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PREDICTION OF RUNOFF AND SEDIMENT FROM AGRICULTURAL WATERSHEDS BY A MATHEMATICAL MODEL. I: INTRODUCING "ANSWERS"[1]

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ABSTRACT

Lumped and distributed parameter models have been used extensively to simulate watersheds and field responses to rainfall events. In lumped parameter models, the averages of the input data are used, while distributed parameter models use spatially distributed inputs to predict the spatial effect of land use, soil types, fertility, and rainfall. In this paper the ANSWERS model is introduced as a tool for prediction of watersheds responses to rainfall events. ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) is an event-oriented model which predicts peak flow rates, total surface runoff, and sediment from agricultural watersheds. This distributed parameter model is also able to predict the yield and concentration of sediment for an event. This model was used for the simulation of two storms, 9-4-80 and 6-22-81 on an experimental watershed, Hoeppner, (located in Allen County, northeast Indiana, USA). The hydro-logic response of this watershed showed that the simulated runoff for both storms was very close to the observed values. The ability of the model to predict sedimentation is also

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demonstrated for the Black Creek watershed of Allen County. The model was used to estimate the effect of different land use management (fallow versus crop coverage) for a natural rainfall event on a small agricultural watershed located in College of Agriculture, Shiraz, Iran.

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پیش‌بینی رواناب و رسوب حاصل از حوزه‌های آبخیز با استفاده از یک مدل ریاضی:
۱ – معرفی مدل "ANSWERS"

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چکیده

برای پیش‌بینی و شبیه‌سازی رواناب حاصل از بارندگی‌هایی که روی حوزه‌های مختلف اتفاق می‌افتند مدل‌های ریاضی میانگینی Lumped و پخشی distributed به‌طور روزافزون مورد استفاده قرار می‌گیرند. در مدل‌های میانگینی، معدل پارامترهای یک حوزه به‌صورت داده‌ها به کامپیوتر داده می‌شود و نتایج حاصل از شبیه‌سازی تابعی از زمان است درصورتی که در مدل‌های پخشی علاوه بر تغییرات زمانی پارامترها، تغییرات مکانی پارامترهای یک حوزه نیز مدنظر قرار دارند. لذا تغییرات در نوع خاک، حاصلخیزی خاک، نحوه کشت، نوع پوشش، و بارندگی می‌توانند دقیق‌تر مورد بررسی قرار گیرند.

در این مقاله مدل ریاضی ANSWERS جهت پیش‌بینی و تخمین عکس‌العمل‌های حوزه‌های آبخیز نسبت به بارندگی‌ها معرفی می‌شود. مدل ANSWERS مدلی است که برای تک بارندگی‌های حوزه‌های آبخیز کاربرد دارد و قادر است ماکزیمم سیلاب، کل حجم رواناب سطحی و فرسایش حاصل از بارندگی‌ها را در حوزه‌های آبخیز کشاورزی پیش‌بینی کند. جهت نشان دادن توانایی مدل ANSWERS رواناب دو بارندگی در تاریخ‌های ۱۹۸۰/۸/۴ و ۱۹۸۱/۶/۲۲ در یک حوزه کوچک کشاورزی به نام Hoeppner که در شمال شرقی ایالت ایندیانای آمریکا قرار دارد شبیه‌سازی شدند. نتایج حاصل از شبیه‌سازی و مشاهدات هیدرولوژیکی دو بارندگی فوق بسیار به هم نزدیک هستند. همچنین توانایی این مدل برای شبیه‌سازی فرسایش در حوزه Black Creek واقع در ایالت فوق‌الذکر نیز نشان داده شده است. نهایتاً "اثرات پوشش گیاهی (آیش و پوشش گیاهی) بر روی پیش‌بینی فرسایش در یک حوزه آبخیز کوچک کشاورزی واقع در دانشکده کشاورزی دانشگاه شیراز نشان داده شده است.

INTRODUCTION

In the past two decades the development of hydrologic and nonpoint simulation models has increased rapidly. Two major type models in simulation of agricultural watersheds are lumped and distributed parameter models.

