ANSWERS: A HYDROLOGIC / WATER QUALITY SIMULATOR FOR WATERSHED RESEARCH

David B. Beasley
Larry F. Huggins

ABSTRACT

In recent years, a greatly increased emphasis has been placed on improving and maintaining the quality of our national water resources. Agencies and individuals from both within and without the various levels of government are seeking information concerning the effects that land use, management, and conservation practices or structures might have on the quality and quantity of water from both agricultural and non-agricultural watersheds.

ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) was developed in an effort to supply the desired information described above for primarily agricultural watersheds. The simulation consists of a hydrologic model and a sediment detachment/transport model along with several routing schemes necessary to describe the movement of water in overland, subsurface, and channel flow phases. This simulation, unlike many large-scale watershed simulations, uses distributed (rather than lumped) parameters and is event (rather than long-term) oriented. These operational features generally yield a better understanding of the hydrologic and water quality interactions involved in a watershed by allowing the user to physically describe those processes at every point within the catchment during the period when the processes are most active, i.e., during an event.

The concepts, as well as the basic mathematical model used in ANSWERS, are presented. General data needs and user considerations are also listed. In addition, the usefulness of ANSWERS as a planning tool is demonstrated by simulating several management schemes for a largely agricultural watershed in northeastern Indiana.

INTRODUCTION

Our national awareness, of water quality problems was greatly increased with the passage of Public Law 92-500 in 1972. Since that time, the nation-wide effort to improve and preserve both the quality and quantity of subsurface waters in the United States has been expanded tremendously. Public Law 92-500 and others passed since 1972 have called for the development of regionalized and state-wide strategies for identifying, assessing the impacts of, and, if necessary, correcting all types of surface water pollution problems.

Point sources of pollution, e.g., sewage treatment plants or industrial process effluents, have been relatively easy to understand and control. Since the source is concentrated at a point, studies to determine the pollutional effect on the downstream environment are farily straightforward. In addition the effluent from a point source generally has a consistent make-up and uniform flow rate.

On the other hand, nonpoint or spatial sources of pollution have been largely ignored due to the complexity of the task of trying to understand and control them. Agriculture is probably the largest contributor of nonpoint source water pollution. The pollutants can take many forms. They may include sediment, animal waste, plant nutrients (fertilizer), pesticides, crop residues, or even excess runoff water. Due to the areal nature of nonpoint sources, they are very difficult, if not impossible, to accurately measure.

Water quality planners are faced with a very difficult challenge. They must decide which set(s) of alternative management practices will produce the most favorable results on water quality. Of course, economics play a vital role. As one can readily see, a trial and error method of solution using actual farms would be prohibitively expensive and time consuming.

What the planners need, then, is a tool which will allow them to try various combinations of management practices on the same area with the same climatic conditions. This would allow them to optimize the distribution of limited financial resources (in the form of cost sharing funds) over the largest possible area while still achieving the sought for water quality goals.

Since the processes involved are highly area-dependent and measurement of their output very difficult, simulation is the logical way to both understand and quantify nonpoint source pollution. This paper presents one such simulator -- ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation).

HYDROLOGIC AND SEDIMENT YIELD MODELING

Until recently, almost all large-scale hydrologic models used the lumped parameter operational concept. The Stanford Watershed Model, developed by Crawford and Linsley (2,3), and and the USDAHL-series of models, developed by Holtan and associates (9,10), both of which use lumped parameters, are certainly the two most widely used hydrologic models presently in existence. Crawford, Donigian, and others (4) have modified the original Stanford Watershed Model in order to predict sediment and chemical movement also. Frere, Onstad and Holtan (8) essentially did the same thing for the USDAHL-series of models when they introduced ACTMO (Agricultural Chemical Transport MOdel).

Although these models have proven that they can simulate the response of natural watersheds to naturally and hypothetically occurring climatic phenomena, they share two common faults. First, since they use lumped parameters, they must necessarily give up a lot of physical significance due to the combination of several physical descriptors into one (or more) lumped term(s). Secondly, lumped parameter models generally predict the response of an entire watershed or subwatershed. The response of smaller areas within the modeled area is, at best, difficult to obtain or describe.

The rapid increases in computer size, speed, efficiency, and availability in the last few years have led to the development of much larger and more physically descriptive modeling efforts. Huggins, Monke and co-workers (11,12,13,14), Freeze and Harlan (7), Kling and Olson (15,16) and Kuh, Reddell and Hiler (17) have all either developed or described various distributed parameter approaches to hydrologic modeling. In addition, Ross, Contractor and Shanholtz (20) have developed a finite element hydrologic model.

