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ANSWERS — USERS MANUAL

ANSWERS

(Areal Nonpoint Source Watershed Environment Response Simulation)

User's Manual

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CHAPTER I: INTRODUCTION

This manual is intended to present the theory behind the ANSWERS simulation model, a broad overview of the computational algorithms employed in the current implementation of the model and, most importantly, a practical guide for persons who want to use the model as a tool in developing nonpoint source pollution control measures. Depending upon the intended application, only certain sections of the manual may be relevant.

Chapter II gives a broad overview of the model and should generally be read by anyone considering its use. Chapter III goes into computational details of the component relationships and is necessary reading only if a thorough understanding of the internal workings of the model is desired. Two different sediment detachment/transport sub-models are presented in this manual. Chapter III details the current, "production" version of the model, while Appendix D describes the new, more detailed model capable of providing information on particle-size distributions. Chapters IV and V, together with Appendices A, B, and C, detail procedures for simulating watershed behavior and interpreting the results.

Finally, it must be noted that developmental work on improving the utility of ANSWERS is still on-going. A listing of the ANSWERS computer program was deliberately excluded from this publication in order that interested users would obtain the latest version of the model rather than attempt to manually reproduce a possibly obsolete listing. In particular, developmental work is nearing completion on a version which includes direct simulation of nutrient losses in addition to the sediment yield discussed herein. A supplement to this manual will be distributed with all releases of the expanded version of the model.

Acknowledgments

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Numerous graduate students of the Department of Agricultural Engineering and professional colleagues have contributed greatly to various components and programming algorithms. Individuals deserving special mention include: J.R. Burney, T.A. Dillaha, III, G.R. Foster, H.M. Galloway, J.V. Mannering, T.D. McCain, E.J. Monke, D.W. Nelson, and W.H. Wischmeier.

Disclaimer

The contents of this publication do not necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commerical products constitute endorsement or recommendation for use. While every reasonable effort has been made in the development of the ANSWERS model to provide a computer program free of logical errors, no absolute assurance can be given that this effort has been entirely successful. Furthermore, neither the U.S. Environmental Protection Agency, the Allen County Soil and Water Conservation District, the Indiana Heartland Coordinating Commission or Purdue University assumes any responsibility for liability, either direct or indirect, as a result of actions predicated on model simulation results.

In order to assure that modeling results are as reliable as possible, **always use the latest release of ANSWERS.** Contact Dr. David B. Beasley in order to determine the most recent version of the ANSWERS model and to obtain information concerning acquisition of ANSWERS and related programs.

CHAPTER II: CONCEPTS

Philosophy

ANSWERS is a model intended to simulate the behavior of watersheds having agriculture as their primary land use, during and immediately following a rainfall event. Its primary application was envisioned to be planning and evaluating various strategies for controlling nonpoint source pollution from intensively cropped areas. For such situations, a watershed's hydrologic response to a storm event is the controlling mechanism for transporting pollutants to the drainage network.

A fundamental characteristic of the ANSWERS model is its distributed parameter approach as contrasted to the more common lumped parameter modeling efforts. While this approach is generally more computationally intensive, its inherent advantages were deemed to more than offset this factor.

A distributed parameter watershed model incorporates the influences of the spatially variable, controlling parameters, *e.g.*, topography, soils, land use, etc., in a manner internal to its computational algorithms. In contrast, lumped parameter models incorporate, to whatever degree they do not ignore, these effects by an *a priori* analysis of a watershed's spatially variable characteristics. In other words, the lumped approach uses some type of averaging technique to generate an "effective" coefficient(s) for characterizing the influence of specific, non-uniform distributions of each parameter. The influence of this distribution is then represented by the "lumped" coefficients, and the resulting model is treated as a mathematical transformation of input into output, *i.e.*, a "black box", for the subsequent simulation.

A primary advantage of a distributed parameter analysis is its potential for providing a more accurate simulation of natural catchment behavior. The term **potential** is used because increased accuracy is by no means a direct consequence of using a distributed analysis; rather, it is realized only if the model is designed to avoid the constraints imposed by lumped parameters.

Lumped models almost invariably employ some weighting function to account for the spatial variability of watershed parameters such as soil type, cover and slope steepness. Such weighting functions, regardless of how elaborate, are applied to the catchment prior to modeling runoff. This constrains the parameter values to be independent of the magnitude and temporal distribution of the storm event. Such a constraint is valid only for linear systems. Thus, the assumptions and limitations of behaving, at least to some degree, as a linear system are subtly imposed on lumped models. Another linear system assumption implicit to almost all weighting functions used with lumped models results from ignoring the influence of geographic placement of spatially varying factors within the watershed boundaries. The magnitude of error associated with such approximations has been demonstrated by Huggins, et al. (1973).

A second major advantage of a distributed model is its inherent ability to simultaneously simulate conditions at all points within the watershed. This ability to depict what is happening throughout the watershed greatly increases the amount and utility of information provided. In addition, it permits simulation of processes that change both spatially and temporally throughout the watershed. The accuracy with which interacting processes can be modeled is thereby increased.

Finally, distributed models greatly facilitate incorporation of relationships developed from small scale "plot-size" studies to yield predictions on a watershed scale. It is much easier to formulate the individual processes being modeled as independent equations applicable at a point, letting the subsequent integration process incorporate effects of spatial and temporal variability, than to develop an elaborate weighting function for each process. This approach also directly accounts for process interactions that would otherwise be ignored or require complex modifications of weighting functions.

A complete discussion of the concepts and chronologic development of the ANSWERS model can be found in Huggins and Monke (1966), Beasley (1977), Beasley, *et al.* (1980), and Dillaha (1981).

Model Structure

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

> "At every point within a watershed, functional relationships exist between water flow rates and those hydrologic parameters which govern them, *e.g.*, rainfall intensity, infiltration, topography, soil type, etc. Furthermore, these flow rates can be utilized in conjunction with appropriate component relationships as the basis for modeling other transport-related phenomenon such as soil erosion and chemical movement within that watershed."

An important feature of the above hypothesis is its applicability on a "point" basis.

In order to apply this approach on a practical 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 a negligible influence upon the response of the entire watershed.

A watershed to be modeled is assumed to be composed of "elements" as shown in Figure 2-1. A square element shape was chosen to ease the task of data file preparation and to facilitate computational convenience. It is this user supplied elemental data file, listing the physical characteristics of each watershed element, which permits ANSWERS to simulate the unique behavior of any particular watershed.

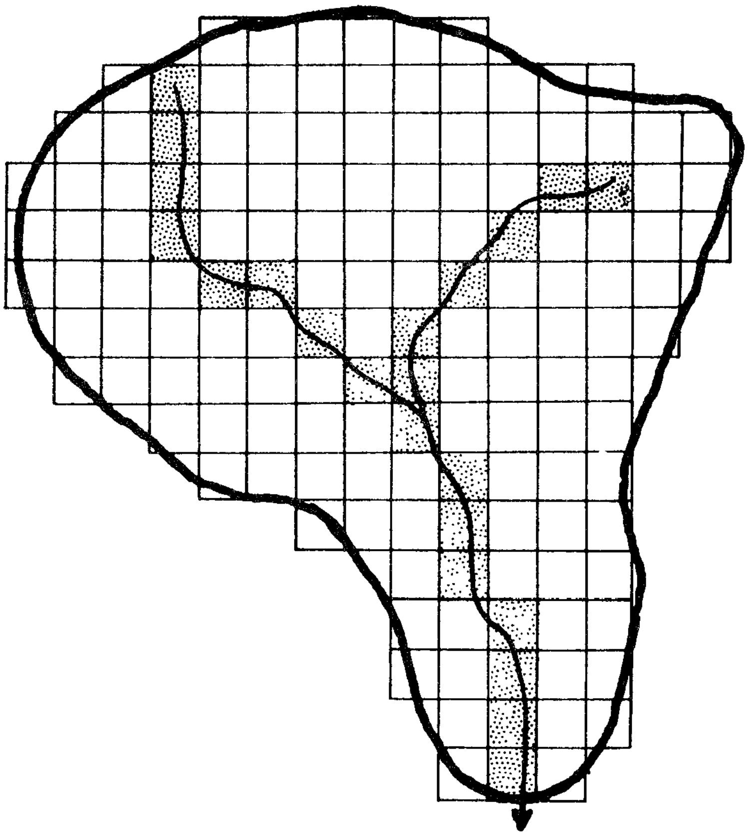


Figure 2-1. Watershed Divided into Elements with Channel Elements Shaded.

Component relationships characterizing water and pollutant production need only simulate the behavior of a small, uniform elemental area. Parameter values are allowed to vary in an unrestricted manner between elements; thus, any degree of spatial variability within a 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. Pollutants are generated and transported by these flows and by raindrop impact.

It is the distributed model structure, which inherently provides the ability to simulate the fate of any type of pollutant and to integrate the response of individual elements to yield a composite watershed simulation, that is the foundation of ANSWERS. The component relationships included in a specific release of the model will determine which pollutant processes are described and to what extent. Specific relationships included have no effect whatsoever on the integration algorithm or distributed model concepts. Of course, relationships chosen have a marked impact upon the accuracy with which the model can characterize real watershed behavior. The significant consequence is that to substitute one component relationship for another when subsequent research develops improved relationships is a relatively trivial task.

Hydrologic Considerations

As indicated earlier, hydrologic processes are the driving force within the model. Consequently, a conceptual understanding of those processes, as they apply to each independent watershed element, is a prerequisite to studying component algorithms.

Hydrologic processes, for which component relationships have been incorporated within ANSWERS, are shown qualitatively in Figure 2-2. After rainfall begins, some is intercepted by the vegetal canopy until such time as the interception storage potential is met. When the rainfall rate exceeds the interception rate, infiltration into the soil begins. Since the infiltration rate decreases in an exponential manner as the soil water storage increases, a point may be reached when the rainfall rate exceeds the combined infiltration and interception rates. When this occurs, water begins to accumulate on the surface in micro-depressions.

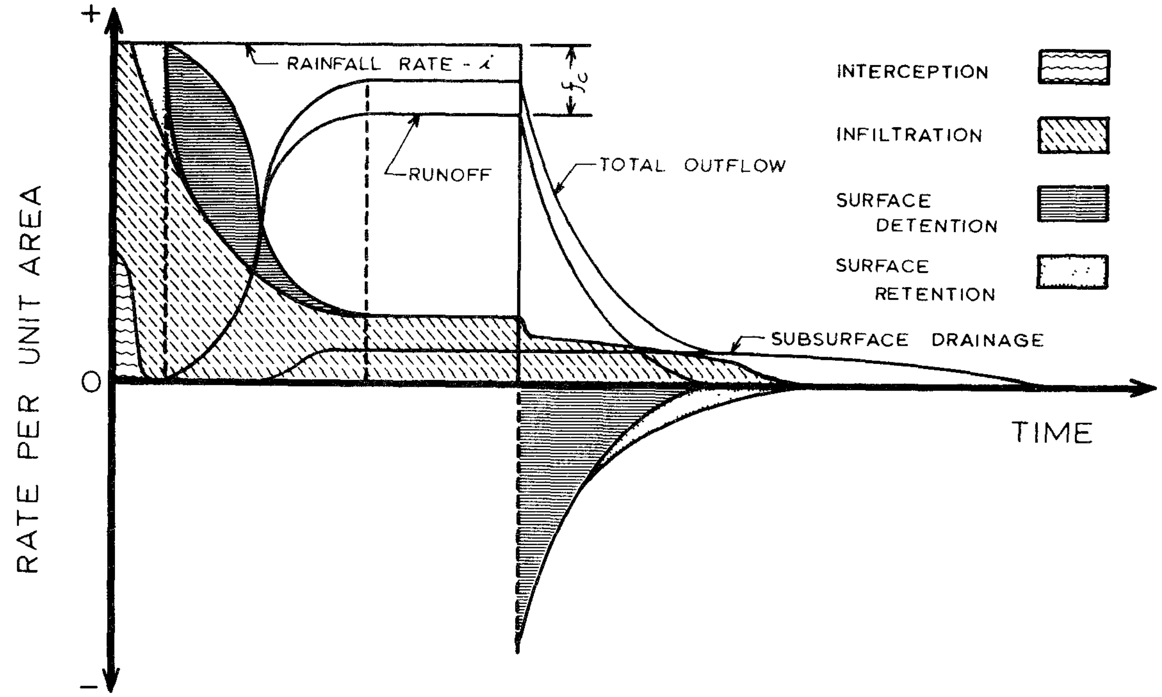


Figure 2-2. Water Movement Relationships for Small Watershed Elements.

Once surface retention exceeds the capacity of the micro-depressions, runoff begins. The accumulated water, when in excess of surface retention capacity, produces surface runoff and is termed surface detention. Subsurface drainage begins when the pressure potential of the groundwater surrounding a tile drain exceeds atmospheric potential. 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 begins to dissipate 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. The long recession curve on the outflow hydrograph, typical of tile drained areas, is then produced. Slowly falling recession limbs are also produced by interflow, the emergence of groundwater into the surface drainage network.

Soil detachment, transport, and deposition are very closely related to concurrent hydrologic processes in a watershed. Detachment and transport can both be accomplished by either raindrop impact or overland flow. Detachment by rainfall occurs throughout a storm even though overland flow may not occur. Thus, most of the soil particles detached prior to flow initiation are deposited and to some extent, reattached. Detachment of soil particles by overland flow occurs when the shear stress at the surface is sufficient to overcome the gravitational and cohesive forces of the particles. Whether or not a detached soil particle moves, however, depends upon the sediment load in the flow and its capacity for sediment transport.

The transport of chemical pollutants from a land area is also highly related to the hydrologic behavior of a catchment and, for certain chemicals, *e.g.*, phosphorus, to the soil erosion that occurs. These processes can be readily incorporated into a distributed model by developing component relationships that characterize what happens within an individual watershed element. These processes may be much simpler than those that must work on the watershed scale required by a lumped approach.