This paper offers a brief discussion about lumped and distributed parameter models used for agricultural watershed simulation. ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation), a distributed parameter model is introduced. In contrast to lumped parameter models which require 3 to 5 years data from a watershed for calibration, the ANSWERS model does not require calibration. Therefore, it can be easily transferred for simulation of different watersheds. In the second and third series of this paper the simulation of three different sized watersheds in the state of Indiana in the USA, and phosphorus movement will be discussed respectively. The fourth paper will deal with the response of a small representative agricultural watershed in southern Iran.

Different Types of Models

A watershed is a complicated system of which all details cannot be understood. Many researchers have tried to make simplifications and abstractions to simplify the various aspects of a watershed behavior. According to Biswas (3), hydrologists have produced symbolic or mathematical models of all types. There are linear and nonlinear models; deterministic and stochastic models; lumped and distributed parameter models; continuous time and discrete time models; and so on. In simulation of a watershed, the lumped and distributed parameter models are used extensively.

Lumped parameter models. A lumped parameter model does not account for the spatial distribution in the input variables (4), and consequently, input and output relations are expressed as a function of time but not space. In these models the characteristics of a watershed are "averaged or lumped" together and the processes of the watershed are described mathematically by some ordinary differential equations or a system of them (2, 13). Some of the advantages of lumped models are that they are simple and basically more economical to use (7). On the other hand, the disadvantages of lumped parameter models are:

1. They do not normally predict contribution from different parts of a watershed.

2. They are based on calibrated coefficients which are not easily transferable to the other watersheds.

3. They are not capable of predicting effects of rapidly changing land use patterns.

The degree of the complexity of the lumped parameter models varies greatly. Two of the simplest examples are USLE (Universal Soil Loss Equation) for estimating the soil loss (12) and the Rational method for predicting the peak runoff rate from small watersheds. A more complex lumped parameter model used in agricultural watershed simulation is ARM (Agricultural Runoff Model) which was developed in 1979 by Davis and Donigian (5).

Distributed parameter models. In distributed parameter models, the spatial variability of a watershed is considered. These models are, therefore, usually more complex than lumped parameter models. The processes of a watershed are governed by partial differential equations or a system of them. Numerical approaches rather than analytical solutions are needed to solve these equations, a procedure which takes time. Huggins and Monke (7) considered this as the main disadvantage of this kind of model. These models require a geometrical network of points (4, 6, 9). Huggins *et al.* (8) listed the advantages of these models as:

1. Increased accuracy due to their inherent capacity to evaluate spatially variable factors within a watershed.

2. The watershed behavior is described in a comprehensive manner.

Distributed parameter models are able to evaluate the effects of different land use and crop management over a watershed. These models are capable of pre-dicting the output from large, medium, and small storms. They also can produce runoff and sediment from a watershed with different soils, land use, and crop management (2).

The ANSWERS Model. The ANSWERS model was developed in 1977 by Beasley (2). This model is a distributed parameter model that uses a grid system to define a watershed. The watershed under the study is divided into a number of small elements or cells as shown in Fig. 1. These cells are independent of each other in soil characteristics, slope, topography, crop coverage and management, etc. The size of each cell must be such that uniformity of all hydrological characteristics of the cell can be assumed. Important hydrological and soil erosion parameters are defined in a predata file for a watershed before a storm event is simulated. The model outputs are a hydrograph of runoff and sediment concentration, total sediment yield from a watershed, and the sediment detachment and deposition from each element of the watershed.

Critique of the ANSWERS Model

Clearly, a distributed parameter model such as ANSWERS needs a large amount of computer storage which increases as the number of cells and elements increases. Routing of runoff on an element by element basis is also time consuming. The number of elements can be reduced by increasing their size, but this may decrease the accuracy of the model to an unacceptable level. All distributed parameter models need a great deal of input data. In the