The ability to describe on a spatial basis, both the processes of hydrology and erosion gives these distributed parameter models a distinct edge over the lumped parameter models. Water quality researchers and planners are turning to these more descriptive, physically based models in an effort to understand the complex processes and interactions that occur during flow events in watersheds.

ANSWERS CONCEPTS

ANSWERS is a deterministic model based upon the fundamental hypothesis that:

> "At every point within a catchment a functional relationship exists between the rate of surface runoff and those hydrologic parameters which influence runoff, e.g., rainfall intensity, infiltration, topography, soil type, etc. Furthermore, these surface runoff rates can be utilized in conjunction with appropriate component relationships as the basis for modeling other transport-related phenomena such as soil erosion and chemical movement within the watershed."

An important feature of the above hypothesis is its applicability on a "point" basis. In order to apply this approach on a particular scale, the point concept is relaxed to refer instead to a watershed "element". An element is defined to be an area within which all hydrologically significant parameters are uniform. Of course, this process of going from a point to an elemental area could be extended indefinitely until one assumed the entire watershed was composed of a single element with "averaged" parameter values, i.e., a lumped model. The actual geometric size of an element is not critical because there is no finite-sized area within which some degree of variation in one or more parameters does not exist. The crucial concept is that an element must be sufficiently small that arbitrary changes of parameter values for a single element have negligible influence upon the response of the entire catchment.

A watershed to be modeled is assumed to be composed of elements, square in shape for computational convenience, with all hydrologic parameters being uniform within each element. Parameter values are allowed to vary in an unrestricted manner between elements; thus, any degree of spatial variability within the watershed is easily represented. Individual elements collectively act as a composite system because of supplied topographic data for each element delineating flow directions in a manner consistent with the topography of the watershed being modeled. Element interaction occurs because surface flow (overland and channel), flow in tile lines and groundwater flow from each element becomes inflow to its adjacent elements. In all other respects, the elements are hydrologically independent.

Mathematically, individual elemental responses are combined into a watershed system response by integration of the continuity equation:

$$\frac{dS}{dt} = I - Q \tag{1}$$

where:

S = volume of water stored in an element,
t = time,
I = inflow rate to an element from rainfall and adjacent elements,
Q = outflow rate.

This equation may be solved when it is combined with a stage-discharge relationship, e.g., Manning's equation.

The governing equation for the erosion simulation is the continuity equation as used by Foster and Meyer (6):

$$\frac{\partial G_F}{\partial x} = R_{DT} + D_F \tag{2}$$

where:

G_F = rate of sediment movement in the flow (weight per unit width per unit time),
x = distance along flow surface,
R_{DT} = rainfall detachment rate (weight per unit area per unit time),
D_F = flow detachment rate (weight per unit area per unit time).

The process was considered to be quasi-steady and dispersion was assumed to be negligible as proposed by Curtis (5).

The major factors that influence the total water flow from a watershed for steady rainfall are shown in Illustration 1. After rainfall begins, some precipitation is intercepted by the vegetal cover until the interception storage potential is met. When the interception storage capacity is exceeded, infiltration into the soil begins. Since the infiltration rate decreases exponentially as the soil water storage increases, a point may be reached when the rainfall rate exceeds the infiltration capacity. When this occurs, water begins to stand on the surface in micro-depressions. Once the micro-depressional storage (surface retention volume) is filled, runoff begins. The volume of water that is temporarily stored during flow across the surface is surface detention. Subsurface drainage begins when the pressure potential of the groundwater surrounding drains exceeds atmospheric pressure. A steady state infiltration rate may be reached if the duration and intensity of the rainfall event are sufficiently large.

When rainfall ceases, the surface detention storage dissipates until surface runoff ceases altogether. However, infiltration continues until depressional water is no longer available. Subsurface drainage continues as long as there is excess soil water surrounding the drains, producing typically long recessions on outflow hydrographs for tile drained areas.

Natural rainfall events do not exhibit the steady appearance shown in Illustration 1. Furthermore, uniformity of rainfall coverage over a watershed will usually vary during an event. In addition, hydrologic responses of various areas within a watershed may vary greatly. Hence, the resultant hydrograph for the entire watershed will contain at least some of the effects of all of these highly complex, unsteady, non-uniform interactions. For these reasons, a distributed model was designed and utilized as a means of describing and quantifying these processes.