Natural rainfall events do not exhibit the steady appearance shown in Figure 2-2. Furthermore, uniformity of 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. The distributed approach provides a straightforward and accurate method of simulating such a complex situation.

All materials leaving an element are assumed to be transported with one of the various flow components. Overland flow either moves into an element's shadow channel element, if a channel is specified for that element, or onto its adjacent elements. Tile and groundwater flows are assumed to outlet directly into the specified channel network. It is this network of interacting flows which causes the "independent" watershed elements to act together as a composite system.

Applicability

The distributed nature of the ANSWERS model is both its strength and ultimate limiting factor. As will be shown with subsequent examples, the degree of information provided to decision making bodies and program planners is extraordinary. However, costs for preparing an elemental data file and for computer time increase with the number of elements required. Thus, economics and the size of computer available limit the feasible number of elements and, consequently, the size of watershed which can be simulated. Of course, selection of a larger element size permits simulation of a larger area for a given number of elements. However, this comes at the expense of inaccuracy in representing the spatial diversity of a watershed and of component relationships within the model. As a practical matter, element sizes normally range from 1 to 4 ha. with watershed sizes commonly less than 10,000 ha. Additionally, the utilization of the expanded capability sediment transport model (which allows particle-size calculations) requires additional computer resources and time. Hence, all other things being equal, the expanded model will not simulate as large an area and it will cost more (as much as two times) on a unit area basis.

CHAPTER III: COMPONENT RELATIONSHIPS

This chapter outlines the specific mathematical relationships currently used to quantify the various model component processes and also gives an overview of the programming algorithms employed. It is intended primarily for the person who is doing research in model development or who is interested in modifying some features of the current release of the model. Parameter names which are given in all capital letters correspond to the programming names used for those variables.

The specific component relationships selected for the current version of ANSWERS are separately discussed below. All except the time integration of the continuity equation are incorporated on a modular basis. Modification or replacement of component relations such as infiltration or sediment production does not affect the algorithms for other components. In other words, the component relationships are sufficiently independent from each other that user-supplied subroutines may be substituted for those supplied with the "official" release of the model. This framework also permits users to append additional component relationships to simulate other processes important to specific applications.

Flow Characterization

Mathematically, each element's hydraulic response is computed, as a function of time, by an explicit, backward difference solution of the continuity equation:

$$I - Q = \frac{dS}{dt} \qquad (3\text{-}1)$$

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

This equation may be solved when it is combined with a stage-discharge relationship. Manning's equation, with appropriately different coefficients, is used as the stage-discharge equation for both overland and channel flow routing.

Within its topographic boundary, a catchment is divided into an irregular matrix of square elements, as shown in Figure 2-1. Every element acts as an overland flow plane having a user specified 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 *i.e.,* are in the shadow of, the grid of overland flow elements.

Elements designated to have channel flow may 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 from a channel segment goes into the next downstream channel segment. This downstream channel segment will also receive flow from any other channel segments which are directed toward it and from its own overland flow element.

Overland and tile outflow from an element flows into neighboring elements according to the direction of the element's slope. The slope direction is designated on input as the angle, in degrees, counter-clockwise from the positive horizontal (row) axis. For the example shown in Figure 3-1 below, slope direction is in the fourth quadrant. The slope direction angle equals 270 degrees plus angle **ANG.**

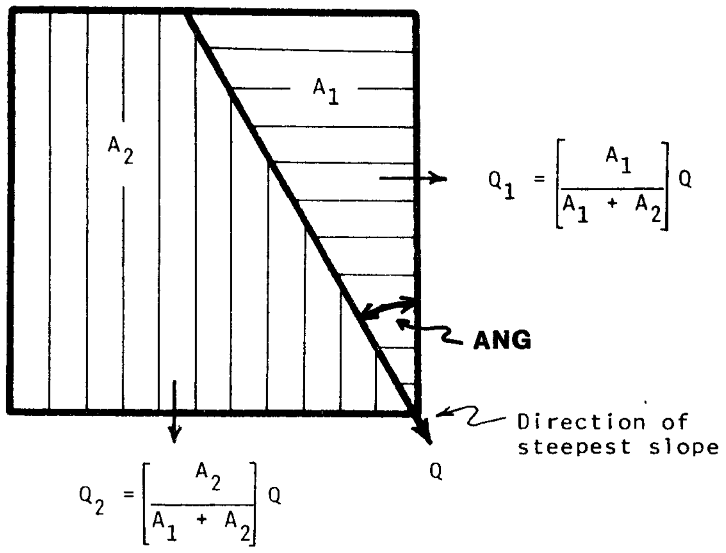


Figure 3-1. Partitioning of Overland Flow.

The fraction of outflow going into the adjacent row element, RFL, is:

$$RFL = \frac{\tan\ (ANG)}{2} \quad \text{if ANG} \leq 45 \text{ deg.} \tag{3-2a}$$

$$RFL = 1 - \frac{\tan\ (90-ANG)}{2} \quad \text{if 45 deg.} < ANG < 90 \text{ deg.} \tag{3-2b}$$

with the remaining outflow going into the adjacent column element. Since everything, including surface slope, within an element is assumed to be constant, this method of partitioning overland flow seems intuitively obvious.

The most appropriate manner to partition tile flow is not as obvious as is overland flow. In general, records are seldom available which delineate the layout of tile systems. However, limitations on feasible installation depths mean that tile slopes must, with only temporary deviations, follow the general topography. Therefore, the use of an element's slope properties was chosen as a close approximation which has the secondary benefit of eliminating the need for additional input information.

Baseflow, the emergence of groundwater into the channel system, is simulated only crudely in the current release of ANSWERS. All infiltrated water which moves past the zone of tile drainage is assumed to enter a single groundwater storage reservoir. Water is then released evenly into all channel segments at a rate proportional to the volume of accumulated storage.

The flow relationship utilized in conjunction with the continuity equation to perform the overland flow routing is Manning's equation. The hydraulic radius is assumed equal to the average detention depth in an element. The flow width is assumed to be the maximum width for that element, *i.e.*, the length measured in a direction perpendicular to the overland flow direction.

Surface detention is the water volume which must build up to sustain overland flow. Detention depth is calculated as the total volume of surface water in an element, minus the retention volume (which can only infiltrate), divided by the area of the element. This implies that the entire specified retention volume of an element be filled before any water becomes available for surface detention and runoff.

Surface detention is a component that can have a pronounced effect on surface runoff and drainage characteristics of a watershed. Rough ground can store large amounts of water. Huggins and Monke (1966), using several field surfaces, developed a relationship describing the surface storage potential of a surface as a function of the water depth in the zone of micro-relief. The form of that equation used by ANSWERS is:

$$DEP = HU * ROUGH * \left(\frac{H}{HU}\right)^{1./ROUGH} \qquad (3\text{-}3)$$

where: DEP = volume of stored water, in depth units,
H = height above datum,
HU = height of maximum micro-relief,
ROUGH = a surface characteristic parameter.

The specified surface roughness determines the volume of surface storage and also influences infiltration rates during the recession limb of a hydrograph, as explained later.

Although the channel flow system is unrestricted in direction and branching, it is necessary that it be continuous and that each element contain only one channel segment. To achieve greater definition it is necessary to assume a smaller element size for all elements, with a consequent increase in core storage and computer execution time.

As all overland flow from a dual element is constrained to enter its shadow channel segment, the surface slope direction of a dual element is irrelevant for partitioning overland flow to adjacent elements. Therefore, instead of specifying the direction of surface slope for a dual element, this parameter position in the data file is used to specify the flow direction for the shadow channel segment. This slope direction is of vital importance in establishing channel continuity. All outflow from a channel segment must enter a single adjacent channel segment located in one of the eight directions of the cardinal axes or the diagonals. Thus, only 45 degree increments in slope direction should be specified for dual elements.

It is permissible to specify the slope, width and Manning's roughness coefficient for each channel segment independent of the corresponding values for its overland flow element. Typically, rather than having a unique set of values for each channel segment, they are grouped into reaches with similar coefficients. Manning's equation is again used as the flow relationship necessary, in conjunction with the continuity equation, to perform the routing calculations.

Much programming effort has been expended to develop computational algorithms which solve the flow routing equations very efficiently. For example, a piece-wise linear segmented curve is used to approximate Manning's equation and thereby eliminate the iteration process that would otherwise be necessary when solving the continuity equation. Unfortunately, this computational optimization has resulted in some very complex programming logic. Therefore, it is recommended that only someone intimately familiar with all aspects of the ANSWERS model attempt to modify this portion of the computer program.

Rainfall Rate

The net rainfall rate, that which reaches the ground surface, is dependent on the user specified pluviograph(s) and on the rate of interception by vegetation. The net rainfall rate for each rain gauge and crop is calculated by FUNCTION RAIN. Since a rain gauge identifier is specified for each watershed element, it is theoretically possible to have each element subjected to a different storm pattern. As a practical matter, the standard release of the model is dimensioned to permit only 4 gauges.

Interception is that water extracted from the incoming rainfall upon contact with and retention by the vegetal canopy. Water retained by the vegetation, *i.e.,* interception storage, is held primarily by surface tension forces. This initial interception volume is quickly satisfied, particularly in more intense storms. Since a dense vegetal cover can expose an immense surface area to rainfall, the amount of moisture evaporating during a long duration storm can be appreciable. Intercepted water which evaporates will be replenished during the storm. This creates a low level of interception demand throughout a storm. However, for the high intensities of primary interest from the standpoint of nonpoint source pollution from cropland, interception is a relatively minor hydrologic component. In order to reduce simulation costs, interception was assumed to be uniform in rate and total volume over each type of vegetation. Evaporation losses during a storm were assumed to be negligible.

Horton (1919) did a great deal of work in the area of estimating the amount and mechanisms controlling interception. He studied the water intercepted by several species of trees as well as some economically important crops. Values from 0.5 millimeter to 1.8 millimeters of interception storage volume were found to exist for trees and nearly as much for well developed crops. Values for potential interception storage, PIT, are based primarily on his recommended relationship.

The maximum potential interception (PIT), supplied as an input value, represents the available leaf moisture storage in depth units (volume per unit land area). In each time increment in which interception storage remains unsatisfied, rainfall supplied to interception storage is calculated as incremental interception (RIT), *i.e.,* the product of the rainfall amount (RATE) and the portion of the element covered by foliage (PER). The value of potential interception (PIT) and the net rainfall (RAIN) are correspondingly decreased until all interception storage is satisfied. At this stage, PIT is set equal to zero and the net rainfall rate is subsequently equal to the gauge rainfall rate for the remainder of the simulation.

Infiltration

Infiltration is one of the components to which ANSWERS is most sensitive, especially during low to medium runoff storms. Although many years of research have been conducted on infiltration phenomena, there is still no universally accepted method for describing infiltration on a watershed scale. The widely used, time-dependent equations of Horton (1939) and Philip (1957) presume a continuous water supply rate adequate to meet all infiltration demands. This approach does not readily allow for the observed recovery in soil infiltration capacity during periods of light or zero rainfall. To avoid this difficulty, the infiltration relation chosen for ANSWERS was the one developed by Holtan (1961) and Overton (1965). In a dimensionally homogeneous form it can be expressed as:

$$FMAX = FC + A * \left(\frac{PIV}{TP}\right)^{P} \tag{3-4}$$

where: FMAX = infiltration capacity with surface inundated,
FC = final or steady state infiltration capacity,
A = maximum infiltration capacity in excess of FC,
TP = total volume of pore space within the control depth,
PIV = volume of water that can be stored within the control volume prior to its becoming saturated,
P = dimensionless coefficient relating the rate of decrease in infiltration rate with increasing soil moisture content.

This form uses the soil water content, rather than time, as the independent variable.

During periods of zero rainfall rate, any infiltration which occurs must be supplied by water stored as either retention or detention. Since the surface of an element is seldom entirely inundated, the computed infiltration capacity is reduced in direct proportion to the percent of the soil surface not submerged. Thus, the specified surface micro-relief parameter also can reduce the infiltration capacity during these recession periods.

According to Holtan's conceptualization of the infiltration process, a "control zone" depth of soil determines the infiltration rate at the surface. He defined the depth of this control zone as the shallower of the depth to an impeding soil layer or that required for the hydraulic gradient to reach unity. Extending this same concept somewhat, the ANSWERS model maintains an accounting of water that leaves this control zone.

Holtan's equation requires six infiltration parameters to be specified for a given soil type: total porosity, field capacity, depth of the control zone, steady-state infiltration rate (FC), and the two unsteady-state coefficients (A and P). Data from both large, plot-sized simulated rainfall tests (Skaggs, et al., 1969) and field rainulator tests conducted in cooperation with USDA-ARS as a part of the Black Creek Project have been used to estimate parameter values. All of these tests indicated that surface crusting conditions have a major impact on the observed infiltration relationship. Experience with Holtan's equation has indicated the influence of crusting can be modeled by adjustment of the specified depth of the control zone. Crusting requires the use of a much shallower control zone.

The rate of water movement from the control zone is a function of the moisture content of that zone. The two conditions which can exist are handled according the following rules:

1. when the moisture content of the control zone is less than field capacity, no water moves from this zone,
2. when the control zone moisture exceeds field capacity, the water moves from this zone according to the equation:

$$DR = FC * \left(1 - \frac{PIV}{GWC}\right)^3 \tag{3-5}$$

where: DR = drainage rate of water from control zone,
GWC = gravitational water capacity of the control zone (total porosity minus field capacity).

This relationship satisfies the continuity requirement that at saturation, when PIV=0, the drainage rate from the control zone equals the steady state infiltration rate, FC. In addition, it exhibits intuitively desirable properties of rapidly decreasing moisture movement as the soil dries from saturation and of asymptotically approaching a zero drainage rate.

Water leaving the control zone contributes to tile drainage, if the element is tiled, or to baseflow. In both cases the water is assumed to re-emerge into the channel segments. Water moves from the infiltration control zone into the "pools" available for tile and/or baseflow at a rate equal to DRA.