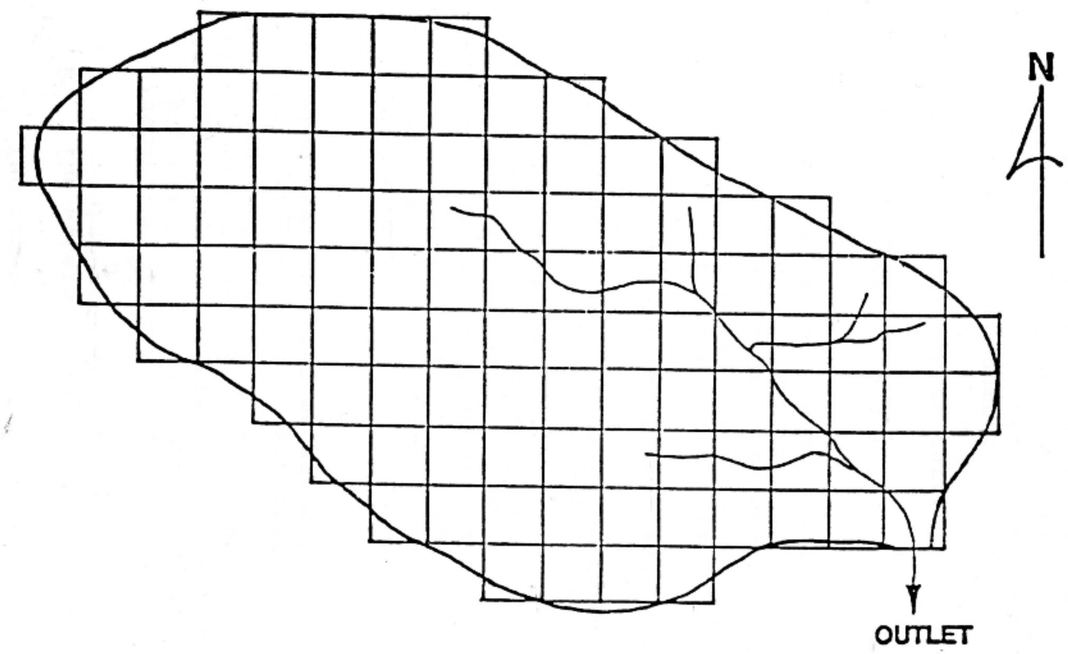

Fig. 1. Grid system representing a watershed. (In this particular case, it is the Hoeppner watershed located in Allen County, Indiana, U.S.A.).

ANSWERS model, approximately four to seven parameters should be evaluated for each element.

A definite advantage of the ANSWERS model is that it can evaluate rapidly changing land use in a watershed. ANSWERS can evaluate the net erosion and depositing from elements or areas which are sensitive to erosion. These areas can be tested with different soil and crop coverage management practices to determine reductions in erosion or even the cost effectiveness of different conservation practices.

The present model uses a fixed element size. Some areas in a watershed like the toe of the concave slope, may need smaller element sizes. The model includes a channel transport component, but currently no erosion is assumed in the channels, except for re-suspension of deposited sediment. This has not been a problem in most of the watersheds which have been investigated, but it could cause significant errors with rapidly aggrading or degrading channels.

Description of Watersheds

The capability of the ANSWERS model to predict runoff and sediment from small and large sized watersheds located in Allen County, northeast Indiana, USA, is demonstrated. To show the effects of crop coverage management the model is used on a third small agricultural watershed in the College of Agriculture, Shiraz, Iran (10).

The Hoeppner and Upper Black Creek watersheds are 4.29 ha and 714 ha, respectively. The area averages 800-1000 mm precipitation. The Hoeppner watershed has an average slope of 2.7 % with a minimum slope of around 0.6% and a maximum slope of around 6.3% (1). The soils in this watershed are silty loam. In 1981, small grain was sown in the upper portion of the Hoeppner watershed, while corn was planted in the lower portion. A topographic map of this watershed is shown in Fig. 2. The Upper