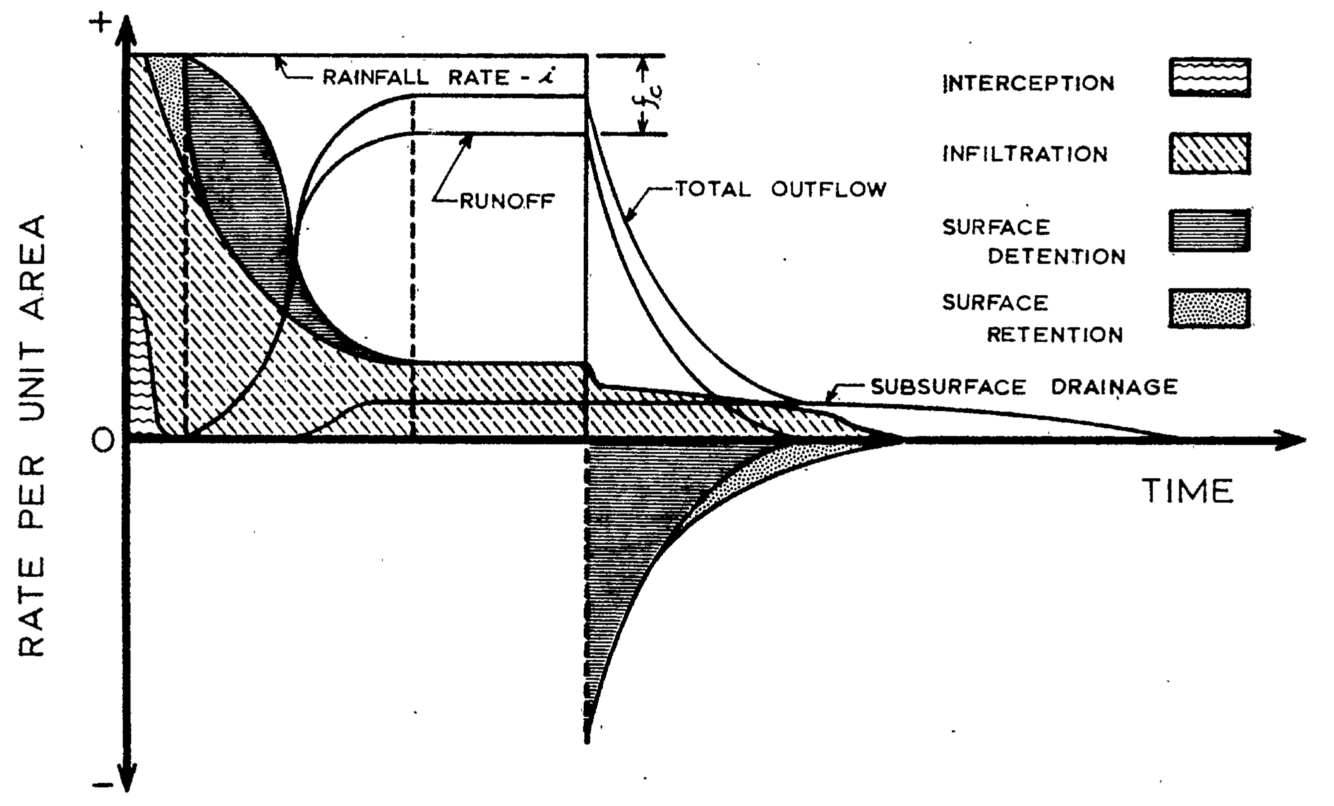
Within its topographic boundary, a catchment is divided into an irregular matrix of square elements, as shown in Illustration 2. Each element acts as an overland flow plane having a fixed slope and direction of steepest descent. Channel flow is analyzed by a separate pattern of channel elements (referred to hereafter as channel segments), which underlie the grid of overland flow elements. Elements designated to have channel flow may, therefore, be viewed as dual elements. These elements act as ordinary overland flow elements, with the exception that all overland flow out of that element goes into its "shadow" channel segment. Flow out of a channel segment goes into the next downslope channel segment. This downslope channel segment will also receive flow from any other channel setments which flow into it and from its own overland flow element.

Overland and tile outflow from an element is assumed to be proportioned as separate surface and tile line inflow into adjacent row and column elements according to the direction of the slope of the element. The slope direction is designated on input as the angular degrees counter-clockwise from the positive horizontal (row)axis. Dividing of the surface and subsurface flow into horizontal and vertical components is accomplished as shown in Illustration 3.