Individual elements may selectively be designated as being tile drained. In addition to water coming from the control zone, tile inflow may be occurring from adjacent tiled elements. The sum of these two rates constitutes the rate of subsurface inflow into an element. Subsurface water moves out the element's tile at this inflow rate up to a maximum outflow rate equal to the tile drainage coefficient. Whenever the rate of subsurface inflow to an element exceeds its drainage coefficient, that excess water is diverted to baseflow storage. Elements which are not tiled have a drainage coefficient of zero.

Subsurface water entering an element at rates in excess of its drainage coefficient is stored in a single "pool." To simulate baseflow it is released directly into channel segments at a rate proportional to the volume of water in storage. Water is released at an equal rate to each channel segment. For small catchments having no defined channels, only overland flow will appear at the outlet.

Sediment Detachment and Movement

Soil erosion, as it relates to nonpoint source pollution, can be viewed as two separate processes, detachment of particles from the soil mass and transport of these particles into the streams and lakes. Detachment of either primary soil particles or aggregates can result from either rainfall or flowing water. These same factors can cause detached particles to be transported to the water supply network. Thus, there are four processes for which quantifying relationships must be developed, as shown in Figure 3-2. Two different transport models are available for use in ANSWERS. The simpler, less descriptive transport relationship is presented in this chapter. A more detailed transport model, which predicts particle size distributions and differential deposition, is presented in Appendix D.

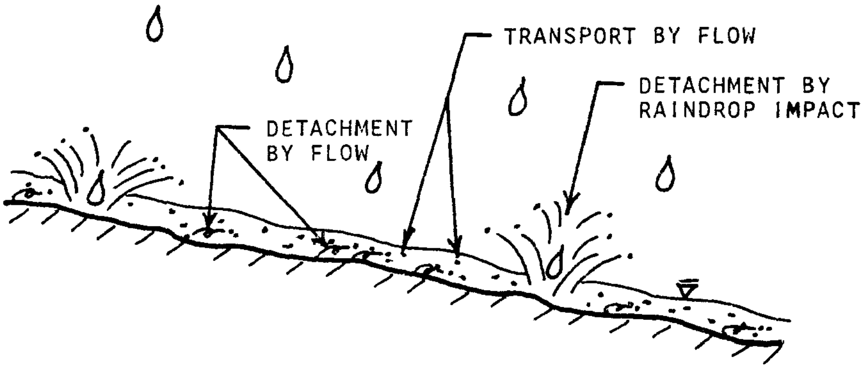


Figure 3-2. Sediment Detachment and Transport.

The detachment of soil particles by water is accomplished by two processes. The first involves dislodging soil as a result of the kinetic energy of rainfall. Rainfall is the major detachment process on relatively flat watersheds. The second process involves the separation of particles from the soil mass by shear and lift forces generated by overland flow.

Detachment of soil particles by raindrop impact is calculated using the relationship described by Meyer and Wischmeier (1969):

$$DETR = .108 * CDR * SKDR * A_i * R^2 \qquad (3\text{-}6)$$

where: DETR = rainfall detachment rate, kg/min,
CDR = cropping and management factor, C (from Universal Soil Loss Equation - Wischmeier and Smith, 1978),
SKDR = soil erosivity factor, K (from Universal Soil Loss Equation),
A_i = area increment, m^2,
R = rainfall intensity during a time interval, mm/min.

The detachment of soil particles by overland flow was described by Meyer and Wischmeier (1969) and modified by Foster (1976) as follows:

$$DETF = .90 * CDR * SKDR * A_i * SL * Q \quad (3\text{-}7)$$

where: DETF = overland flow detachment rate, kg/min,
SL = slope steepness,
Q = flow rate per unit width, m^2/min.

Once a soil particle has been detached, sufficient energy must be available to transport it or the particle will be deposited. The transport of sediment by overland flow is self-regulating, *i.e.*, soil particle detachment by overland flow does not occur unless there is excess energy available in addition to the amount required to transport suspended sediments. However, detachment by rainfall impact often occurs when there is little or no flow available for transport.

After a literature study which included Yalin (1963), Meyer and Wischmeier (1969), Foster and Meyer (1972), and Curtis (1976), as well as an inspection of soils data, a relationship for particle transport in overland flow was chosen as shown in Figure 3-3. The two portions of the curve generally represent the laminar and turbulent flow regions. Obviously, the transport capacity does not continue to increase as the square of flow forever. However, within the range of flows generally encountered in ANSWERS simulations, this generalized relationship (based in part on Yalin's work and in part on observed data) has produced reasonable results. Equations and their region of application are:

$$TF = 161 * SL * Q^{.5} \quad \text{if } Q \leq .046 \ m^2/min \quad (3\text{-}8a)$$

$$TF = 16{,}320 * SL * Q^2 \quad \text{if } Q > .046 \ m^2/min \quad (3\text{-}8b)$$

where: TF = potential transport rate of sediment, kg/min-m.

The erosion portion of the ANSWERS model was simplified further by the following assumptions:

1. Subsurface or tile drainage produces no sediment. (Data indicate around two percent of the average annual loading originated from subsurface systems on the Black Creek Watershed).
2. Sediment detached at one point and deposited at another is reattached to the soil surface.
3. Re-detachment of sediment requires the same amount of energy as required for the original detachment.
4. For channel segments rainfall detachment is assumed to be zero and only deposited sediment is made available for flow detachment, *i.e.*, original channel linings are not erodible.

Although these assumptions were made primarily to reduce the computational cost of using the model, some were also required because little or no data were available in the literature to quantify the particular process. Also, after consideration of the relative magnitude of the four detachment/-transport processes, the transport of soil particles by rainfall was assumed negligible.

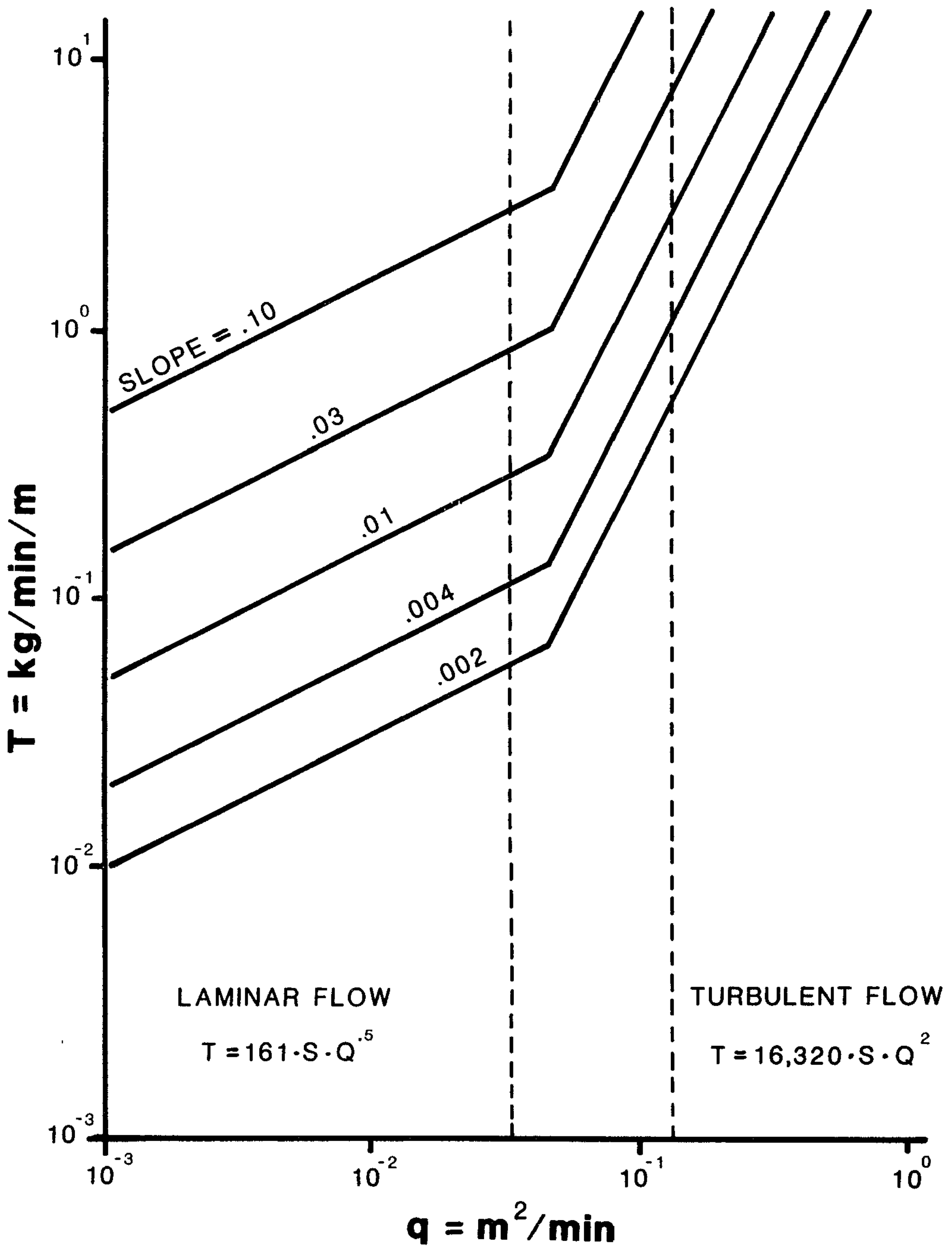


Figure 3-3. Transport Relationship Used in the ANSWERS Model.

Combining the above equations and assumptions gives a composite soil movement model wherein soil particles are dislodged from the soil mass by both rainfall and flowing water. Detached solids then become available for transport by overland flow. Within an element the material available for transport is the combination of that detached within the element and that which enters with inflow from adjacent elements.

Once the available detached sediment within an element is known, the transport capacity is computed. If it is insufficient to carry the available material, the excess is deposited in the element. The overall accounting relationship for this process is the differential form of the continuity equation as applied above to water flow. Sediment carried out of an element is apportioned between adjacent elements in direct relation to overland flow.

Best Management Practices

Land use changes, tillage techniques and management procedures which qualify as Best Management Practices (BMPs) for controlling nonpoint source pollution are simulated with ANSWERS by using appropriate parameter values for the component relationships discussed above. For example, conservation tillage generally results in a rougher surface, reduced C-factor and increased infiltration. Gully stabilization structures such a drop spillways or chutes may be simulated by reducing the slope steepness of the associated channel segments. Certain structural BMPs cannot be adequately accommodated with these component relationships. Currently, four specific BMPs which require special computational provision have been included: ponds, parallel tile-outlet terraces, grass waterways and field borders.

The four special structural BMPs are dealt with by a subroutine named STRUCT. The programming philosophy for STRUCT was to have it adjust "standard" parameter values for those elements which contain a structural BMP. These modifications are made when subroutine DATA is called. This approach permits simulating the important impacts of the BMP without major modification to the fundamental computational logic of the entire computer program.

Both ponds and PTOs are handled in a similar manner using a trap efficiency concept. Sediment trapped from the water flowing into a pond or PTO is diverted into a special, psuedo element which provides a means of tabulating the combined effectiveness of all such BMPs. Water is also assumed to be diverted, in the same ratio as sediment is trapped, into the tile drainage system. In this manner, effects of both reduced sediment loads and downstream overland flow rates are simulated.

Grass waterways and field border strips are also treated similarly to one another. It is assumed that the vegetated area within the affected element is no longer subject to any sediment detachment. Computationally, this is accomplished by adjusting the specified slope steepness by an amount which produces the desired change in sediment detachment rate for the element. Deposition within the vegetation of a grass waterway is deliberately prohibited, since any waterway that effectively traps sediment would soon fill and become ineffective. Specifying that an element has a grassed waterway forces the presence of a shadow channel element if none was already present.

Programming Overview

ANSWERS is programmed with a MAIN section which includes all the logic to simulate the various component processes each one of which is structured as an independent subroutine. Prior to beginning any simulation calculations, which follow the descriptions given above, MAIN calls a large subroutine named DATA.

It is the responsibility of DATA to read the user supplied data file and convert that parametric and geographic information into a structure which maximizes the computational efficiency of the lengthy simulation calculations. Specifically, it converts the gridded watershed into a one-dimensional array structure. This is done to avoid wasting machine memory with incomplete two-dimensional arrays that would result from irregularly shaped watersheds. Computational speed is also significantly improved by this process. The process of transforming the two-dimensional layout of a watershed elemental map into one-dimensional computational arrays is primarily accomplished by subroutine RELEM.

Subroutine RELEM is designed to utilize three adjacent rows of elements in a watershed file to determine position sequence numbers for all elements. The three-row system is utilized in order to be able to account for discontinuous rows of elements. The subroutine operates in such a manner that it can detect whenever the specified slope direction of an element would direct any portion of the runoff from that element into a non-existent element, *i.e.,* out of the catchment. A warning message is printed for each offending element.

Specifically, subroutine RELEM returns to subroutine DATA a 3-dimensional array, IEL. The first subscript refers to the row's position in the 3-row array. Eventually, each row of watershed elements "ripple through" all three row positions in IEL. The second subscript in IEL refers to the element's watershed column number. The third subscript corresponds to the parameter number for that watershed element according to:

1. — contains the element's watershed row number,
2. — contains its column, except for IEL(i,1,2) which contains the column no. of the last element in a given row,
3. — contains the position sequence number for the element,
4. — contains the element's slope steepness,
5. — contains the flow direction for the element,
6. — contains the channel designator and soil type,
7. — contains the crop type,
8. — contains the rain gauge name,
9. — contains the tile flow designator,
10. — contains the slope steepness of any shadow channel element,
11. — contains the identifier number for a structural BMP,
12. — contains size information about any structural BMP,
13. — contains size information about any structural BMP.