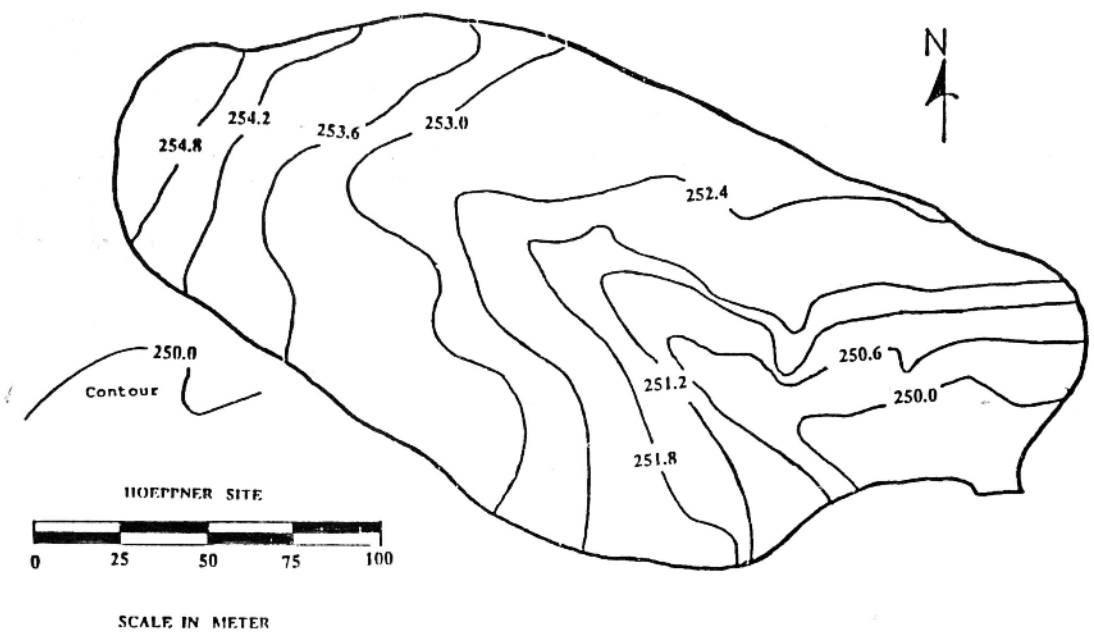

Fig. 2. Contour map of the Hoeppner watershed, Allen County, Indiana, USA.

Black Creek watershed is relatively flat, the elemental slope of the watershed averaging 1.0 - 1.2%. The soils in the watershed are loam, silty loam, silty clay loam, clay loam and silty clay. The predominant land use of the area of this watershed is cropland, 60% small grain, forage, and pasture, and the flatter, lower 40% is predominantly row crop (11).

The third watershed is a small agriculture watershed with an area of 4.83 ha. The soils in this watershed are sandy loam in the upper portion and clay loam in the lower part. This watershed has an average slope of 2.6% with a minimum slope of 0.2% and a maximum slope of around 4.8%. The upper part of this watershed was sown with wheat while the lower part of the site was fallow during the time of data collection.

RESULTS AND DISCUSSION

1. Hoeppner Watershed

The ANSWERS model was used to simulate the storms of 9-4-80 and 6-22-81 on the Hoeppner watershed. The storm of 9-4-80 produced about 21 mm rainfall and 6.78 mm runoff. The duration of the storm was about 2 hr. Figure 3 shows the actual and simulated hydrographs for this rainfall event. Observed and predicted runoff show reasonable agreement. The observed peak rate of runoff for this storm was 9 mm hr^{-1} and it occurred 78 min after the beginning of the rainfall event. The simulation of this storm gave the same peak rate and time of peak. The storm of 6-22-81 produced more runoff from the Hoeppner watershed than the 9-4-80 storm. Total rainfall of the 6-22-81 storm was 72.5 mm over a duration of 2.5 hr. Runoff from the site was 31 mm. Figure 4 shows the watershed response to this storm. Again, there is a reasonable agreement between observed and simulated runoff. The storm of 6-22-81 produced an observed peak runoff rate of 29 mm hr^{-1} at 171 min. The simulation of this storm shows the same time of peak with a 31.8 mm hr^{-1}