Every hydrologic or erosion component of the ANSWERS model is expressed as a rate. Thus, infiltration and interception rates can both be subtracted from the rainfall rate to provide the excess rainfall rate

ILLUSTRATION 1

SURFACE AND SUBSURFACE WATER MOVEMENT RELATIONSHIPS



used in satisfying surface retention and detention. The difference between the inflow and outflow rates is integrated to provide a volume. When divided by the elemental area, this yields the average depth of water over an element. The depth, in turn, is used to determine an outflow rate by applying a runoff function that accounts for both runoff and detention.

The component relationships used to quantify the hydrologic and erosion processes are, in general, empirical equations developed from many years of modeling and watershed research experience by various individuals and organizations. The detachment and transport relationships in the erosion model are somewhat experimental in nature and are based in large part on water quality observations from plot-size watersheds by Mannering and others (18,19). Beasley (1) gives a complete description of the component relationships used in ANSWERS.

USER CONSIDERATIONS

ANSWERS represents an attempt to develop a comprehensive model intended to be of use in quantitatively evaluating the impact of nonpoint source pollution in an ungaged catchment and in determining the relative effectiveness of alternative corrective measures. One of its primary strengths arises from the use of a distributed parameter type of analysis which inherently accounts for the importance of the areal distribution of the many relevant factors. The distributed analysis provides a very complete characterization of hydrologic response and erosion/deposition occurring at all points in the watershed throughout a storm event.

The primary effort required in preparing a data base to use the ANSWERS model on a particular watershed concerns characterizing the topography and soil type of each element. Where computer compatible data

ILLUSTRATION 2

WATERSHED DIVIDED INTO ELEMENTS (WITH CHANNEL ELEMENTS SHADED)

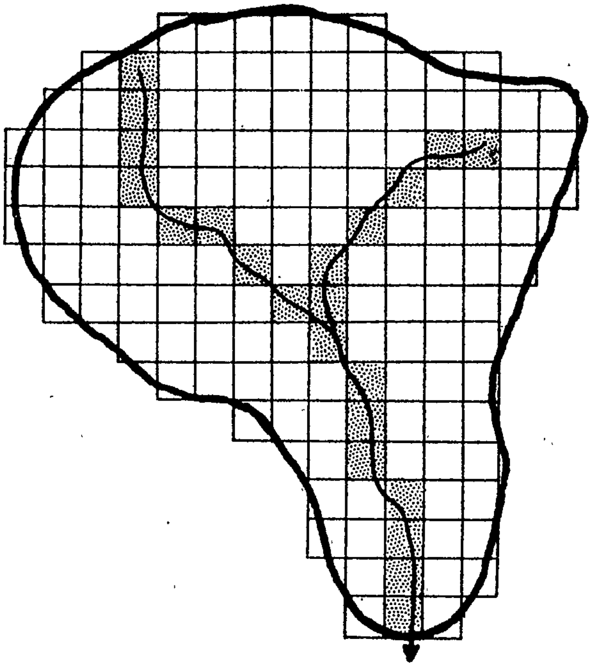
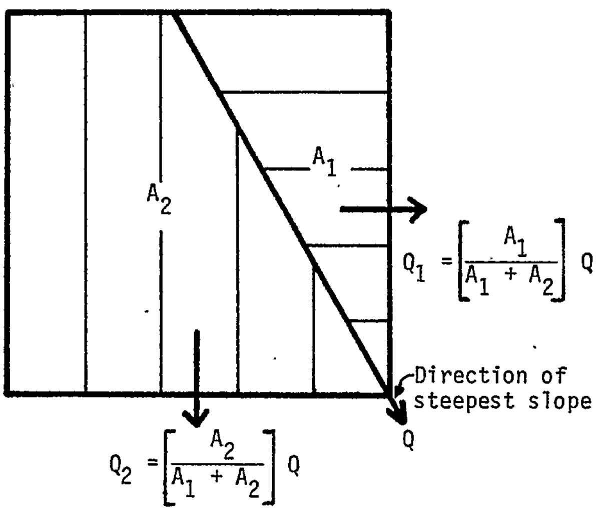


ILLUSTRATION 3

PARTITIONING OF OVERLAND FLOW



files with such information are not available, U.S. Geological Survey topographic maps and County Soil Survey maps must be used. While these sources of information are quite adequate, the effort required to digitize the information is not trivial.

