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PREDICTION OF RUNOFF AND SEDIMENT FROM AGRICULTURAL WATERSHEDS BY A MATHEMATICAL MODEL
II: MATHEMATICAL SIMULATION

S. AMIN SICHANI AND B.A. ENGEL [1]

Irrigation Department, College of Agriculture, Shiraz University, Shiraz, Iran; and Department of Agricultural Engineering, Purdue University, West Lafayette, Indiana, USA.

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ABSTRACT

The ANSWERS [Areal Nonpoint Source Watershed Environment Response Simulation (3)] model was used to simulate runoff and sediment yield from two small agricultural watersheds near Fort Wayne, Indiana and on the Stafford watershed located near Martinsville, Indiana, USA. These three watersheds were chosen because of differences with respect to soil type, tillage and topography. The simulation results indicate that the Hoeppner watershed gave the highest sediment yield on an area basis. The Stafford watershed yielded about one-half and the Ward Road watershed yielded about one fifth of the yield at the Hoeppner site. The results suggested there might be effects of soil and topography on sediment and runoff from a watershed. The hydrorgaphs of the predicted and observed runoff were very similar.

1- *Assistant Professors.*

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برآورد سیلاب و رسوب از حوزه‌های آبخیز کشاورزی با استفاده از یک مدل ریاضی ۲ : شبیه سازی حوزه‌های آبخیز

سیف‌اله امین سیچانی و ب. الف. انگل
به ترتیب استادیار بخش آبیاری دانشکدهٔ کشاورزی دانشگاه شیراز و استادیار بخش مهندسی کشاورزی دانشگاه پردو، لافایت‌غربی، ایندیانا، آمریکا.

چکیده

مدل کامپیوتری ANSWERS *(Beasley, 1977)* برای شبیه‌سازی روان آب و رسوب حاصله از آن در دو حوزهٔ آبخیز کشاورزی کوچک به‌نامهای *Ward road, Hoeppner* واقع در نزدیکی *Fort Wayne* و حوزهٔ آبخیز دیگری به‌نام *Stafford* در نزدیکی *Martinsville* در ایالت ایندیانای آمریکا مورد استفاده قرار گرفت. این سه‌حوزهٔ آبخیز بعلت تفاوتهائی که در نوع خاک، کشت و توپوگرافی داشتند انتخاب شدند.

نتایج شبیه سازی نشان دادند که حوزهٔ *Hoeppner* بیشترین فرسایش را در واحد سطح داشته است. در حالیکه حوزهٔ *Stafford* تقریباً نصف و حوزهٔ *Ward Road* تقریباً یک پنجم حوزهٔ *Hoeppner* فرسایش داشته‌اند. نتایج حاصله بیانگر اثر نوع خاک و توپوگرافی حوزهٔ آبخیز روی فرسایش خاک یک حوزه هستند. هیدروگرافهای سیل حاصله که از طریق شبیه‌سازی بدست آمده اند خیلی نزدیک به هیدروگرافهای مشاهده‌شده بودند.

INTRODUCTION

The assessment of water pollution from agricultural nonpoint sources for developing better management strategies requires both an estimation of their magnitudes and the evaluation of potential control factors. Mathematical models can be used to quantify the loading levels of the pollutants from agricultural watersheds. Modeling of nonpoint source pollution also serves as a guide for investigating various watershed soil and crop management schemes for controlling water quality under various climatic conditions.

ANSWERS [Areal Nonpoint Source Watershed Environment Response Simulation (3)] is an event-base model, and here was used to predict runoff and sediment from three small agricultural watersheds with different topographies, soil characteristics, and crop management styles.

In the first of this series of papers (2) the ANSWERS model and its capabilities were introduced. The main purpose of this paper is to describe the ability of the ANSWERS model to predict runoff and sediment from different-sized watershed.

EXPERIMENTAL WATERSHEDS

Three small agricultural watersheds, were simulated namely, Hoeppner, Ward Road, and Stafford (1). The first two watersheds are located in the Black Creek watershed, northeast of Fort Wayne, Indiana, USA. The third watershed is located near Martinsville, southwest of Indianapolis, Indiana. These three watersheds were chosen because of differences with respect to soil type, tillage and topography. Topographic maps of these watersheds are shown in Figs. 1, 2 and 3. The Hoeppner watershed is the steepest of the three watersheds as well as the smallest. The Stafford and Ward Road watersheds are of comparable size. The Ward Road watershed is the flattest of three watersheds and the Stafford watershed has relief somewhat between the other two watersheds.