Array ITEMP is used to temporarily hold parameter values for the most recently read element. Subroutine RELEM must be entered with array ITEMP loaded with parameter values for the very first element of the catchment. The first task of RELEM is to transfer row-2 values for array IEL into row-1 and row-3 values into row-2. Once entered, execution continues within RELEM until an entire row of watershed elemental parameters has been read and stored in row-3 of IEL.

Upon return to subroutine DATA from RELEM, DATA works with row-2 of IEL to transfer its parameter data into the single dimension, sequential arrays that will ultimately be used for simulation computations. After an entire watershed row has been so set up, it again returns to subroutine RELEM which "ripples" the data in array IEL so it is ready to accept the next row of watershed elemental parameter values.

After all watershed elements have been set up by RELEM and DATA, the shadow channel elements that have been detected are moved to occur sequentially at the end of the regular elements. Parameter values for each element are next combined into computationally efficient coefficients and control is returned to MAIN for the actual simulation.

CHAPTER IV: DATA PREPARATION FOR ANSWERS

General

The data file used by the ANSWERS model provides a detailed description of the watershed topography, drainage networks, soils, land uses, and BMPs. Most of the information can be readily gleaned from USDA-SCS Soil Surveys and land use and cropping surveys or summaries. Also, aerial photographs of the area, USGS topographic maps, and BMP construction or implementation data is quite useful in developing descriptions of actual watershed areas. This chapter will detail the techniques used in putting together the data files necessary for running ANSWERS. In addition, information describing various surface conditions, soil responses, and BMP data is included in the Appendices. The formats shown in this section are for the current release of the ANSWERS program. The expanded sediment detachment/transport model, detailed in Appendix D, utilizes additional information which is described in that section.

Input information for the ANSWERS model contains six general types of data:

1. Simulation requirements (measurement units and output control),
2. Rainfall information (times and intensities),
3. Soils information (antecedent moisture, infiltration, drainage response and potential erodibility),
4. Land use and surface information (crop type, surface roughness and storage characteristics),
5. Channel descriptions (width and roughness),
6. Individual element information (location, topography, drainage, soils, land use and BMPs).

The individual element information is the largest body of data and the most time consuming to collect. However, once the topography, soils, land use and drainage patterns have been determined for all of the elements, changes in watershed management or BMPs can be added very easily without having to totally reconstruct the input file.

Figure 4-1 shows the configuration of a typical ANSWERS data file. Each of the six data areas listed above are noted and will be covered individually in succeeding sections. The ANSWERS data file was designed to be self explanatory. The information contained in the soils, land use, and individual element information sections are physically measurable and can be checked for validity without having to go through a complicated process of differentiating one or more lumped parameters.

Data File Construction

The configuration of an ANSWERS input data file allows the file to be constructed in two parts. All data except for the individual element data can be contained in a separate file. This first or "predata" file contains all of the general information necessary to describe the various soils, land uses, and management systems in a given county, planning region, state, etc. This "predata" file can be used with numerous elemental data files which describe greatly differing watersheds. Therefore, once a "predata" file has been constructed for a given area, subsequent simulations, even on different watersheds, may be possible with very little or no additional general information collection.

Simulation requirements. Figure 4-2 depicts the portion of the ANSWERS input file that supplies data on simulation requirements. The first line of this two-line portion of the "predata" file contains an alpha-numeric header used to describe which "predata" file is being used. All 80 columns of the card are used, and this information will be reprinted at execution time. Metric or English units are acceptable for input/output. The system of units used must be specified in columns 2-8 (left justified) on the second card. Inches and feet are both used when **ENGLISH** units are specified. Millimeters and

1

```
 STANDARD PREDATA FILE FOR  ALLEN CO., INDIANA--800823
ENGLISH UNITS ARE USED ON INPUT/OUTPUT                        PRINT
```

2

```
RAINFALL DATA FOR 2 GAUGE(S) FOR EVENT OF:   --TEST--
 GAUGE NUMBER   R1
0      0.      0.00
0      9.       .52
0     15.      1.55
0     20.      2.40
0     30.      1.59
0     35.       .85
0     45.       .50
1    300.      0.00
 GAUGE NUMBER   R2
0      0.      0.00
0      7.       .45
0     14.      1.25
0     18.      2.66
0     25.      1.65
0     33.       .60
0     42.       .35
1    300.      0.00
```

3

```
 SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS =   8
S 1, TP =.46, FP =.75, FC =  .40, A =  .80, P =.65, DF =  4.0, ASM =.70, K =.36
S 2, TP =.46, FP =.65, FC =  .40, A =  .80, P =.65, DF =  3.0, ASM =.70, K =.32
S 3, TP =.46, FP =.70, FC =  .40, A =  .80, P =.75, DF =  3.0, ASM =.70, K =.17
S 4, TP =.42, FP =.70, FC =  .60, A =  1.0, P =.65, DF =  4.0, ASM =.70, K =.36
S 5, TP =.44, FP =.80, FC =  .60, A =  1.0, P =.65, DF =  5.0, ASM =.70, K =.32
S 6, TP =.46, FP =.75, FC =  .60, A =  1.0, P =.65, DF =  5.0, ASM =.70, K =.36
S 7, TP =.46, FP =.75, FC =  .40, A =  .80, P =.65, DF =  3.0, ASM =.70, K =.38
S 8, TP =.35, FP =.65, FC =  .90, A =  1.6, P =.60, DF =  6.0, ASM =.70, K =.35
DRAINAGE COEFFICIENT FOR TILE DRAINS = 0.25 IN/24HR
GROUNDWATER RELEASE FRACTION =   .005
```

4

```
 SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOW
NUMBER OF CROPS AND SURFACES =  6
C 1, CROP= S1 CORN, PIT=.01, PER=0.0, RC=.47, HU= 2.0, N=.075, C=.50
C 2, CROP= CORN-NT, PIT=.06, PER=.75, RC=.55, HU= 3.5, N=.150, C=.30
C 3, CROP=BEANS TP, PIT=.01, PER=.45, RC=.47, HU= 1.5, N=.070, C=.60
C 4, CROP=S.GRAINS, PIT=.04, PER=.90, RC=.55, HU= 2.0, N=.150, C=.15
C 5, CROP= PASTURE, PIT=.03, PER=1.0, RC=.40, HU= 1.5, N=.200, C=.04
C10, CROP=  WOODS , PIT=.10, PER=.90, RC=.55, HU= 3.5, N=.250, C=.15
```

5

```
 CHANNEL SPECIFICATIONS FOLLOW
NUMBER OF TYPES OF CHANNELS =  4,
CHANNEL 1 WIDTH =15.0  FT, ROUGHNESS COEFF.(N) = .035
CHANNEL 2 WIDTH =10.0  FT, ROUGHNESS COEFF.(N) = .040
CHANNEL 3 WIDTH = 7.5  FT, ROUGHNESS COEFF.(N) = .045
CHANNEL 4 WIDTH = 5.0  FT, ROUGHNESS COEFF.(N) = .070
```

6

```
 ELEMENT SPECIFICATIONS FOR MIDDLETOWN WATERSHED
EACH ELEMENT IS 528.0ft   SQUARE
OUTFLOW FROM ROW  21 COLUMN    3
 1 15    4 270   1   1   R1        0                          827.8
 1 16    5 259   3   1   R1        0                          828.8
 .  .    .   .   .   .   .    .    .                              .
 .  .    .   .   .   .   .    .    .                              .
 7 20    9 186   2   1   R1        0  2                       822.8
 7 22    2 135   1   2   R1        0                          835.3
 7 23    3 180   3   5   R1 TILE   0                          835.3
 8 11   20 270 201   2   R2 TILE   5  4  32                   799.7
 8 12   17 180 302   2   R2 TILE   5  4  20                   799.3
 8 13   16 180 303   1   R2 TILE   5  4  20                   802.2
 8 14   12 148   1   1   R2 TILE   0  1                       809.2
 .  .    .   .   .   .   .    .    .                              .
 .  .    .   .   .   .   .    .    .                              .
20 19    8 180   1   2   R2 TILE   0  3  20                   802.0
20 20    8 180   1   2   R2 TILE   0                          803.0
21  3    9 270 102   1   R2 TILE   3  4  40                   766.5
21  4   28 180 108   1   R2 TILE   3  4  40                   762.0
 .  .    .   .   .   .   .    .    .                              .
 .  .    .   .   .   .   .    .    .                              .
22 13    2   0   3   4   R2        0                          799.5
22 14 9  5  90   1   4   R2        0                          798.0
```

Figure 4-1. Typical ANSWERS Input Data File.

meters are used when **METRIC** units are chosen. The presence of the word **PRINT** in the second line of the "predata" file in columns 58-62 causes ANSWERS to produce a detailed listing of all predata information. The absence of the word **PRINT** on line 2 suppresses this output.

```
STANDARD PREDATA FILE FOR  ALLEN CO., INDIANA--800823
ENGLISH UNITS ARE USED ON INPUT/OUTPUT                    PRINT
```

Figure 4-2. Simulation Requirements.

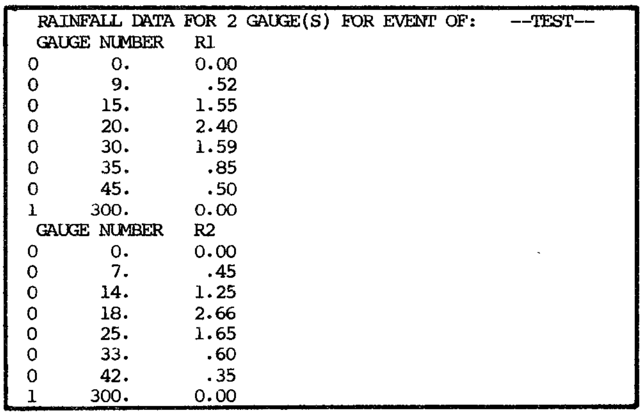
Rainfall information. Figure 4-3 shows the portion of the "predata" file dedicated to the description of the precipitation event to be simulated. The first line must contain the word **RAINFALL** beginning in column 2. The number of gauges used in the simulation are inserted in column 20. ANSWERS permits up to four rain gauges to be used. Beginning in column 47, an eight character identifier of the particular storm being modeled is inserted. Each new rain gauge file contains a two character identifier for the gauge in columns 17-18.

The Thiessen polygonal method is used to determine which areas of a watershed are affected by specific rain gauges. For hypothetical situations, the various gauges can be used to simulate the movement of a storm across the watershed.

The three columns contain the following data:

1. Data column 1 - last entry? (indicated by 1),
2. Data columns 3-10 - time (in minutes),
3. Data columns 11-20 - precipitation intensity (in inches/hour or millimeters/hour, depending on units chosen) which ended at corresponding time (Column 2).

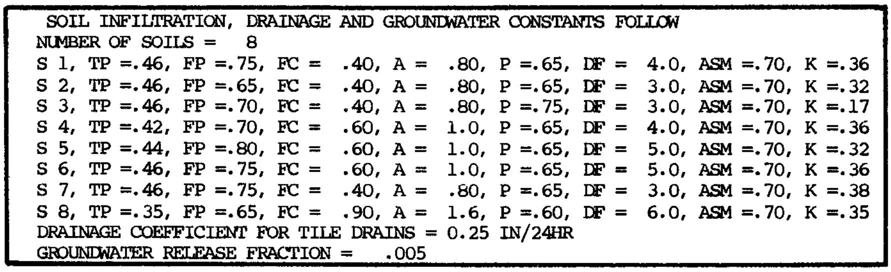
In this example, the intensity was 0.52 iph from 0 to 9 minutes and 1.55 iph from 9 to 15 minutes for gauge R1. During a similar time interval, the rates were 0.45 iph from 0 to 7 minutes and 1.25 iph from 7 to 14 minutes at gauge R2. The last entry for both gauges, at 300 minutes, indicates the end of simulation us, although the precipitation ended at approximately 45 minutes, ANSWERS would continue simulating the watershed response until the time was equal to or greater than 300 minutes.



```
 RAINFALL DATA FOR 2 GAUGE(S) FOR EVENT OF:     --TEST--
  GAUGE NUMBER   R1
0      0.       0.00
0      9.        .52
0     15.       1.55
0     20.       2.40
0     30.       1.59
0     35.        .85
0     45.        .50
1    300.       0.00
  GAUGE NUMBER   R2
0      0.       0.00
0      7.        .45
0     14.       1.25
0     18.       2.66
0     25.       1.65
0     33.        .60
0     42.        .35
1    300.       0.00
```

Figure 4-3. Rainfall Information.

Soils information. Figure 4-4 lists the information necessary to describe the response of the various soils to precipitation inputs. The word **SOIL** must be found in columns 3-6 of the first data card. The number of identified soil groups or types is entered in columns 19-22 (right justified) of the second card. ANSWERS is normally dimensioned to handle up to 20 different soils. If additional soils are present, the model can be easily set up to accept as many soils as are needed.



```
 SOIL INFILTRATION, DRAINAGE AND GROUNDWATER CONSTANTS FOLLOW
NUMBER OF SOILS =   8
S 1, TP =.46, FP =.75, FC =  .40, A =  .80, P =.65, DF =  4.0, ASM =.70, K =.36
S 2, TP =.46, FP =.65, FC =  .40, A =  .80, P =.65, DF =  3.0, ASM =.70, K =.32
S 3, TP =.46, FP =.70, FC =  .40, A =  .80, P =.75, DF =  3.0, ASM =.70, K =.17
S 4, TP =.42, FP =.70, FC =  .60, A =  1.0, P =.65, DF =  4.0, ASM =.70, K =.36
S 5, TP =.44, FP =.80, FC =  .60, A =  1.0, P =.65, DF =  5.0, ASM =.70, K =.32
S 6, TP =.46, FP =.75, FC =  .60, A =  1.0, P =.65, DF =  5.0, ASM =.70, K =.36
S 7, TP =.46, FP =.75, FC =  .40, A =  .80, P =.65, DF =  3.0, ASM =.70, K =.38
S 8, TP =.35, FP =.65, FC =  .90, A =  1.6, P =.60, DF =  6.0, ASM =.70, K =.35
DRAINAGE COEFFICIENT FOR TILE DRAINS = 0.25 IN/24HR
GROUNDWATER RELEASE FRACTION =   .005
```

Figure 4-4. Soils Information.