The frequent complaint voiced by potential users of comprehensive watershed models is the large volume of data required concerning watershed characteristics. The comment is often directed at distributed parameter models because a large data base is usually required. However, one of the fundamental strengths of comprehensive models is their potential ability to characterize the many processes for which input coefficients must be specified. When data are not available to quantify some coefficients, assumed values can be supplied. While one is never comfortable in such a situation, it is easy to use a comprehensive model to evaluate the sensitivity of the prediction to changes in assumed values.

In contrast, "simpler" models that require less input have incorporated, at creation time, implicit assumptions concerning all variables for which explicit numerical values are not demanded from the user. Because these assumptions are implicit, the user has neither control over them nor any means of evaluating their importance. Thus, while it is desirable to have available hard data to quantify all parameters of comprehensive model, it is better to assume values for a model than to submit to the rigidity of implicit assumptions inherent with simpler models.

SIMULATION RESULTS

Absolute verification of the accuracy or applicability of a complex watershed model (such as ANSWERS) is, in a strict sense, impossible. This is due to the extremely large number of degrees of freedom designed into the model in an effort to be more physically descriptive. Optimization techniques could be used to provide a "best fit" set of input coefficients. However, collection of field data to verify these optimized parameters would not be feasible. Thus, optimization would probably not yield any more accurate answers, since there would not be any additional data to prove or disprove any assumptions.

Planners, fortunately, are not interested in simulating observed events only. They are in fact, much more interested in having the capability of simulating hypothetical events with hypothetical management practices. ANSWERS lends itself very well to these "what if" simulations.

Despite the impossibility of absolute model verification, a real need exists to provide some measure of the accuracy of a model's simulation during its developmental period. Ultimately this comes down to comparing its output with gaged data from specific events on natural watersheds. Several complex storm events which occurred during 1975 and 1976 were simulated for two gaged subcatchments of the Black Creek watershed in northeastern Indiana. These subcatchments were 714 and 942 ha (1765 and 2328 A) in size. Beasley (1) gives a detailed discussion of these results. While they varied somewhat from one storm to another and on the basis of evaluation criteria, the results were generally within 30 percent of gaged values for all criteria.

Illustrations 4 and 5 show some of the more applicable outputs available from an ANSWERS simulation. They were produced by simulating the behavior of a 714 ha subcatchment of the Black Creek watershed using 1 ha elements together with cropping, management and rainfall data for the specified date.

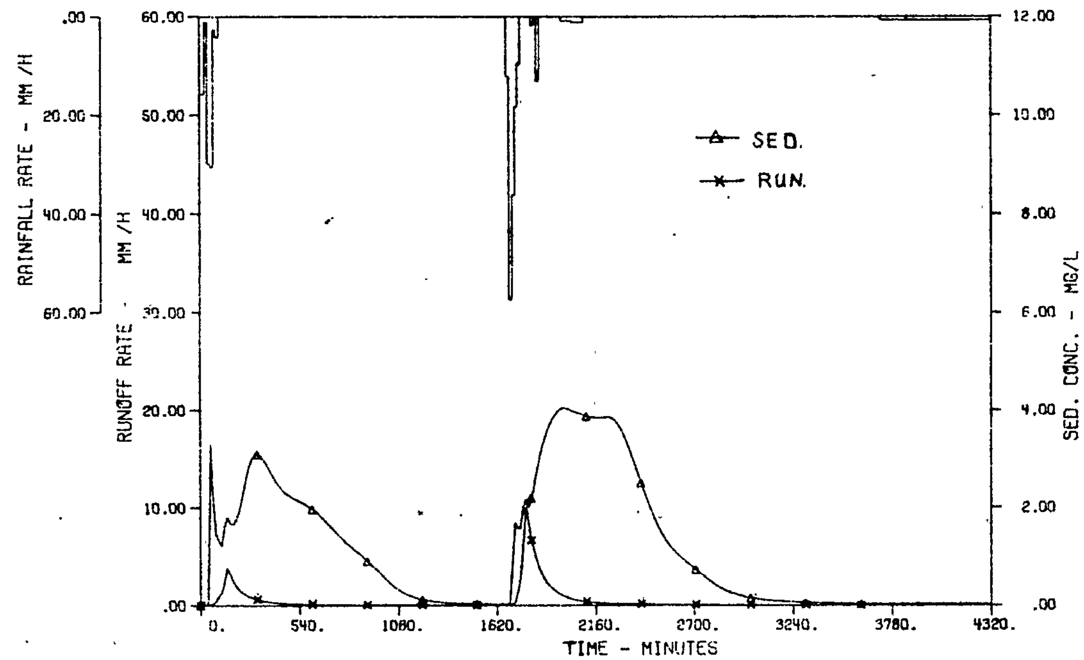
Illustration 4 gives output typical of a lumped model, runoff and sediment concentration hydrographs at the watershed outlet. The simulated volume was within 9 percent of the gaged amount (19 mm) and the total sediment yield within 13 percent of the observed amount (325000 kg). These quantities were produced from a storm with 64 mm of rainfall.