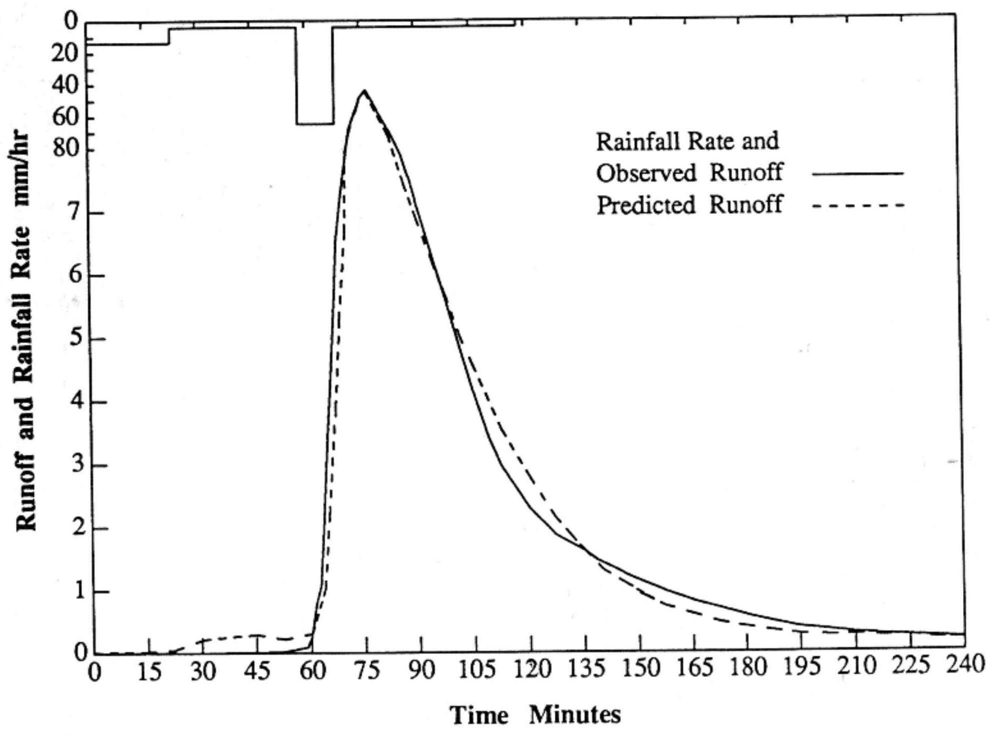

Fig. 3. Rainfall and observed versus predicted runoff hydrographs at Hoeppner watershed (storm:9-4-80).

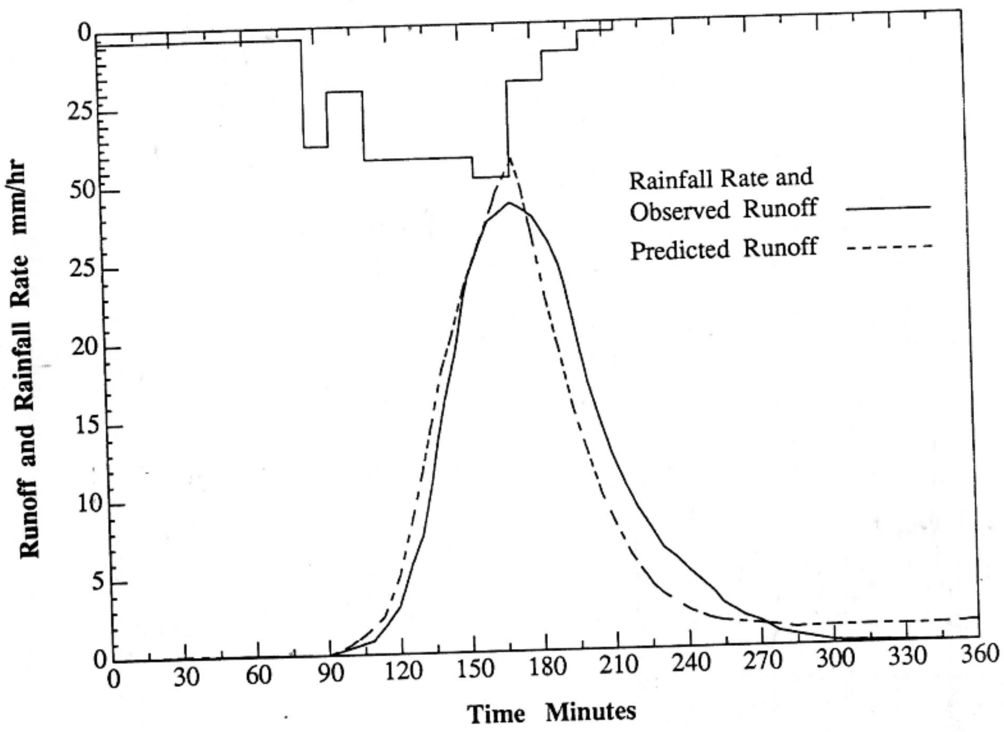

Fig. 4. Rainfall and observed versus predicted runoff hydrographs at Hoeppner watershed (storm:6-22-81).

peak rate. This difference in peak flow rate is only about 9.6%.

2. Upper Black Creek Watershed

Figure 5 shows the observed and predicted hydrologic response and sediment losses from the Upper Black Creek watershed for a storm of 9-4-75. The storm duration was 2043 min with 28.19 mm rainfall and 2.80 mm of runoff. It can be seen that the observed and predicted values of runoff and sediment are in close agreement.