A grid was superimposed on all three topographic maps and the elevations at the grid intersections were determined. From this the mean elevation and the direction of flow were found for each grid element. Available field data were used to apply ANSWERS. Table 1 gives the general characteristics of each of these watersheds. Additioanl information is given in the results and discussion section whenever a particular watershed is analyzed.

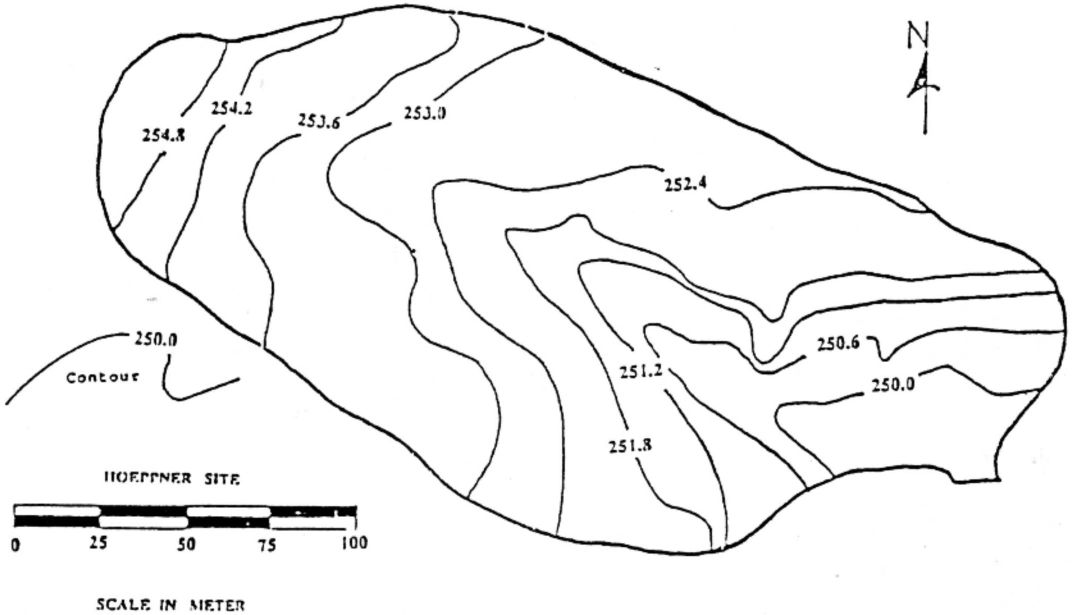

Fig. 1. Contour map of Hoeppner watershed, Allen county, Indiana, USA.

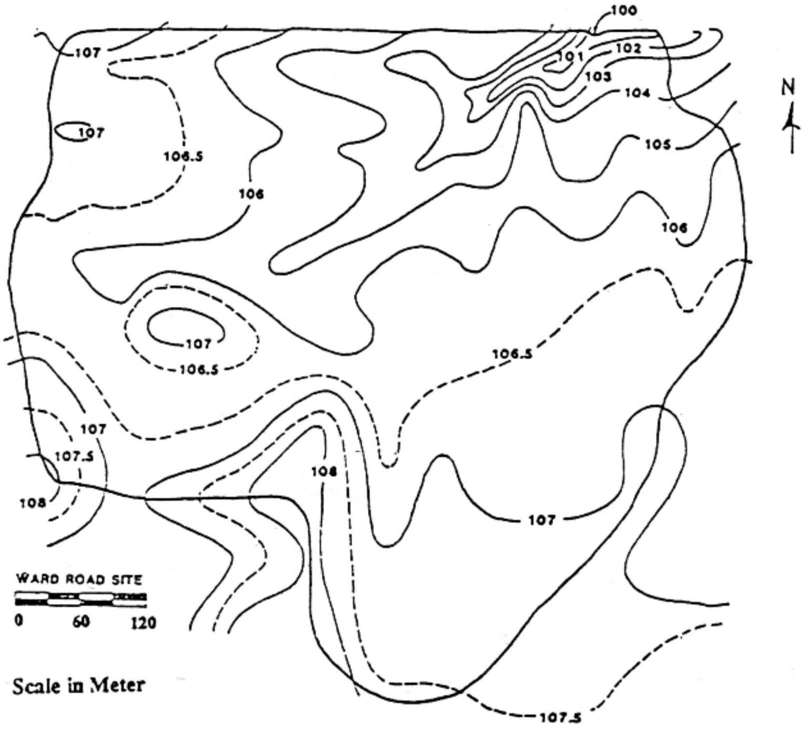

Fig. 2. Contour map of the Ward Road watershed, Allen county, Indiana, USA.