The infiltration descriptors, antecedent moisture content, and the potential erodibility of the various soils are listed in this section. Table 4-1 describes each parameter and gives its location on the data card. Methods for determining the values of TP, FP, FC, A, P, DF, and ASM are presented in Appendix A. The K parameter is identical to the K parameter in the Universal Soil Loss Equation. Because the soil parameters may be used to describe the response of several similar soil types, the listed K value is usually an effective or average value.

The next two user-selectable constants are used to help describe the contribution of subsurface drainage to the total water yield in the watershed. The tile drainage coefficient indicates the design coefficient (inches/day or millimeters/day) of tile drains in those areas designated as having tile drainage. Generally, this value is 0.25 to 0.5 inches/day (6.4 to 12.7 millimeters/day). The groundwater release fraction is a measure of the contribution of lateral groundwater movement or interflow to total runoff. Appendix A contains information to be used in the selection of a release fraction.

The tile drainage coefficient is contained in columns 40-44 (right justified). The groundwater release fraction is contained in columns 32-41 (right justified).

Table 4-1. Soils Information File Construction.

Parameter	Definition	Column(s)	Appendix
TP	Total porosity (percent volume)	11-13	A.1
FP	Field capacity (percent saturation)	20-22	A.1
FC	Steady state infiltration rate	29-33	A.2
A	Difference between steady state and maximum infiltration rate	39-43	A.2
P	Exponent in infiltration equation	49-51	A.2
DF	Infiltration control zone depth	58-62	A.1
ASM	Antecedent soil moisture (percent saturation)	70-72	A.1
K	USLE "K"	78-80	A.3

All entries are right justified.

Land use and surface information. The layout of the land use and surface description portion of the "predata" file is given in Figure 4-5. Line one should contain the word **SURFACE** in columns 3-9. The number of different land uses defined in this section is contained in columns 32-34 (right justified) of the second card. ANSWERS is normally set up to handle up to 20 different combinations of land use, management, and surface conditions. The model can be easily re-dimensioned to accept more entries, if necessary.

The particular land use and, in some cases, the management system used are noted in the crop section. The potential interception (PIT), percentage cover (PER), surface storage (RC and HU), surface roughness (N), and relative erosiveness (C) parameters are listed and described in Table 4-2. Methods for determining the values of these descriptors are given in Appendix B. The C value used in this section is a seasonally-adjusted combination of the C and P factors used in the Universal Soil Loss Equation.

```
  SURFACE ROUGHNESS AND CROP CONSTANTS FOLLOW
 NUMBER OF CROPS AND SURFACES =  6
 C 1, CROP= S1 CORN, PIT=.01, PER=0.0, RC=.47, HU= 2.0, N=.075, C=.50
 C 2, CROP= CORN-NT, PIT=.06, PER=.75, RC=.55, HU= 3.5, N=.150, C=.30
 C 3, CROP=BEANS TP, PIT=.01, PER=.45, RC=.47, HU= 1.5, N=.070, C=.60
 C 4, CROP=S.GRAINS, PIT=.04, PER=.90, RC=.55, HU= 2.0, N=.150, C=.15
 C 5, CROP= PASTURE, PIT=.03, PER=1.0, RC=.40, HU= 1.5, N=.200, C=.04
 C10, CROP=  WOODS , PIT=.10, PER=.90, RC=.55, HU= 3.5, N=.250, C=.15
```

Figure 4-5. Land Use and Surface Information.

Table 4-2. Land Use and Surface Condition File Construction.

Parameter	Definition	Column(s)	Appendix
CROP	Specific land use and management	12-19	B.1
PIT	Potential interception volume	26-28	B.1
PER	Percentage of surface covered by specific land use (CROP)	35-37	B.1
RC	Roughness coefficient (a shape factor)	43-45	B.2
HU	Maximum roughness height	51-54	B.2
N	Manning's n	59-62	B.1
C	Relative erosiveness of a particular land use (function of time and USLE "C" and "P")	67-69	B.1

All entries are right justified.

Channel descriptions. The part of the "predata" file used to describe the channels in the watershed is shown in Figure 4-6. The first line must contain the word **CHANNEL** in columns 3-9. The number of different channel configurations (width or roughness) is listed in columns 31-33 (right justified) on the second line. The assumption is made that the channel is rectangular in cross-section. The width of the channel is noted in columns 19-22 and the value of Manning's n is listed in columns 50-54 (both right justified). The channel is also assumed to be sufficiently deep to handle the runoff. ANSWERS does not predict flooding, nor does it presently use variable geometry in the channel cross-section.

```
 CHANNEL SPECIFICATIONS FOLLOW
NUMBER OF TYPES OF CHANNELS =  4,
CHANNEL 1 WIDTH =15.0  FT, ROUGHNESS COEFF.(N) = .035
CHANNEL 2 WIDTH =10.0  FT, ROUGHNESS COEFF.(N) = .040
CHANNEL 3 WIDTH = 7.5  FT, ROUGHNESS COEFF.(N) = .045
CHANNEL 4 WIDTH = 5.0  FT, ROUGHNESS COEFF.(N) = .070
```

Figure 4-6. Channel Descriptions.

Individual element information. This file allows the user to describe, in detail, the particular watershed and its special characteristics. Information on topography, soils, land use, drainage and BMPs is included in this section. Figure 4-7 shows the configuration of the individual element information file.

```
 ELEMENT SPECIFICATIONS FOR MIDDLETOWN WATERSHED
EACH ELEMENT IS 528.0ft   SQUARE
OUTFLOW FROM ROW   21 COLUMN     3
 1 15    4 270   1   1   R1        0                            827.8
 1 16    5 259   3   1   R1        0                            828.8
 .  .    .   .   .   .    .    .   .                                .
 .  .    .   .   .   .    .    .   .                                .
 7 20    9 186   2   1   R1        0  2                         822.8
 7 22    2 135   1   2   R1        0                            835.3
 7 23    3 180   3   5   R1 TILE   0                            835.3
 8 11   20 270 201   2   R2 TILE   5  4   32                    799.7
 8 12   17 180 302   2   R2 TILE   5  4   20                    799.3
 8 13   16 180 303   1   R2 TILE   5  4   20                    802.2
 8 14   12 148   1   1   R2 TILE   0  1                         809.2
 .  .    .   .   .   .    .    .   .                                .
 .  .    .   .   .   .    .    .   .                                .
20 19    8 180   1   2   R2 TILE   0  3   20                    802.0
20 20    8 180   1   2   R2 TILE   0                            803.0
21  3    9 270 102   1   R2 TILE   3  4   40                    766.5
21  4   28 180 108   1   R2 TILE   3  4   40                    762.0
 .  .    .   .   .   .    .    .   .                                .
 .  .    .   .   .   .    .    .   .                                .
22 13    2   0   3   4   R2        0                            799.5
22 14 9  5  90   1   4   R2        0                            798.0
```

Figure 4-7. Individual Element Information.

The top three lines of this file are header information. The first card contains the watershed name or identifier in columns 29-72. The size of the element is shown in columns 17-22 on the second card. The third card contains the row and column coordinates for the outlet element in columns 18-21 (row) and 30-33 (column). All information is right justified.

Each subsequent line of this file contains the information necessary to characterize the physical configuration of each element. The position and definition of all of the parameters used in describing each element are shown in Table 4-3. Appendix C describes various methods for setting up the elemental data file.

Table 4-3. Element Information File Construction.

Parameter Definition	Column(s)	Appendix
Row number of element	1-3	
Column number of element	4-6	
Last element flag, this field should be blank except for the last watershed element; that element should have a value of 9 entered here	7-8	
Slope steepness of the element, entered in tenths of a percent, e.g., an element with a slope of 2.9 percent would be entered as 29	9-11	C.1
Direction of steepest slope, entered in degrees counterclockwise referenced to a horizontal line from the center of the element and directed to the right	12-15	C.1
Channel size category, if this element has a well defined channel flowing through it, otherwise these columns should be blank	16-17	
Soil type number	18-19	A
Crop/management type number	20-23	B
Rain gauge designator (alpha-numeric)	27-28	
Tile flag; presence of the letters "TI" indicate tile drainage, anything else indicates no tile	30-31	
Channel slope steepness in tenths of a percent; when no value is present and a channel exists, the slope will be taken to be equal to the overland slope	34-37	
BMP identification number	39-40	C.2
First BMP descriptor	41-44	C.2
Second BMP descriptor	45-48	C.2
Mean elevation of element (optional)	64-70	C.2

All entries are right justified.

CHAPTER V: ANSWERS OUTPUT

General

By using a very descriptive data file and the distributed parameter concept, the ANSWERS model is capable of producing a detailed accounting of the erosion and hydrologic response of a watershed subjected to a precipitation event. Figure 5-1 displays a condensed version of the typical ANSWERS output. The output listing consists of five basic sections:

1. An "echo" of the input data (can be suppressed by removing **PRINT** parameter in line 2 of input data),
2. Watershed characteristics (calculated from elemental data),
3. Flow and sediment information at the watershed outlet and effectiveness of structural BMPs,
4. Net transported sediment yield or deposition for each element,
5. Channel deposition.

The various tabular output sections of the ANSWERS model can be used with several plotting programs to yield graphical depictions of the watershed's hydrologic and erosion response.

This chapter will describe the five sections of the ANSWERS tabular output as listed above. In addition, examples of graphical representation of the output (to lend spatial significance) will be presented.

Input information "echo". This portion of the ANSWERS, when enabled with the **PRINT** parameter in line 2 of the input file, essentially reprints the "predata" file. It can be quite useful in tracking down problems with input formats, since the output will be exactly what it read.

Watershed characteristics. Included in this section is the header information from the elemental data file. The size of the elements is calculated from the side length and the area of the watershed is displayed, based on the total number of elements. Also, a count of the number of channel elements is made to give some feeling for drainage density. Information on the minimum, average and maximum slopes for both overland flow and channels is collected. Information on subsurface drainage, mean antecedent moisture and outlet element location is given.

The second section of this portion of the output contains a short synopsis of each of the land uses and soils that are actually present in the watershed. Percentage of area occupied as well as several pertinent descriptors for each soil or land use are displayed.

The final section of the watershed characteristics involves the number of elements containing those BMPs which involve structures or land use changes (identified in elemental data file). If no BMPs of this type are present, this section will not appear.

Flow and sediment information and BMP effectiveness. This portion of the output most nearly resembles the "normal" output from most watershed models. A flow hydrograph, along with associated sediment concentration and accumulative yield, is displayed. The time interval between print points is determined by the number of hydrograph print points (set internally to 101). This parameter can be changed easily.

An accounting of total rainfall, total flow and average sediment yield is presented at the end of the hydrograph. Also, the amount of sediment trapped by each structural BMP (if any) is noted.

Although the only hydrograph printed is that of the outlet element, it is possible to access the output information from any element(s) within the watershed. A rather minor modification to the output section of the ANSWERS model is all that is required to produce a hydrograph and associated sediment information for any point in the basin.

```
DISTRIBUTED HYDROLOGIC AND WATER QUALITY SIMULATION
               BY ANSWERS VER 4.800326
  STANDARD PREDATA FILE FOR  ALLEN CO., INDIANA--800429

    RAINFALL HYETOGRAPH FOR EVENT OF  B-DIST

    GAGE NUMBER GA
    TIME - MIN.          RAINFALL RATE - IN./HR.
          0.0                       0.00
          9.0                       0.52
         18.0                       0.76
         23.0                       0.92
         29.7                       1.59
         37.6                       5.52
         45.0                       1.63
         54.0                       1.15
         63.0                       0.83
         72.0                       0.72
         90.0                       0.60
        350.0                       0.00


SOIL PROPERTIES
SOIL  POROSITY  FIELD CAP.  INFILTRATION CONSTANTS  CONTROL  ANTECEDENT EROSION
       (PERCENT   (PERCENT     FC       A      P      ZONE    MOISTURE   CONST.
        VOL.)       SAT.)    IN./HR. IN./HR.           IN.   (PERCENT SAT)
  1     46.0        75.0       0.4     0.8   0.65      4.0      70.0     0.36
  2     46.0        65.0       0.4     0.8   0.65      3.0      70.0     0.32
  3     46.0        70.0       0.4     0.8   0.75      3.0      70.0     0.17
  4     42.0        70.0       0.6     1.0   0.65      4.0      70.0     0.36
  5     44.0        80.0       0.6     1.0   0.65      5.0      70.0     0.32
  6     46.0        75.0       0.6     1.0   0.65      5.0      70.0     0.36
  7     46.0        75.0       0.4     0.8   0.65      3.0      70.0     0.38
  8     35.0        65.0       0.9     1.6   0.60      6.0      70.0     0.35

TILE DRAINAGE COEFF. = 0.25 IN./24H
GROUNDWATER RELEASE FRACTION = 0.500E-03

COVER/MANAGEMENT PRACTICES
  CROP       MAX. POT.   PERCENT  ROUGH.  ROUGH.  MANNING≠S  EROSION
           INTERCEPTION   COVER   COEFF.  HEIGHT      N       CONST.
               IN.                         IN.
 1   FALLOW  0.00           0.     0.47    2.5     0.100     1.00
 2  S1 CORN  0.02          20.     0.47    2.8     0.075     0.50
 3  S2 CORN  0.04          60.     0.55    2.4     0.070     0.50
 4  CORN-NT  0.06          85.     0.55    4.1     0.150     0.30
 5 BEANS TP  0.03          75.     0.47    2.1     0.060     0.60
 6 BEANS FC  0.03          75.     0.53    2.6     0.065     0.55
 7 S.GRAINS  0.04          95.     0.55    3.0     0.090     0.15
 8  PASTURE  0.02         100.     2.00    0.4     0.100     0.04
 9   WOODS   0.10          90.     0.55    5.1     0.200     0.15
11 HOMESITE  0.02         100.     0.40    2.4     0.090     0.20

CHANNEL PROPERTIES
TYPE   WIDTH   MANNING≠S N
         FT.
  1    10.0      0.035
  2     8.0      0.040
  3     6.0      0.040
  4     5.0      0.050
  5     3.0      0.050

      BRUNSON - 1980 PRACTICES
    WATERSHED CHARACTERISTICS
NUMBER OF  6.40 AC. OVERLAND FLOW ELEMENTS =  257
NUMBER OF CHANNEL SEGMENTS =  41
AREA OF CATCHMENT =  1644.8 AC.
CATCHMENT SLOPE: MIN =   0.20  AVE =   1.35  MAX =   4.00 PERCENT
CHANNEL SLOPE:   MIN =   0.45  AVE =   1.63  MAX =   2.50 PERCENT
PERCENT OF AREA TILED = 100.0 WITH A D.C. OF 0.25 IN./24H
MEAN ANTECEDENT SOIL MOISTURE = 70., FIELD CAPACITY = 70. PERCENT SATURATION
GROUNDWATER RELEASE FRACTION = 0.0005
OUTLET IS ELEMENT  255 AT ROW  18 COL   2
```