Any benefits of using a distributed parameter model instead of a lumped one are not obvious from Illustration 4. While it was claimed above that the distributed approach makes possible a more accurate simulation, a single example of close agreement between gaged and simulated results is totally inadequate to judge the validity of such a claim. Futhermore, even an extensive set of comparative simulations using ANSWERS and the best of available lumped models could establish only the relative merit between the two specific models. This would not offer conclusive evidence concerning which of the two fundamental philosophies was superior.

Illustration 5 clearly depicts one major advantage of a distributed model -- more comprehensive output information. The "contour" lines on the map result from connecting points within the watershed which experienced equal soil detachment during the storm. Thus areas with closely spaced lines correspond to regions of intense erosion. Such maps readily identify those regions where control measures should first

ILLUSTRATION 4

RUNOFF RATE VERSUS TIME IN MINUTES



be considered. Illustration 5 indicates the bulk of the erosion occurred in the upland portion of the watershed (the most steeply sloping region) with two small areas experiencing a loss of more than 14,000 kg/ha. The general location of severe erosion could certainly have been predicted by any person familiar with the area and reasonably knowledgeable of erosion processes. The reason for modeling the area's behavior is not to identify the location of problem areas, but to obtain a quantitative estimate of both the amount of soil eroded and its impact on water quality.

Illustration 6 shows what ANSWERS predicts would be the effect of a hypothetical change in tillage practice for the entire catchment. The actual tillage practice used on almost all row crop and small grain fields in the watershed is fall moldboard

ILLUSTRATION 5

LOCAL SOIL DETACHMENT (STORM OF 6/23/75)