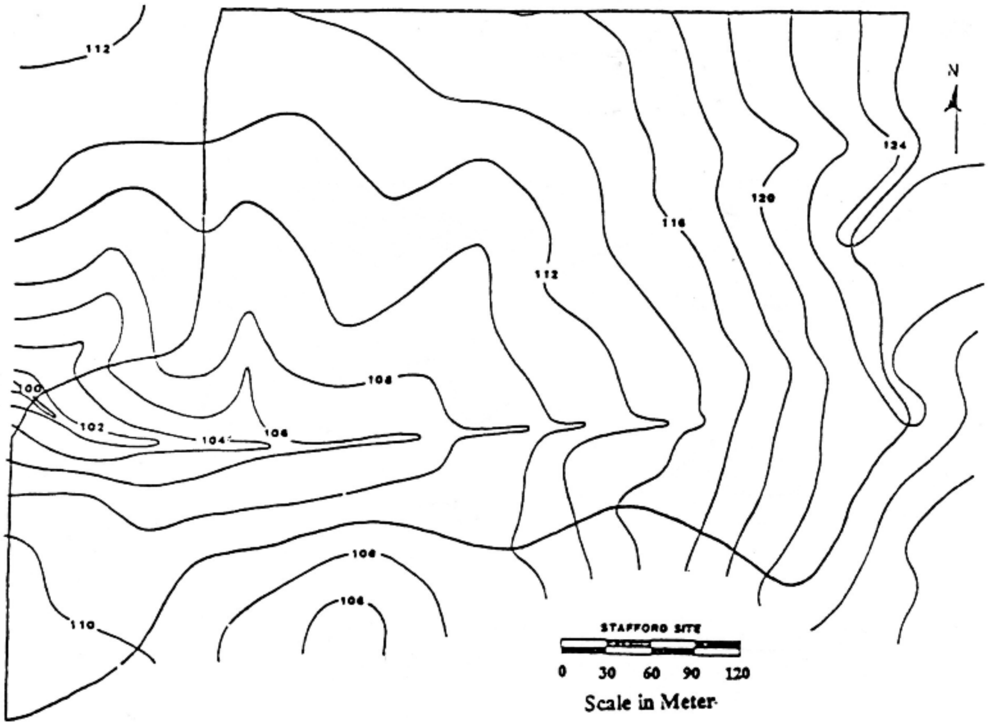

Fig. 3. Contour map of the Stafford watershed, Martinsville, Indiana, USA.

in 1981, the Hoeppner watershed had a small grain crop in the upper portion and corn in the lower portion of the watershed. For the same year, the Ward Road watershed had corn in the upper portion and a small grain crop in the lower portion of the watershed. The Stafford watershed was planted continuously with corn throughout the course of this study.

Table 1. General description of the experimental watershed used for simulation.

Watershed	Area (ha)	Crop coverage	Area (%)	Soil type	Area (%)
Hoeppner	4.3	Small grain	41	Blount (BmA)	41
		Corn	56	Morley (MrB2)	42
		Pasture	3	(MsC3)	17
Stafford	18.3	Corn	100	Fincastle	100
Ward Road	29.0	Small grain	50	Hoyville (Hs)	45
		Corn	50	Nappanee (Na)	55

Data relating to soil types for the Hoeppner and Ward Road watersheds were obtained from Allen Country Soil Survey (5). For the Stafford watershed, information was obtained from the Morgan Country Soil Survey (6). The other data needed for simulation such as potential interception values of the crop coverage, typical surface storage coefficient, and surface roughness coefficient, were obtained from the model user's manual (4).

RESULTS AND DISCUSSION

The main focus of this study was to simulate the response of the three agricultural watersheds to selected rainfall events. The output of these simulations was compared with observed field data. The simulation result of each watershed is described under each watershed name.

Hoeppner Watershed

This experimental watershed has an area of 4.3 ha and a relatively short time of concentration of 28 min due to the slope steepness and small size. The watershed has an average slope of 2.7 % with a minimum slope of around 0.6 % and a maximum slope around 6.3%. A topographic map of this watershed is shown in Fig. 1. It is located approximately three kilometers northeast of Black Creek watershed in Indiana.

