to-one relation in estimated volumes, which suggests that, with respect to volumes, the two methods are equivalent.

SUMMARY OF TRACER STUDY RESULTS

To determine diffuse pollutant source areas, runoff and sediment source areas must be determined. Analytic procedures suggested that for the small watershed studied, 40 to 100% of the watershed contributed runoff. Results of a tracer study in 1976 supported the partial area or variable source area concept.

The principle of corresponding runoff and pollutant discharge rates was used to develop two methods of runoff hydrograph estimation from each of the geomorphic subzones. Results from the two methods suggested that they may be equivalent with respect to runoff volume but that Method -2 may be more consistent with respect to peak discharge.

Finally, Method -1 uses the inverse of the mean total concentration as the coefficient in Eq. 5. Therefore, Method -1 matches the mean of the observed concentration data at the sampling times. Method -2 uses the inverse of the instantaneous total concentration as the coefficient in Eq. 6. Therefore, Method -2 matches the total instantaneous concentration data at the sampling times.

SUMMARY

Based on the concept of a partial area response, a tracer study was conducted on two small semiarid watersheds that were partitioned into geomorphic subzones or hydrologic response units. Each of four zones on both watersheds was treated with about 1 kg/ha of four individual water-soluble herbicides.

Herbicide yields in surface runoff during the 1976 summer season amounted to 0.21% and 0.56% of the total amounts applied. For individual runoff events, herbicide yields were not related to runoff volume alone, but were influenced by storm sequence.

Runoff volumes for each zone of the watershed (as estimated from the tracer study data) agreed with analytical results indicating a partial area response. These results were consistent in identifying runoff and pollutant source areas on these small watersheds.

Based on the corresponding rates principle, two methods were developed to relate runoff rate and herbicide (pollutant) discharge rates. Method -1 matches the mean total concentration and total runoff volume. Method -2 matches the instantaneous total concentration and the instantaneous runoff rate from the entire watershed.

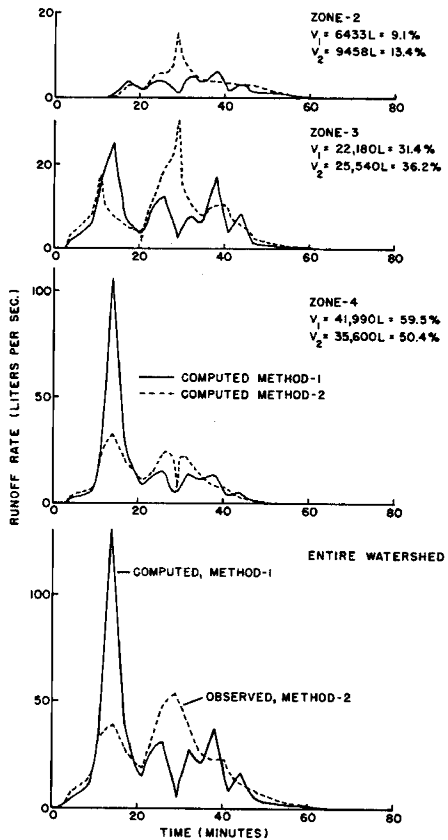

Figure - 11. Computed runoff hydrographs for event of 7/27/76 on Watershed 76.001.

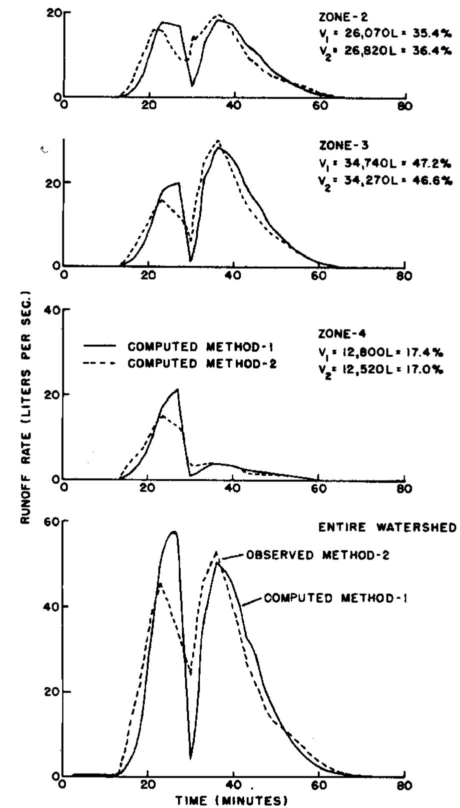

Figure - 12. Computed runoff hydrographs for event of 7/27/76 on Watershed 76.002.

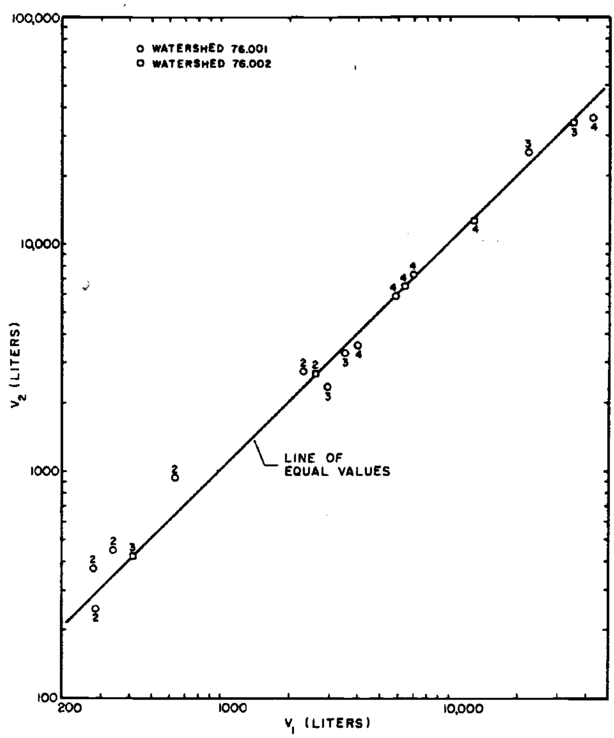

Figure - 13. Volumes of runoff as estimated by the two tracer study methods.

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