The observed peak flow rate for this storm from the site was 0.53 mm hr^{-1} at 644 min, while the simulated values for this storm are 0.48 mm hr^{-1} at 579 min. The peak flow rates are in close agreement while the simulation peak rate time showed 65 min before the observed peak rate. The predicted total volume of runoff is almost the same as measured value and 65 min represent only 3.2% of the total duration of the storm which shows again the power of the computational model.

3. Agricultural College Small Watershed

The two previous watersheds and their corresponding storms were used to demonstrate the ability of the ANSWERS to closely predict actual response to a natural storm. An understanding of the capability of the ANSWERS model for planning can best be illustrated with a third example. This example is based on the response of the Agricultural College small watershed when subjected to the storm of 11-30-86 (Azar 9, 1365).

Figure 6 shows ANSWERS prediction of sediment detached through the catchment with fallow conditions during that storm. The "contour" lines were created by connecting equal soil detachment points. Thus, areas with closely spaced lines correspond to regions of intense erosion activity. Measurements are not available to directly determine the accuracy of these predictions. However, the detachment

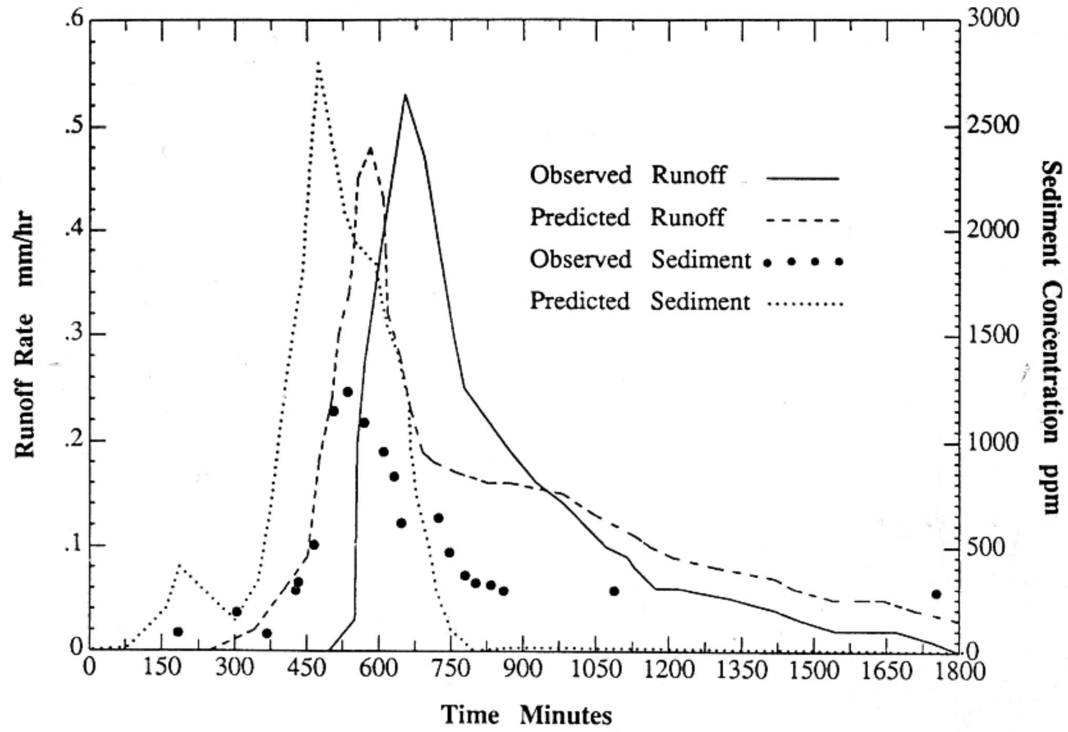

Fig. 5. Black Creek watershed response (storm:9-4-75).