Figure 5-1. Typical ANSWERS Output Listing.

```
SURFACE COVER/MANAGEMENT CONDITIONS          SOIL ASSOCIATION PROPERTIES
  CROP  PERCENT PERCENT  N     C       NO. PERCENT   FC     INITIAL  CONTROL  K
        PRESENT  COVER                     PRESENT IN./HR. IN./HR. DEPTH IN.
 S2 CORN  87.5    60. 0.070  0.50       1   28.4    0.4      0.8      4.0   0.36
 PASTURE   0.4   100. 0.100  0.04       2   35.4    0.4      0.8      3.0   0.32
  WOODS    9.3    90. 0.200  0.15       3   18.7    0.4      0.7      3.0   0.17
HOMESITE   2.7   100. 0.090  0.20       6    6.2    0.6      1.1      5.0   0.36
                                        7   10.5    0.4      0.8      3.0   0.38
                                        8    0.8    0.9      1.7      6.0   0.35

  STRUCTURAL MEASURES INCLUDED
         TYPE          NUMBER
    1  PTO TERRACES      17
    3  G. WATERWAYS      15
    4  FIELD BORDER       5

               OUTLET HYDROGRAPHS--VER 4.800326
                                   YIELD        CONC.
  TIME  RAINFALL   RUNOFF      SEDIMENT     SEDIMENT
  MIN.   IN./HR.   IN./HR.        LB.          PPM
   0.0     0.00    0.0000           0.           0.
   3.5     0.52    0.0000           0.           0.
   7.0     0.52    0.0000           0.           0.
  10.5     0.76    0.0000           0.           0.
  14.0     0.76    0.0000           0.           0.
  17.5     0.76    0.0001           0.           0.
  21.0     0.92    0.0001           0.           3.
  24.5     1.59    0.0001           0.         200.
  28.0     1.59    0.0002           3.        1179.
  31.5     5.52    0.0004          19.        3524.
  35.0     5.52    0.0019         139.        6097.
  38.5     1.63    0.0126        1247.        8150.
  42.0     1.63    0.0554        7200.        8226.
  45.5     1.15    0.1705       26052.        7198.
  49.0     1.15    0.3071       63336.        6663.
  52.5     1.15    0.3877      114398.        6517.
  56.0     0.83    0.4237      172411.        6500.
  59.5     0.83    0.4403      233857.        6520.
  63.0     0.83    0.4479      296959.        6520.
  66.5     0.72    0.4495      360548.        6508.
  70.0     0.72    0.4469      423912.        6502.
  73.5     0.60    0.4411      486639.        6506.
  77.0     0.60    0.4325      548385.        6515.
  80.5     0.60    0.4217      608831.        6527.
  84.0     0.60    0.4092      667707.        6538.
  87.5     0.60    0.3957      724795.        6547.
  91.0     0.00    0.3820      780001.        6551.
  94.5     0.00    0.3663      833187.        6560.
     .       .        .             .            .
     .       .        .             .            .
 276.5     0.00    0.0160     1503945.        2105.
 280.0     0.00    0.0159     1504636.        1913.
 283.5     0.00    0.0158     1505257.        1725.
 287.0     0.00    0.0157     1505810.        1544.
     .       .        .             .            .
     .       .        .             .            .
 336.0     0.00    0.0155     1508849.         107.
 339.5     0.00    0.0155     1508879.          78.
 343.0     0.00    0.0155     1508901.          56.
 346.5     0.00    0.0155     1508916.          39.
 350.0     0.00    0.0155     1508926.          27.
   RUNOFF VOLUME PREDICTED FROM   1.96 IN. OF RAINFALL =  0.625 IN.
                AVERAGE SOIL LOSS =   917.  LB./AC
 STRUCTURAL PRACTICE  1 REDUCED TOTAL SEDIMENT YIELD BY  563841. LB.
```

Figure 5-1, cont.

Net transported sediment yield or deposition. Statistics are kept, throughout the simulation, on the actual amount of soil removed from or deposited on each element. Although this soil actually leaves the element (in the case of a negative number), it may or may not reach the channel system. This is due to the fact that deposition may occur further down slope.

Another problem with treating "hot spots" identified with this information is that the removal of one "hot spot" may actually cause another one. If the management practice removes sediment, yet still allows nearly the same amount of water to flow downslope, the detachment rate will increase in the

```
                          INDIVIDUAL ELEMENT SEDIMENTATION
 ELEMENT SEDIMENT  ELEMENT SEDIMENT  ELEMENT SEDIMENT  ELEMENT SEDIMENT
   NO.    LB./AC     NO.    LB./AC     NO.    LB./AC     NO.    LB./AC
    1      -301.      2       40.       3      -189.      4     -2201.
    5      -839.      6      -909.      7     -2214.      8     -1069.
    9      -980.     10      -887.     11     -1744.     12       151.
    .         .       .         .       .         .       .         .
    .         .       .         .       .         .       .         .
  137      -109.    138     -1779.    139     -1072.    140     -1966.
  141     -2160.    142     -1882.    143     -2066.    144      -928.
  145      -568.    146      -183.    147      -393.    148     -1925.
  149     -1762.    150      2203.    151        56.    152      -615.
  153     -2255.    154        21.    155     -1895.    156     -1654.
    .         .       .         .       .         .       .         .
    .         .       .         .       .         .       .         .
  241     -1958.    242      -839.    243      -851.    244      -149.
  245     -1663.    246     -1884.    247     -1745.    248     -1410.
  249     -1993.    250     -1882.    251     -1187.    252     -1434.
  253     -1653.    254     -2018.    255     -1137.    256     -1933.
  257     -1884.
MAX EROSION RATE =  2948. LB./AC   MAX DEPOSITION RATE =  2203. LB./AC
                     STD. DEV. =   893. LB./AC

                         CHANNEL DEPOSITION -- LB.
  NO.       AMOUNT   NO.     AMOUNT     NO.      AMOUNT     NO.      AMCUNT
   43          0.    57         0.      60          0.      64          0.
   72        125.    75         0.      78          0.      89        467.
   91        324.    92        79.      93        234.     108        661.
    .          .      .          .       .          .       .           .
    .          .      .          .       .          .       .           .
  194         37.   193         0.     200          0.     201         94.
  206          0.   207        27.     222          0.     239          0.
  255          0.
```

Figure 5-1, cont.

downhill elements, since the load is less from above. In most cases, however, practices which reduce the sediment load also reduce the runoff rate in the downslope area.

Channel deposition. This section of the output information details the amount of sediment deposited in each of the "shadow" or channel elements. ANSWERS does not presently predict channel erosion. It does allow the channel flow to entrain deposited sediment if the flow regains enough excess transport capacity to do so.

Graphical Output

Several plotting programs have been constructed to use the input to and the output from the ANSWERS model to provide visual enhancement and better understanding of the information provided by this program. The QCKPLT program, mentioned in a previous section, uses the elemental data portion of the input file to produce the map shown in Figure 5-2. The arrows indicate the flow direction for each element. The shaded areas indicate "dual" elements or overland elements with companion channel elements. This map can be produced so that it will fit any scale. This feature allows one to check input data on maps with different scales by producing overlays at the specific scale needed. The grid is also very useful in physically locating the predicted "hot spot" areas.

Figure 5-3 shows the graphic output from the HYPLT program. HYPLT uses standard CALCOMP-compatible calls and plots the rainfall hyetograph, the runoff hydrograph and the sediment concentration curve. The program directly uses the hydrograph portion of the output listing.

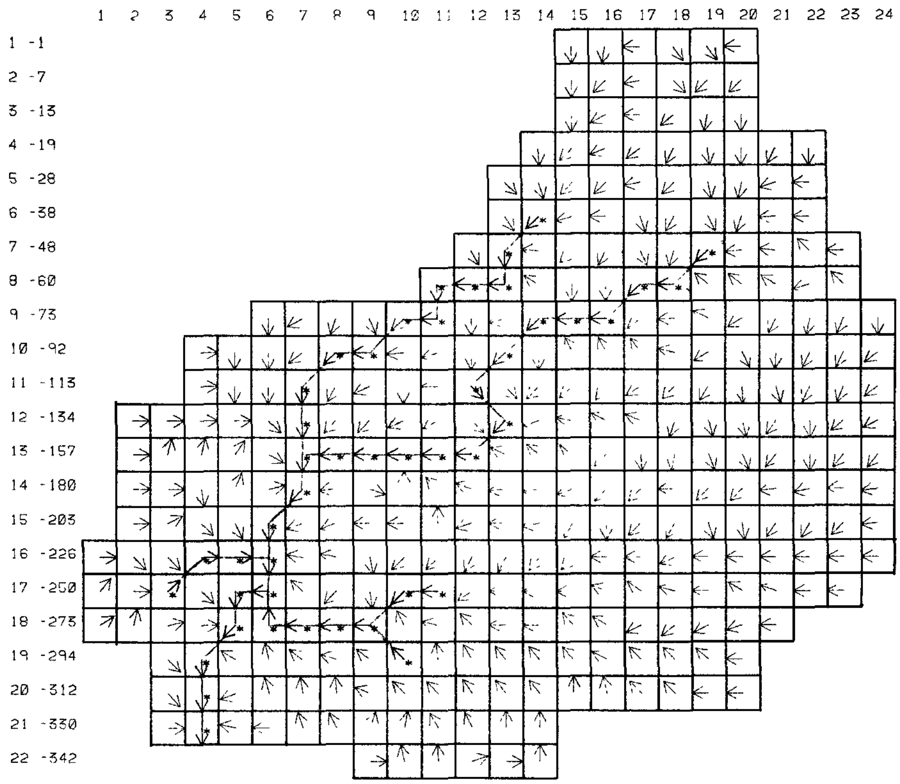


Figure 5-2. Example Elemental Map Produced by QCKPLT Program.

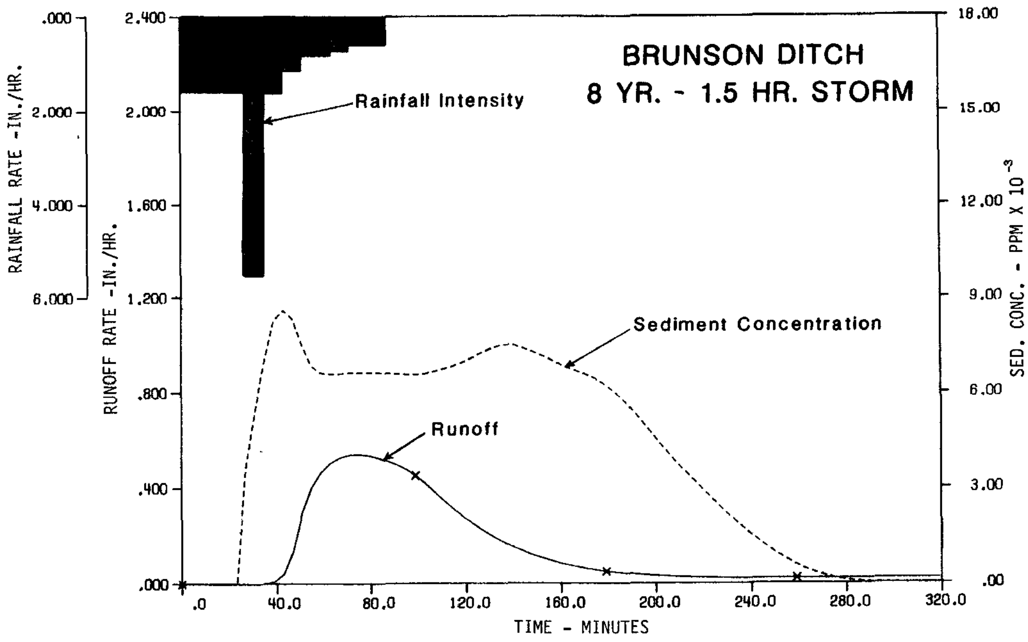


Figure 5-3. Example Output of HYPLT Plotting Program.

The information presented in Figure 5-4 comes directly from the net transported sediment yield or deposition section of the ANSWERS output. Several programming steps are required to "reconstruct" an elemental data format (row and column coordinates) and input the individual element information to a program called CONTUR. CONTUR allows the user to set the levels of sediment yield or deposition at which contours are desired. The program produces a map at any desired scale (up to the maximum size the plotter allows). The shading in Figure 5-4 is for additional visual effect. The portions of the watershed with closely spaced contours show areas with excessive transported soil loss or deposition. In general, high transported soil loss areas will be found near high deposition areas. This is due to the fact that steep slopes blend into flat slopes near the channels.