The Hoeppner watershed consists of three soil types. The Blount silt loam (fine, illitic, mesic Aeric Ochraqualfs), BmA, lies in the upper portion of the watershed. This soil has slope ranging from 0% to 2% and is somewhat poorly drained. The Morley silt loam (fine, illitic, mesic, Typic Hupludalfs), MrB2, is located in the middle and near west side of the watershed. It has a slope ranging from 2% to 6%. Another Morley soil, MsC3, with slopes ranging from 6% to 12%, occupies the lower portion of the watershed. In 1981, a small grain crop was sown in the upper portion (see Table 1).

A great deal of runoff, sediment, and nitrogen data were collected from this watershed. Storms were selected for which runoff hydrographs and water quality information were available. The storm of 6-25-81 was chosen. This simulation allowed determination of the effect of an antecedent storm 6-22-81.

Figure 4 shows the hydrologic response from the Hoeppner watershed for the storm of 6-25-81. The storm of 6-25-81 produced about 35 mm rainfall and runoff about 11.5 mm from the Hoeppner watershed in 2 hr. The predicted hydrographs and that observed are very similar.

Ward Road Watershed

This small watershed has a drainage area of 29 ha and is located in the south part of the Black Creek watershed. A topographic map of this watershed is shown in Fig. 2. It is quite flat having an average slope of 0.38% and a time of concentration of 75 min. Although the two soil types are scattered throughout this watershed, the upper part is primarily Hoytville silty clay (fine, illitic, mesic, Mollic Ochraqualfs), Hs, and the lower part primarily Nappance silt loam (fine, illitic, mesic, Aeric Ochraqualfs), Na. These two soils were formed on the plain of glacial lake Maumee. In general, these soils have a mild slope and poor drainage. In 1981 this site had corn in the upper portion (see Table 1).

The storm of 6-22-81 was used in a simulation study. It was recorded at a weather station, less than half a kilometer from the watershed. This storm produced 16.1 mm rainfall and runoff of about 0.30 mm in 3 hr storm duration. This amount of rainfall was not enough to produce a high peak and volume of runoff from this flat watershed. A comparison of the observed and predicted hydrographs are depicted in Fig. 5. The hydrographs are in fairly close agreement.

As Fig. 4 shows, Hoeppner watershed responses after about 30 min from the beginning of the storm and the observed runoff peak of runoff flow rate for this storm was 16 mm/hr. The storm duration for 6-26-81

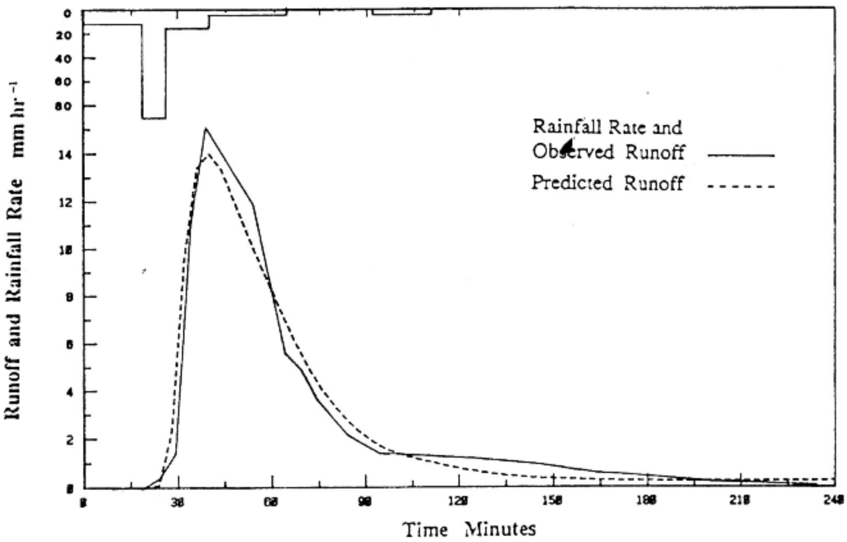

Fig. 4. Rainfall and observed versus predicted runoff hydrographs at Ward Road watershed (storm: 6-25-81).

event on the Hoeppner watershed was about 115 min and the response of watershed to this storm lasted about 4 hr. After 100 min, the greatest portion of the runoff volume was discharged from the catchment area. In contrast to Hoeppner watershed, the Ward Road site due to its flatness, large size and high time of concentration responded with delay to the storm of 6-22-81 which occurred on this site. Runoff discharge from this watershed was very low. Consequently, the duration of discharge increased over 8 hr for this watershed (Fig. 5). These two examples showed the ability of the ANSWERS model in simulation of different sizes of watersheds with topographic differences.