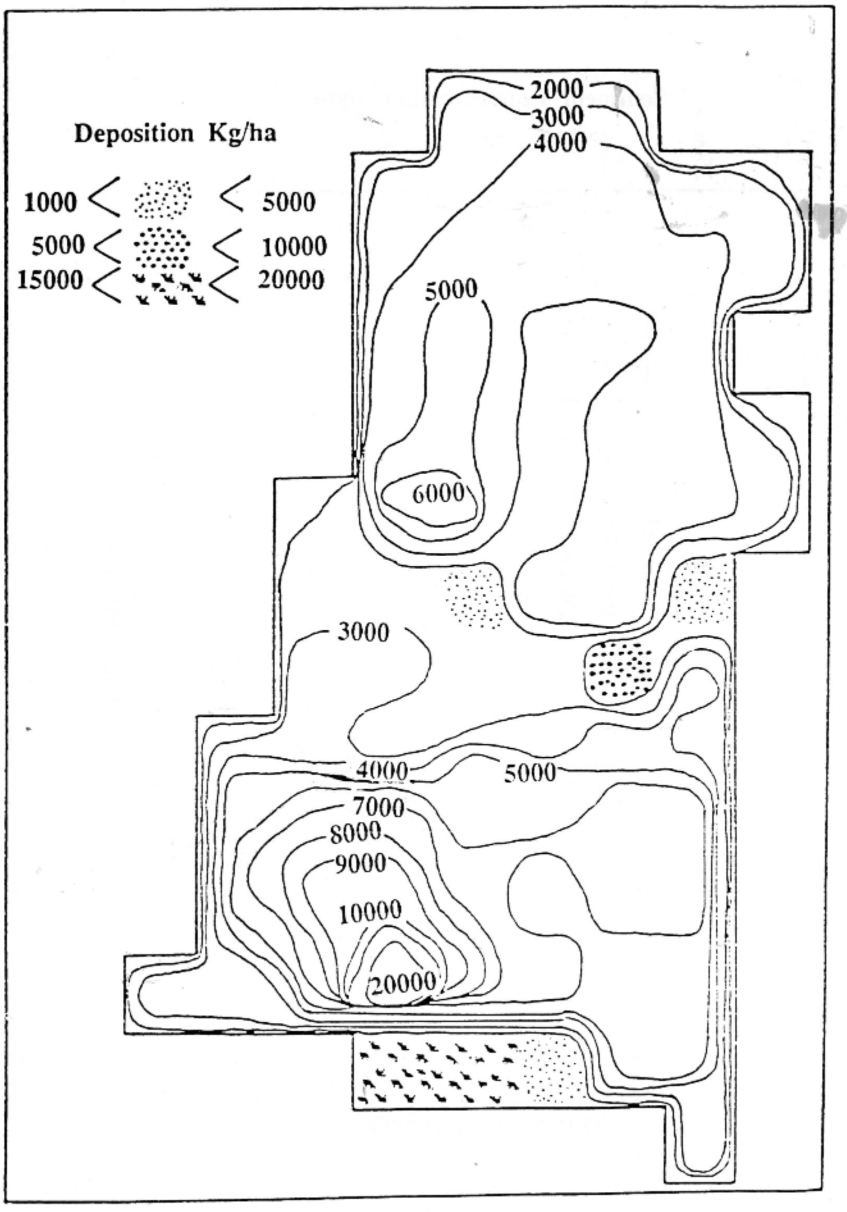

Fig. 6. Response of the small agricultural watershed of the College of Agriculture, Shiraz, Iran. Storm:11-30-86 (fallow situation).

patterns shown in Fig. 6 resulted from a simulation which predicted the total storm discharge from a 111.25 mm event to within 16.25% of 18.12 mm and predicted total sediment yield of 157,595 kg (10).

Figure 7 represents simulation results which analyze the relative benefits of changing the coverage of the watershed surface from fallow to small grain, such as wheat, to reduce sediment yield and its associated pollution. The predicted sediment yield is less than one-tenth of the previous watershed response.

SUMMARY AND CONCLUSIONS

The ANSWERS model, a distributed, rate oriented, single event type model which was originally designed for agricultural applications, is introduced in this paper. The model was briefly discussed and the capabilities of it in simulation of hydrologic response were demonstrated using two storm events in simulation of a small agricultural watershed with 4.3 ha area located in Allen County, northeast Indiana, USA. The simulated and observed values of runoff were very close. The capability of the model in simulation of detachment and transport of soil from a large watershed was next demonstrated using Upper Black Creek watershed with 714 ha area. The simulation results of sedimentation from this site were higher than the observed values. However, the values are in reasonable and acceptable agreement.