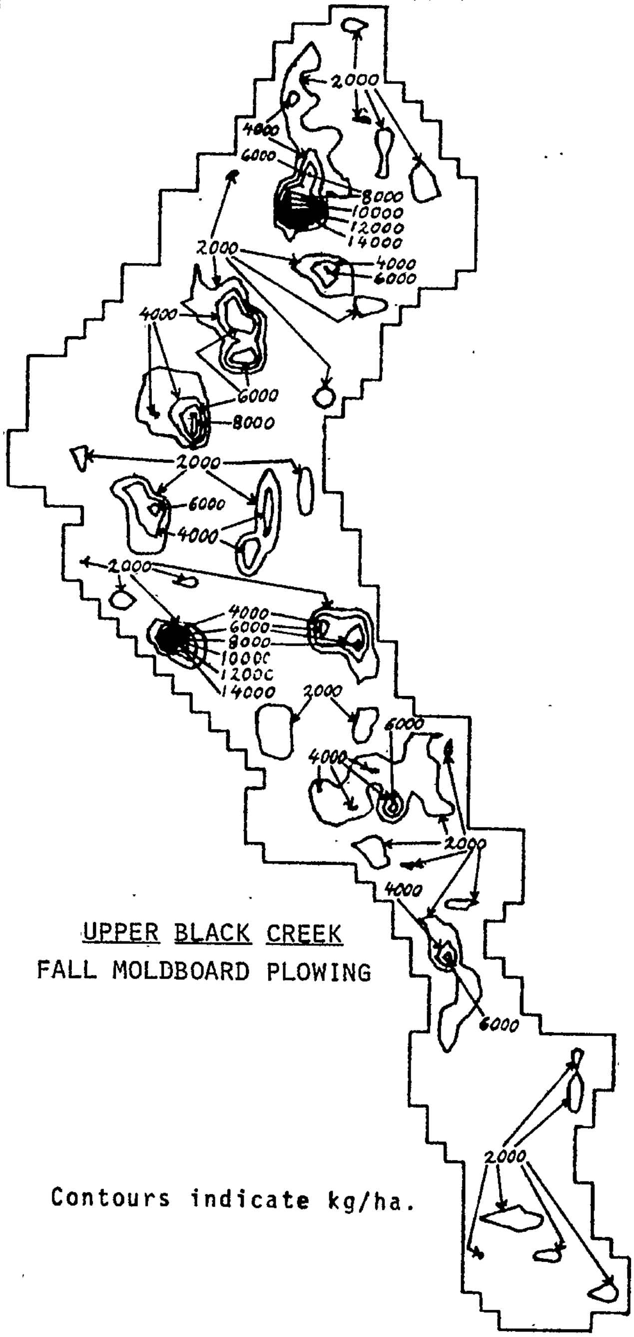
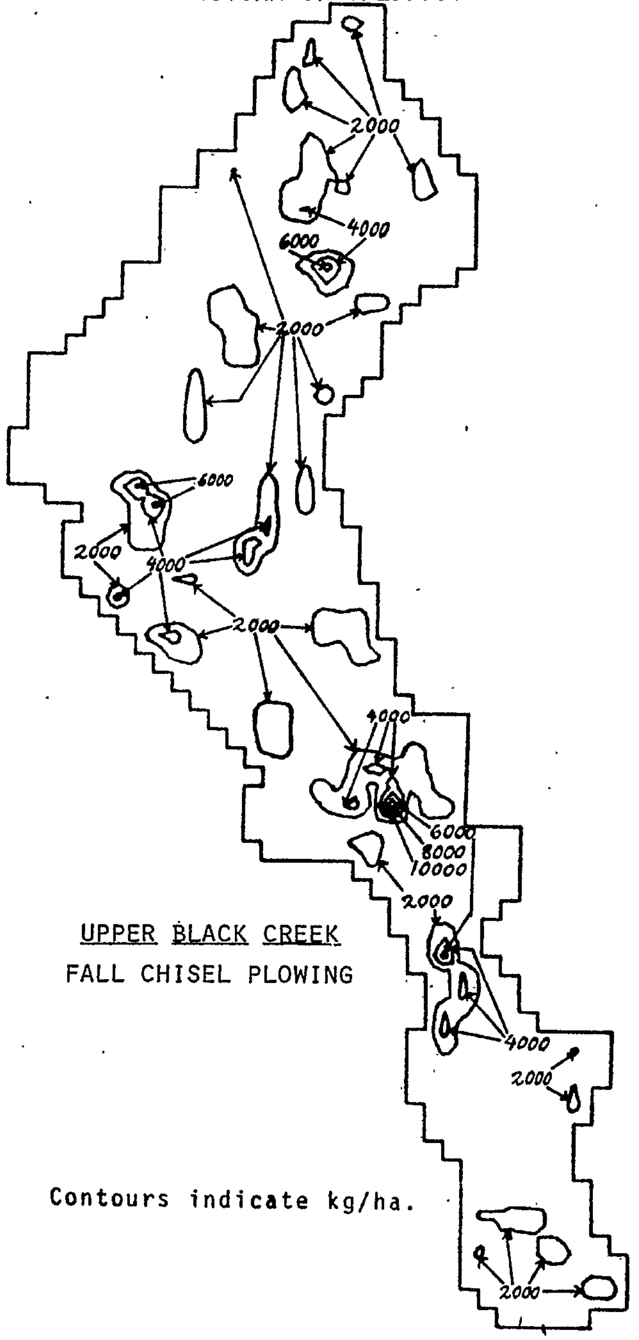