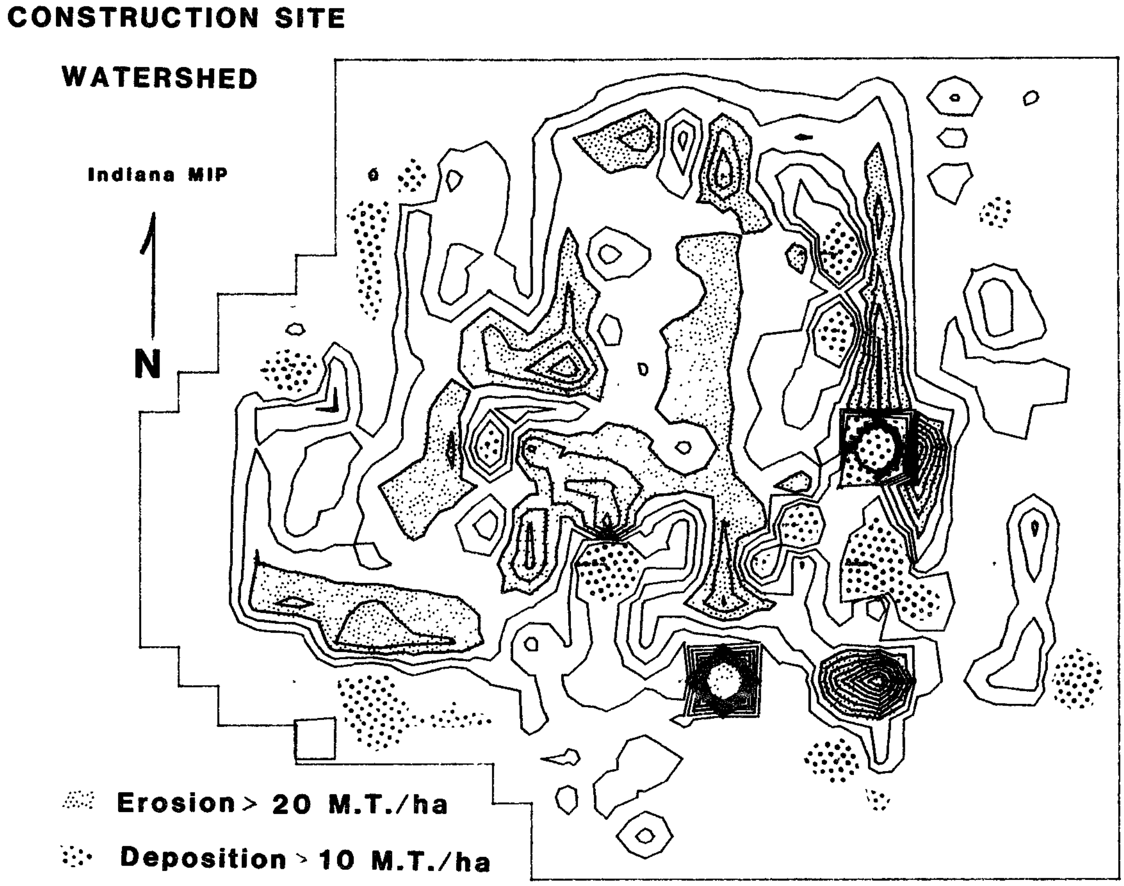


Figure 5-4. Example Output from CONTUR Program.

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APPENDIX A - SOIL PARAMETERS

Section A.1

The parameters described in this section are concerned with the physical description of the soil condition. The parameters do have some seasonal variation, since the bulk density of a soil does vary somewhat throughout the year. The total porosity (TP) is a measure of the bulk density. The field capacity (FP) describes the upper limit of available water in the soil. It also quantifies that portion of the pore volume which can contain only gravitational water (above the moisture holding capacity of the soil). The control zone depth (DF) identifies the volume of soil (depth) that actually influences the rate of infiltration at the surface. The antecedent soil moisture (ASM) quantifies the starting point for the soil moisture-based infiltration equation. Methods for determining each of these important parameters will be presented in this section.

Total Porosity (TP). The volume of pore space within the soil is directly related to the bulk density (weight per unit volume) of the soil. The total porosity (percent pore space) of a soil is defined as:

$$TP = 100 - \left(\frac{BD}{PD}\right) * 100 \qquad \text{(A-1)}$$

where: TP = total porosity, percent,
BD = bulk density,
PD = particle density (assumed to be 2.65).

In some cases, comprehensive soil surveys will contain information on the bulk density of the mapped soil types. However, most soil surveys, even the newer ones, do not contain this kind of data. One bit of information that is available in all soil surveys is the textural class of the individual soil types. Without specific information on the bulk density of a particular soil, the modeler can still make a reasonably good estimate of the bulk density, and thus the total porosity, by utilizing the textural class definition.

Table A-1 lists bulk densities and other soil physical properties for several different soil textural classes. For those classes not listed, an interpolation can be performed. Very sandy soils or organic soils have much larger ranges of values.

Field Capacity (FP). As the moisture content of the soil is increased, a point is reached when water begins to drain due to gravitational forces. Another way of describing this phenomenon is to say that the moisture holding tension within the soil becomes less than 1/3 atmosphere. The point at which this gravitational drainage begins is called field capacity (FP) and is expressed as a percentage of saturation. Saturation occurs when the total pore space within the soil is filled with water. Thus, a soil with a total porosity of 50 percent and a field capacity of 70 percent contains 35 percent water (by volume) at field capacity.

Although some soil surveys contain information about the actual field capacity of the individual soil types, most soil surveys only state what the available water capacity of the soil is. Using the information in Table A-1 and the available water capacity of the individual soils (A horizon), the modeler can easily estimate the field capacity (percent saturation) when that information is not available. By definition, the available water capacity of a soil is that water held within the pores between field capacity (tension of 1/3 atmosphere) and the wilting point (tension of 15 atmospheres). In addition, the assumption is made that approximately one half of the water in the soil is

Table A-1. Some Representative Physical Properties of Soils.

Soil Texture	Bulk Density*	Total Porosity*	Field Capacity*	Wilting Point*
	(g/cc)	(% volume)	(% saturation)	(% saturation)
Sandy	1.65 (1.55-1.80)	38 (32-42)	39 (31-47)	17 (10-24
Sandy loam	1.50 (1.40-1.60)	43 (40-47)	49 (38-57)	21 (15-26)
Loam	1.40 (1.35-1.50)	47 (43-49)	66 (59-74)	30 (26-34)
Clay loam	1.35 (1.30-1.40)	49 (47-51)	74 (66-82)	36 (32-40)
Silty clay	1.30 (1.25-1.35)	51 (49-53)	79 (72-86)	38 (34-42)
Clay	1.25 (1.20-1.30)	53 (51-55)	83 (76-89)	40 (37-43)

*Numbers in parentheses indicate normal range.

Adapted from: (Israelsen and Hansen, 1962).

unavailable. Thus, if the available water is listed as .15 inches/inch (15 percent by volume), the field capacity of the soil is twice that amount or .30 inches/inch (30 percent by volume). Further, if the total porosity has been listed as 50 percent, that means that the field capacity of the soil is 30 percent divided by 50 percent or 60 percent of saturation.

Infiltration Control Zone Depth (DF). Of all of the parameters used in the ANSWERS, this one is the least well defined and most arbitrary. Essentially, it describes the volume of soil (depth) that influences the infiltration rate at the surface of the soil. Experimental data and simulation experience have lead to the conclusion that the control zone depth (DF) varies with time. However, not enough information exists to describe a seasonal influence exactly. In general, the control zone depth is equal to or less than the depth of the A horizon. For most of the soils that have been modeled in the Midwest, the control depth (DF) has been assumed to be equal to .25 to .75 of the depth of the A horizon. In general, a starting value of one half of the A horizon has been used.

Antecedent Soil Moisture (ASM). The infiltration equation in the ANSWERS model is based on the moisture content of the soil. Since the infiltration rate will be much greater when the soil is "dry" than when it is "wet", it is very crucial that the correct antecedent moisture content be used when simulating actual situations. For hypothetical or "wet weather" simulations, moisture contents at or above field capacity will generally be used.

This section details a simple moisture balance approach for determining the antecedent moisture content in each soil. The form of the moisture balance equation is:

$$\mathrm{ASM} = \mathrm{ASML} + \mathrm{RAIN} - \mathrm{ET} - \mathrm{RO} - \mathrm{PERC} \tag{A-2}$$

where: ASM = antecedent soil moisture,
ASML = last known (initial) soil moisture,
RAIN = daily rainfall,
ET = evapotranspiration,
RO = runoff,
PERC = percolation.

In this equation, percolation refers to drainage of gravitational water (water in excess of field capacity). In order to simplify the moisture balance calculations, several assumptions are made:

1. The depth of the soil layer that influences the moisture content is equal to the control zone depth (DF),
2. The evapotranspiration rate is one half of normal on days that have rainfall in excess of 0.2 inches,
3. The soil drains down to field capacity within 1 day at the steady state infiltration rate (FC),
4. When the soil moisture content reaches the wilting point, no additional moisture is lost due to ET,
5. On days when rainfall is less than 0.3 inches, RO (runoff) is zero,
6. On days when rainfall is between 0.3 and 0.8 inches, RO 0.10*RAIN,
7. On days when rainfall is between 0.8 and 1.5 inches, RO 0.15*RAIN,
8. On days when rainfall is greater than 1.5 inches, RO 0.20*RAIN.

The rate of evapotranspiration can be calculated using any of several different equations. Each method entails certain assumptions and the user must determine which equation best serves his purposes and utilizes his data. The average monthly rates shown in the following example are representative of cropland rates in northern Indiana.

The antecedent moisture calculations should be started approximately one month prior to the time to be simulated. Field capacity or any other reasonable moisture content can be assumed as a starting point. During the period of calculation, the soil moisture is **not** allowed to go below the wilting point. Once enough rainfall has occurred within the calculation period to equal or exceed field capacity, the previous history is wiped out. Table A-2 shows example moisture calculations for a soil with a total porosity of 50 percent, control depth (DF) of 6 inches, field capacity of 70 percent saturation (wilting point of 35 percent saturation) and a steady state infiltration rate (see Section A.2) of 0.3 inches per hour. Using the above information and assuming that an ANSWERS simulation is to be started on June 14, the ASM value for this soil type would be 67 percent.

Section A.2

The parameters which specifically describe a soil's infiltration response as described by the modified form of Holtan's equation used in ANSWERS are defined in this section. The steady state infiltration rate (FC) indicates the rate at which the soil will absorb water when the soil is saturated. The difference between the maximum and steady state infiltration rates (A) combined with the infiltration exponent (P) helps to describe the typical exponential "drawdown" of the infiltration rate.

Infiltration Rate Descriptors (FC and A). A simple procedure for selecting values for the steady state infiltration rate (FC) and the difference between maximum and steady state rates (A) is described here. The user is, of course, free to use any information he has concerning these values. Soil survey information is used in this procedure due to its general nature and ready availability.

Table A-2. Antecedent Soil Moisture (ASM) Calculation Example.

Day	Soil Moisture	Rain	ET	Runoff	Percolation
	(% saturation)	(in.)	(in.)	(in.)	(in.)
1 (5/15)	70	.01	.05	0	0
2	69	0	.05	0	0
3	67	0	.05	0	0
4	65	0	.05	0	0
5	64	0	.05	0	0
6	62	3.16	.03	.63	0
7	100	.90	.03	.14	2.26
8	94	.80	.03	.08	.73
9	93	.02	.05	0	.69
10	69	0	.05	0	0
11	67	.29	.02	0	0
12	76	0	.05	0	.18
13	68	0	.05	0	0
14	67	0	.05	0	0
15	65	.05	.05	0	0
16	65	.27	.03	0	0
17	73	.27	.03	0	.09
18 (6/1)	78	.21	.03	0	.24
19	76	.25	.03	0	.18
20	77	.35	.03	.04	.22
21	79	.39	.03	.04	.28
22	81	.53	.03	.05	.32
23	85	.03	.06	0	.45
24	69	0	.06	0	0
25	67	0	.06	0	0
26	65	0	.06	0	0
27	63	.02	.06	0	0
28	62	1.11	.03	.17	0
29	92	.04	.06	0	.66
30	69	0	.06	0	0
31 (6/14)	67				

The range of permeabilities for a given soil type (as listed in the USDA Soil Survey format) are used in the following manner:

1. The midpoint of the lower 1/3 of the range is used for FC,
2. The midpoint of the upper 2/3 of the range is assumed to be the maximum rate,
3. The value of A is equal to the maximum rate minus FC.

Assuming a permeability range of 0.2 to 1.5 inches per hour, the following example illustrates the technique:

The total range = 1.3 inches per hour

1/3 of range = 1.3/3 = .43 inches per hour

Thus, FC equals the midpoint of the lower 1/3 of range

FC = .2 + (.43/2) = .42 inches per hour

The maximum rate is the midpoint of the upper 2/3 of the range

maximum rate = ((.2 + .43) + 1.5)/2 = 1.07 inches per hour

The A value equals the maximum rate minus FC

A = 1.07 - .42 = .65 inches per hour

Using the entire range, FC would be 0.2 iph and A would be 1.3 iph. The method detailed above appears to give more realistic numbers.

Infiltration Exponent (P). As stated in the section on component relationships, the infiltration exponent (P) relates the rate of decrease of infiltration capacity to increasing moisture content. This property varies among soil types and is most closely related to the textural class of the soil. The heavier the texture (more clay), the larger the value of P. Conversely, sandy soils show little change in infiltration rate with increasing soil moisture content and, thus, have a much smaller value of P. Table A-3 lists some starting point values for several textural classes.

Table A-3. "P" Values for Various Soil Testures.

Soil Texture	Suggested Values for "P"
Clay	.75 - .80
Silty clay	.65 - .75
Clay loam	.60 - .70
Loam	.55 - .65
Sandy loam	.50 - .60
Sand	.35 - .50

Section A.3

Two different types of information are included in this section. The USLE "K" factor or soil erodibility of each soil type is described. The general subsurface drainage characteristics of the watershed are described by the combination of the tile drainage coefficient and the groundwater release fraction. Both of these drainage terms are defined and methods of parameter value assignment are discussed.