Stafford Watershed

This 18.4 ha watershed is located near Martinsville, Indiana, southwest of Indianapolis. A topographic map of the Stafford watershed is presented in Fig. 3. The catchment has an average slope of 1.5%, ranging from 0.2% to 4.5%, and a time of concentration of 64 min. Only one soil type, the Fincastle silt loam (fine, silty, mixed, mesic Aeric Ochraqualfs), FcA, is located in this watershed. It is also somewhat poorly drained. This site was planted continuously with corn during the course of this study (see Table 1). At the begining of this research the observed data were not available due to lack of instrument installation. The simulated hydrograph is shown in Fig. 6.

Comparison of watersheds

Simulation of a watershed under different crop management conditions provides an evaluation of the transport of sediment and other pollutants to receiving waters. To evaluate the predictive capability of the ANSWERS model it was assumed that all three watersheds were planted with corn. The storm of 6-22-81 at the Hoeppner watershed with 72.5 mm

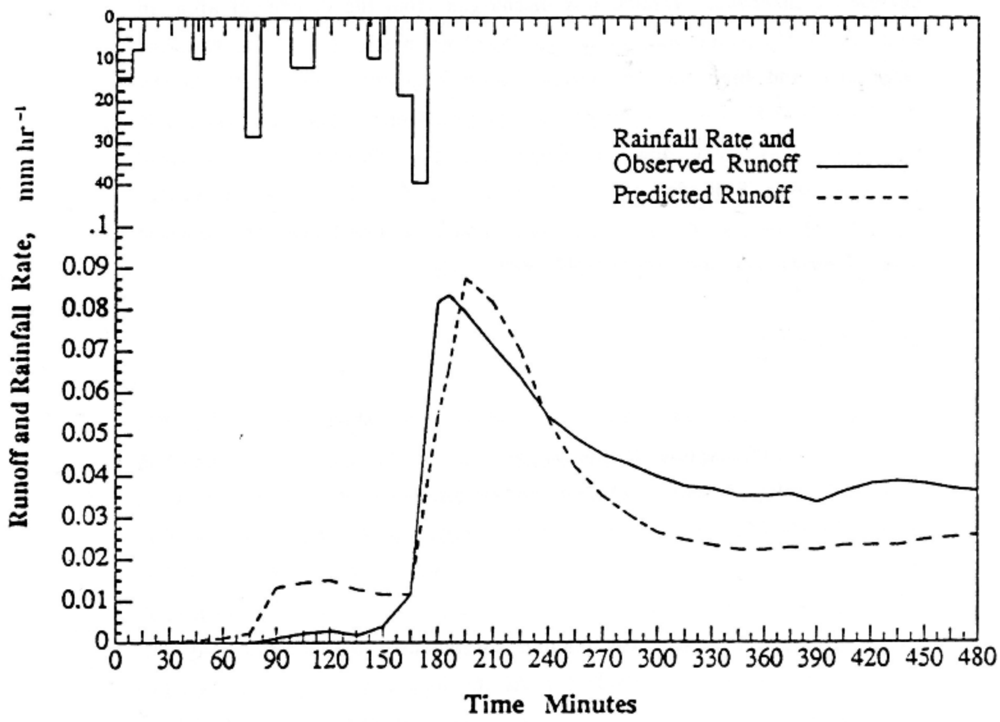

Fig. 5. Rainfall and observed versus predicted runoff hydrographs at Ward Road watershed (storm: 6-22-81).

rainfall and 2.5 hr duration (see Fig. 6) was used for all simulations so that loadings could be compared. Figure 6 shows hydrographs of runoff from these three watersheds for this particular storm. On a unit area basis, runoff peaks for the Hoeppner and Stafford watersheds were very similar, but the Ward Road watershed had a later response and a smaller peak. This is due to topographic and soil difference between the watersheds. Volumes of runoff were 26.7 mm, 24.7 mm, and 21.0 mm for the Hoeppner, Stafford, and Ward Road watersheds, respectively. Predicted sediment yields for this simulated rainfall are shown in Fig. 6. The Hoeppner watershed gave the highest yield on an area basis. However, the Stafford watershed gave only about one-half and the Ward Road watershed only about one-quarter of the yield experienced at the Hoeppner site. The difference between the Hoeppner and Stafford watersheds is due primarily to differences in soil characteristics, while the sediment yield difference between the Hoeppner and Ward Road watersheds is due to topography and soil.