The model was finally used for estimating the effects of different land use management including crop coverage and fallow on a small agricultural watershed located in the College of Agriculture, Shiraz, Iran. This third example shows the utilization of a particular distributed model such as ANSWERS in planning. The ANSWERS model can be used for simulation of watershed responses in Iran. Data monitoring from a small agricultural watershed is continued. When the required data are acquired, being the results of the simulations will be published in a separate paper.

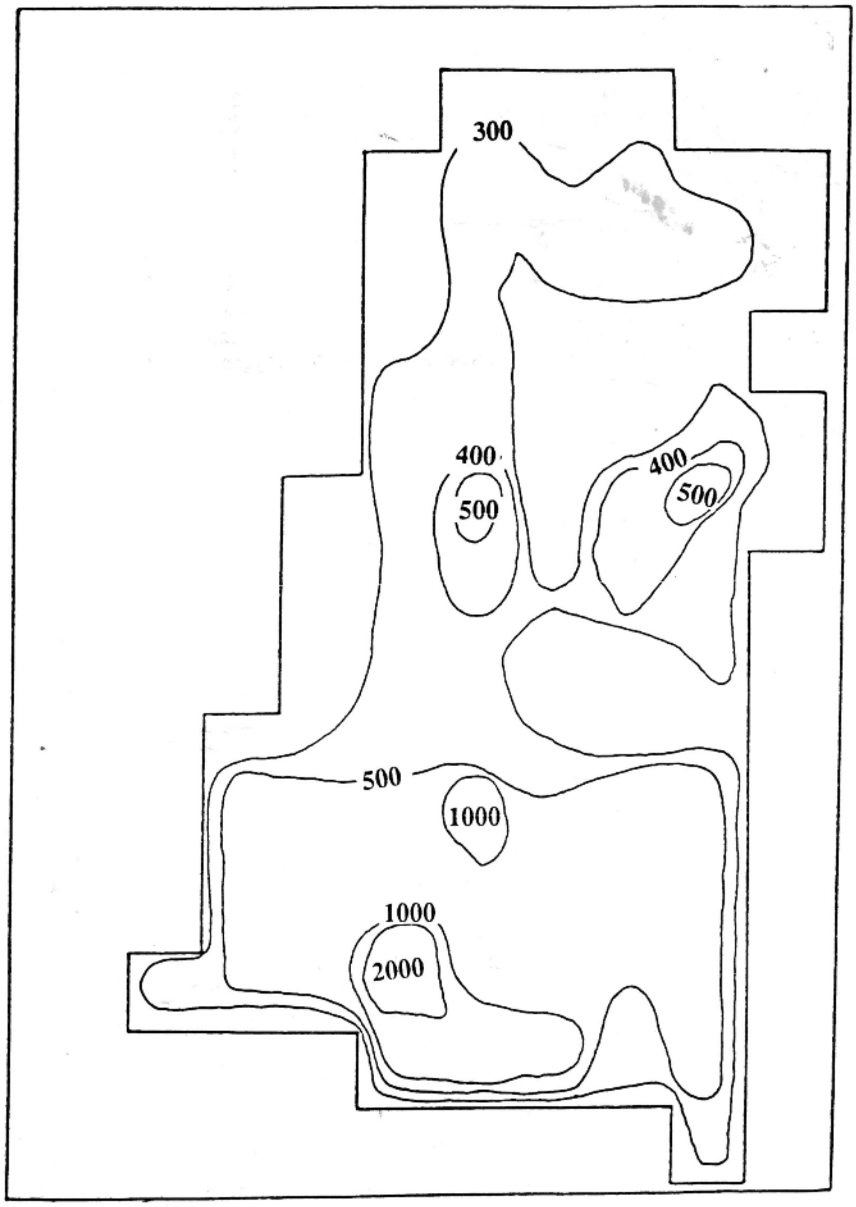

Fig. 7. Response of the small agricultural watershed of the College of Agriculture, Shiraz, Iran. Storm:11-30-86 (small grain coverage situation)

The ANSWERS model has been tested in several climatic conditions in the USA and the results have been found to be in close agreement with respect to observed values. Further work is necessary to apply the ANSWERS model to the particular soil and climatic conditions of Iran, using both small and large watersheds in various parts of Iran. This should allow prediction of current soil loss rates as well as pinpointing areas in which soil conservation techniques would have the most beneficial effects on both reducing soil erosion and improving water quality.

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