ILLUSTRATION 6

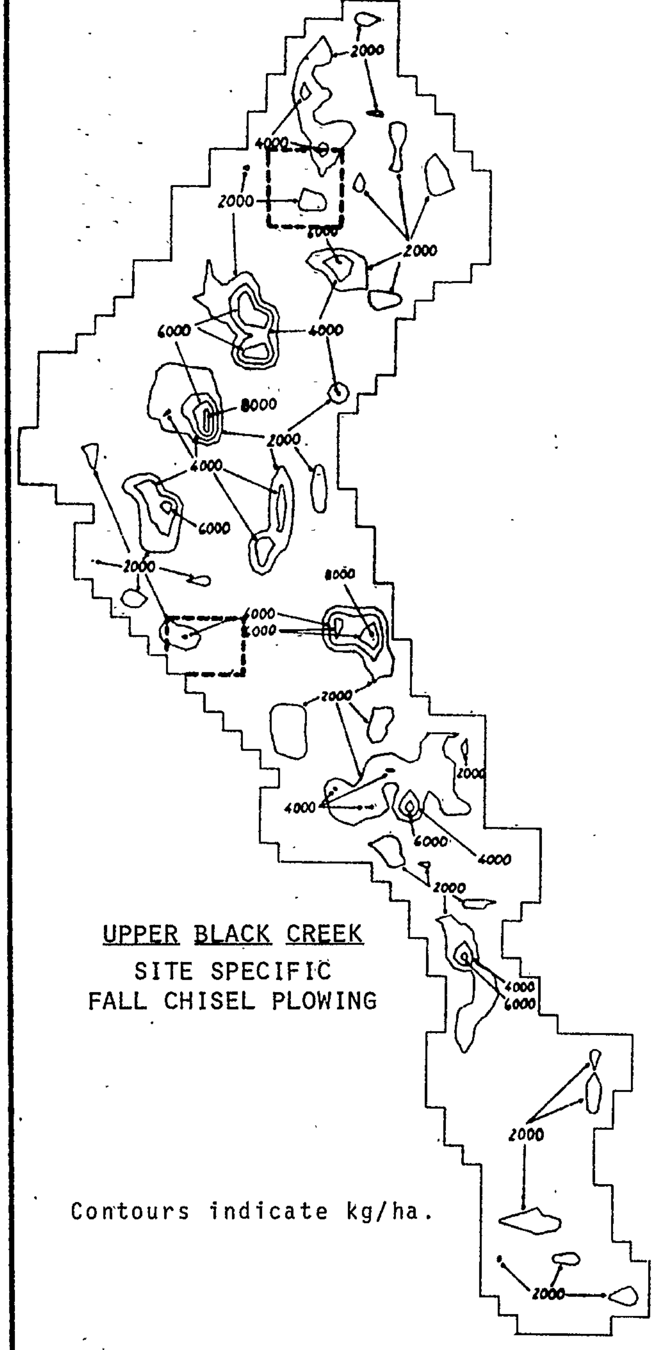
LOCAL SOIL DETACHMENT (STORM OF 6/23/75)



plowing. Illustration 5 was generated with that tillage practice specified. Illustration 6 was generated under the assumption that moldboard plowing would be replaced by fall chisel plowing for all cropland in the catchment. In contrast to the moldboard plow, the chisel plow leaves more crop residue on the surface and a rougher microrelief which tends to enhance infiltration. Comparison of the two simulation results shows the impact of such a management change on the resulting erosion pattern. Integration of the sediment concentration hydrograph at the watershed's outlet indicates only 1/3 of the sediment yield simulated for current management practices.

Illustration 7 shows an ANSWERS simulation of the effect of changing to chisel plowing in only two of the highest erosion regions, those enclosed by broken lines. The total area of these two regions is only 32 ha of the watershed area of 714 ha. Integration of the outflow hydrographs indicates that changing tillage on only these two small areas would achieve 40 percent of the sediment yield reduction that could be achieved by changing the management of the entire watershed.

ILLUSTRATION 7
LOCAL SOIL DETACHMENT
(STORM OF 6/23/75)



CONCLUSIONS

A comprehensive, non-point source watershed simulator, named ANSWERS, has been developed. It was designed around a distributed parameter concept with the intention of giving an accurate, comprehensive description of a watershed's behavior during and immediately following storm events.

The primary strengths of the distributed parameter approach are its inherent accuracy, especially for ungaged situations such as evaluating the influence of hypothetical changes to a watershed, and its detailed description of the behavior of all interior points within a catchment's boundaries. The primary disadvantage of the approach is that the cost, for both data preparation and computer time, to use it increases somewhat proportionally to the area being simulated.

Although the area to which ANSWERS can be applied is probably limited to 200 square kilometers or less due to present computer technology, water quality planners should not be seriously handicapped. The planners will use ANSWERS to gain detailed information on small areas, while larger and grosser estimators will be used to determine which subregions require a more detailed examination.

Extrapolation of unit cost data for various nonpoint pollution control measures and the watershed simulation example discussed above lead to the same conclusion. In order to be feasible, any nonpoint source program must be highly site specific. Attempts to treat large areas with a uniform set of practices or regulations will so dilute available funds that the program will have little chance of being effective or publicly accepted. ANSWERS offers a unique planning tool to help formulate site specific nonpoint source programs for agricultural areas.

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