SUMMARY AND CONCLUSION

The ANSWERS model which was introduced in the first paper of this series (2) was used in a simulation study for three different-sized watersheds, all located in Indiana, USA. These watersheds differed in topography, soil type, size, and slope steepness. The smallest watershed was Hoeppner and the largest was Ward Road watershed. The area of the Stafford watershed fell somewhere between the other two.

The storm of 6-22-81 was used for runoff simulation comparison of all three watersheds. The response of the watersheds differed according to their topography, and soil characteristics. The Hoeppner watershed produced the same peak flow rate as Stafford watershed and almost the same amount of runoff volume. This was due to the steepness of the Hoeppner watershed which produced a high volume of runoff in a short time of concentration. The Stafford watershed is not as steep as

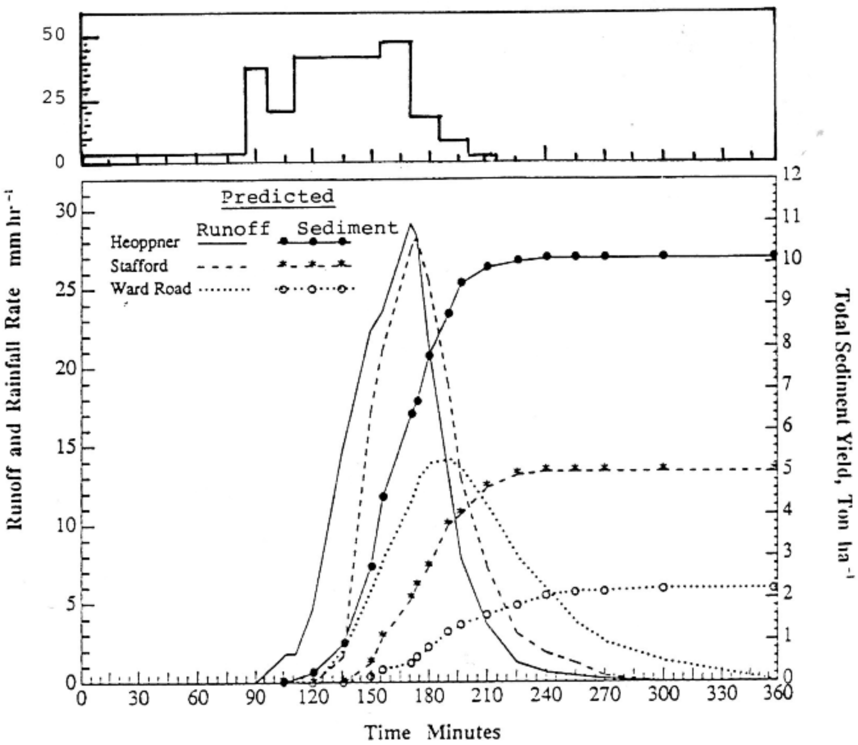

Fig. 6. Predicted runoff and total sediment yields from the Hoeppner, Stafford, and Ward Road watersheds using the storm of 6-22-81 at the Hoeppner watershed.

Hoeppner, and accordingly produced low rates of runoff. However, the size of the Stafford watershed was about four times that of Hoeppner, so it ultimately produced the same amount of runoff as Hoeppner. The Ward Road watershed produced the smallest peak rate as well as the smallest runoff volume. This watershed is the flattest of the three so the runoff and sediment from it is the lowest of the three.

The simulated sediment yield of these watershed sites was high for Hoeppner, medium for Stafford and low for Ward Road . The utilization of the erosion part of the model is visualized in the simulation of the 6-22-81 event. In Hoeppner the slope steepness caused more erosion while in Ward Road, due to its flatness, there was minimum soil erosion. The ANSWERS model can be easily used in simulation of different sized watersheds and it corresponds reasonably well with the topography and soil characteristics of the watershed under consideration. Because of this capability of estimating runoff and simulating sediment, the ANSWERS model could be modified for the simulation of plant nutrients and agricultural chemicals transport. The next paper deals with phosphorus transport from agricultural watersheds.

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