Soil Erodibility - USLE "K" (K). Most of the newest USDA Soil Surveys contain information on the "K" factor for each soil type mapped. Other sources of this information include statewide soil loss handbooks or brochures which are published by most state SCS offices. Wischmeier et al. (1971) have produced a nomograph technique for determining the USLE "K" factor based on textural class and other soil characteristics.

Section A.4 details a method for simplifying the soils description file presented in this Appendix. Essentially, the technique involves the grouping of soils by similarities in drainage response. When soils are grouped in this manner, the (K) parameter for the various individual soils may not be equal. If they are not, one of two methods can be used to arrive at an "effective" (K).

1. Use an area weighted average of "K" values within a drainage class, or
2. Use the value of "K" for the predominant soil(s).

Subsurface Drainage Characteristics. The two parameters which describe the rate of subsurface water movement are the tile drainage coefficient and the groundwater release fraction. The tile drainage coefficient is simply the design value for tile drainage. Interflow or groundwater release is described by putting a fraction of the water in the subsurface reservoir into the channel system at each time step. Experience has shown that the value of the fraction varies from as little as zero to approximately 0.01. Small values of the fraction may actually cause an increase in the flow rate on the recession limb of the hydrograph due to the fact that the drainage rate from the control zone is greater than the groundwater movement rate. Thus, the subsurface reservoir of water increases, and the interflow rate rises accordingly. Higher values of the fraction will cause the hydrograph to "level off" for a period of time and then decrease as the rate of subsurface drainage becomes less than the interflow rate.

Section A.4

In order to reduce the number of soils that must be described in the "predata" file, a technique has been developed for identifying soils with similar drainage characteristics. The similar soils are then placed in a general group with drainage and erosion characteristics which describe the "average" response of the soils making up the group.

The procedure requires information about the drainage classification and hydrologic soil group of each soil type. The technique involves the following:

1. Soils are listed by their drainage classification (*i.e.,* well drained, poorly drained, very poorly drained, etc.) and by hydrologic group (i.e., A, B, C or D).
2. The soils are first grouped by drainage classification. Then, those soils are examined for hydrologic group. Soils that have the same drainage classification and hydrologic group are considered to have similar responses. It is possible that within one drainage classification there may be soils with two or more hydrologic groups. The soils in each hydrologic group should be considered as a separate soil group.
3. The soil(s) that predominate the area in each soil group are chosen as representative. A more complex method would be to select the descriptive parameters based on area weighting.

APPENDIX B - LAND USE AND SURFACE PARAMETERS

Section B.1

The information presented in this section involves the extent of crop cover, the flow retardance of the surface and the relative erosiveness of the various crops or land uses. The specific land use or crop (CROP) is simply an identifier that is printed during output. The potential interception (PIT) and percent cover (PER) are used to describe the interception of rainfall. Manning's n (N) describes the surface roughness or retardance to flow. The relative erosiveness parameter (C) is actually a combination of the USLE "C" and "P" values with seasonal adjustment.

Interception Parameters (PIT and PER). A certain amount of the precipitation during any event never reaches the soil surface. Contact with and storage on vegetation accounts for this removal and is called interception. The potential interception volume (PIT) describes the volume of moisture that could be removed if the area were completely covered by that crop or land use. The actual percentage of cover (PER) assumes the non-covered area has no interception. Table B-1 lists some example values for PIT.

Table B-1. Potential Interception Values.

Crop	PIT (mm)
Oats	.5 - 1.0
Corn	.3 - 1.3
Grass	.5 - 1.0
Pasture and Meadow	.3 - .5
Wheat, Rye and Barley	.3 - 1.0
Beans, Potatoes and Cabbage	.5 - 1.5
Woods	1.0 - 2.5

Manning's n (N). The measure of surface roughness or flow retardance used in the flow equation in ANSWERS is Manning's n. This information, when combined with element slopes, rainfall, interception, infiltration and routing considerations, helps yield the solution to the continuity equation, which is the basis of ANSWERS. There are numerous sources for obtaining reasonable values of n for channel and overland flow situations.

Relative Erosiveness (C). This parameter is used in determining how much soil could potentially erode due to a particular crop or land use, when compared to fallow ground under identical conditions. It is a direct combination of the USLE "C" and "P" parameters with a seasonal adjustment. Thus, conventionally tilled corn at crop stage 1 will have a higher (more erosive) C value than the same corn at crop stage 2, when there is more foliage and root structure. Agriculture Handbook No. 537 (Wischmeier and Smith, 1978) contains information for determining the USLE "C" and "P" values throughout the year for numerous crops and management systems.

Section B.2

Figure B-1 shows a profile of a section of the soil surface. The combination of the peaks and valleys yields a certain depressional storage volume. In addition, the amount of the surface that area that is inundated at any time is a direct function of the depth of water on the surface. The infiltration rate within an element is greatly affected by the amount of pondage within the area.

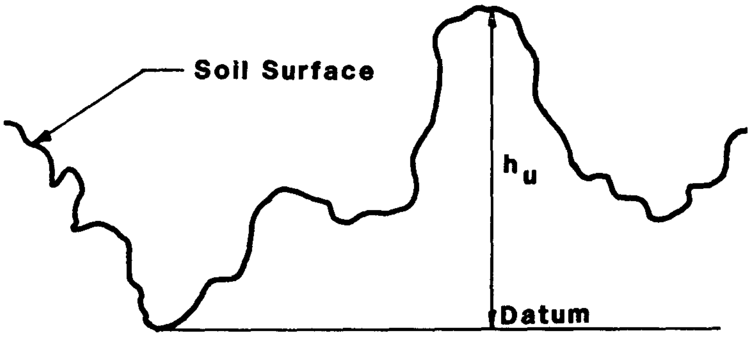

Figure B-1. Soil Surface Profile.

Surface Storage Descriptors (HU and RC). The ANSWERS model uses the maximum roughness height (HU) and a roughness coefficient (RC) to describe the surface storage characteristics and the ponded surface area. The roughness coefficient (RC) is, essentially, a shape factor which describes the frequency and severity of the roughness. The maximum roughness height (HU) is used to establish the upper limits of the surface roughness and is physically measurable. Table B-2 shows some typical values for both HU and RC.

Table B-2. Typical Surface Storage Coefficients.

Surface Condition	HU (mm)	RC
Plowed Ground:		
Spring - smooth	100	.53
Spring - normal	130	.48
Spring - rough	130	.59
Fall - smooth	60	.37
Fall - normal	70	.33
Fall - rough	130	.45
Disked and Harrowed:		
Very smooth	30	.42
Rather rough	60	.43
Corn Stubble	110	.59

APPENDIX C - INDIVIDUAL ELEMENT INFORMATION

Section C.1

One of the strengths of the ANSWERS model is its ability to describe spatially those processes which affect the hydrologic and erosion responses of a watershed. In order to accomplish this, the topographic influences of the various sub-areas within the watershed must be quantified. By applying a square grid to a soils or topographic map, the element pattern is defined. Once done, additional information concerning specific soils, land use, drainage and BMPs can be added easily.

In the rather rare situation in which the necessary watershed data is available on machine readable media, the only requirement is to develop a simple computer program to reformat the data in a manner compatible with the above definitions. Unfortunately, the more common situation is to have only maps available from which the necessary information must be manually extracted. Because the format outlined in Chapter IV is rather tedious, a series of programs have been written to facilitate the manual transcription of map information into the file format required by ANSWERS.

It is recommended that a transparent overlay be prepared with a grid of squares drawn to the map-scale size desired for watershed elements. It is further suggested that this grid have its rows and columns numbered beginning in the upper left-hand corner with number 1 for the rows and for the columns of elements. This overlay can then be superimposed on topographic and soils maps to delineate the elements of which the catchment is composed. The map should be oriented in such a manner that the direction of predominate water flow is from the top (row 1) to the bottom of the map, *i.e.,* the watershed outlet should be as near to the highest numbered row of elements as possible while still maintaining an orientation which is compatible with most field boundaries. This often means that the rows will be oriented in one of the four cardinal directions. Although not an absolute necessity, this arrangement does facilitate computation.

Available data formatting programs are written with the expectation that separate files will be manually prepared for each different physical parameter in the element file (*i.e.,* soil, crop, channel type, rain gauge). Data for these programs may be prepared in a free-format style with each numeric entry separated by a comma. Any number of data entries may be entered on a single line. For those locations which do not have a FORTRAN compiler which accepts free-format input, it is a simple matter to modify the input format statements in whatever manner desired.

The method for describing the direction of slope applies to both overland and channel flow directions. In those elements which contain channels, the direction is in 45 degree increments which contribute all of the flow to one of the eight surrounding (and touching) elements. The channel direction takes precedence over the overland direction.

Simplified Data File Construction. The basis of the simplified data file construction technique is the use of USDA-SCS Soil Survey information to provide a map base for the grid and slope information from the mapping units themselves. Although the mapping units used in modern Soil Surveys give a range of slopes for each defined area, there is no information provided on slope direction. Therefore, directions must be chosen using a "common sense" approach in conjunction with topographic information.

An additional degree of slope descriptiveness can be obtained by using the surrounding elements to determine which part of the slope range should be used. For example, when a soil with a range of 3-6 percent is surrounded by soils with steeper slopes, the high end of the range (approximately 6 percent) should be used. On the other hand, a soil with 6-12 percent slopes surrounded by lesser slopes would use the low end of the range. An element surrounded by soils with similar slopes would use the midpoint of the range.

Data File Construction Using Topographic Maps. ANSWERS requires that the average slope steepness and direction of steepest slope be specified for each element in the catchment. Rather than attempt to obtain this information directly from a topo map a program, called ELEVAA, has been written which requires instead that the elevations of the corners of each element be input. That program calculates the slope steepness and flow direction of each element and then sets up the complete format for the elemental data file. That file is subsequently updated to add information concerning the soil type and crop/management practice for each element and to identify those elements which contain a well defined channel.

ELEVAA is organized so that the identification of the location of the elevation data requires a slight mental transposition of the element's row and column number to refer to the elevation at the upper left-hand corner of the element. For example, position 4,6 for an elevation actually refers to the upper-left corner elevation for the element in row 4 and column 6 of the watershed. The elevation in the lower right-hand corner of element 4,6 would be identified by the position numbers 5,7 (note that this elevation is also the elevation of the upper left-hand corner of element 5,7; thus, since a single point elevation is normally used to help compute the slope direction and steepness of four different elements, one never needs to be concerned with specifying the location of anything except the upper left-hand corner elevation for each element).

Begin preparing the input data file for ELEVAA by starting with the upper corner elevations of the top row of elements in the catchment. Generally this will be row number 1. The first two entries on a data line must be, respectively, the corresponding row number and the column number of the first elevation that will appear on that line. The remaining entries on that line will be the elevations of sequential elements in that given row. Any number of elevations, up to a maximum of 28, may be entered on a single line, but they must be for **sequential** columns. Thus, if a row is discontinuous (watershed boundaries are irregular and often exclude some element positions) or whenever all elements in a given row have been specified, it is necessary to start a new line of data. The end of data input to ELEVAA is signified by including a blank line after all elevation data has been specified.

There are some difficulties that arise as a result of trying to generate the elemental data file from corner elevations. It is almost certain that some slope directions calculated on the basis of corner elevations will be unsatisfactory and will need to be manually edited. This is especially true for boundary elements of the catchment. They will often be computed in a direction which would result in some of their outflow moving out of the watershed. Also, it is mandatory that all of the outflow from the outlet element move directly out of the catchment, *i.e.,* it should have one of the cardinal (0, 90, 180 or 270) directions and will usually be specified as a channel element as discussed below. It is also likely that elements located near to stream channels will not have appropriate slope directions of slope steepness returned from ELEVAA due to topographic irregularities along a channel. Most of these difficulties will be automatically corrected when the channel data file is processed. In any case, it is recommended that all manual editing of the elemental data file be postponed until after the basic soils and channel data have also been processed.

One final warning should be given concerning possible difficulties with the output of ELEVAA for cases where the watershed of concern has substantial areas which are relatively flat or even depressional. For such situations, it is likely that ELEVAA will return element flow directions for a group of elements which results in a computational ponding of water, *i.e.,* the flow pattern for the of elements has no outlet for surface flows. These areas, due to the cumulative flow depths that result from the circulating runoff, will often show a false very high erosion rate. There are at least two ways to discover such problem areas. One is to plot an elemental map with the flow direction show for each element and to visually inspect it for such regions. A GCS (Graphics Compatibility System)-based plotting program, called QCKPLT has been devised for this purpose (see Chapter V for an example). Even if that procedure is followed, the second method is recommended as a final check. This second method involves running an initial watershed simulation assuming a fallow (no vegetation) condition and then making a critical examination of all regions which show high erosion rates to make sure they are not the result of circulatory regions caused by erroneous element slope directions. Once such regions are detected it is necessary to manually correct the flow directions to provide a drainage outlet for the region. An interactive editing program for this purpose has been written in the "C" language for use on computers utilizing the UNIX operating system. A FORTRAN-based version of this editor is planned.

Section C.2

In order to fully utilize the ANSWERS model as a planning or evaluation tool, it must be able to simulate the particular practices that users might apply to a watershed. ANSWERS handles BMPs in two different ways. Practices which are strictly tillage-oriented are described in both the soils and land use files. This is due to the fact that tillage-based management changes can affect both the infiltration response and the surface condition of the soil. On the other hand, those BMPs which are structural in nature or which require a change in land use (row crop to grass for waterways or field borders, for example) are described in the individual element data file.

The primary tillage based BMPs considered by ANSWERS are:

1. Change from conventional tillage (fall turning plow) to chisel plowing,
2. Change from conventional tillage to minimum tillage,
3. Change from conventional tillage to no-till.

Each of these changes has similar effects, but to a different degree upon both the soils and land use (surface) descriptors. This necessitates describing both "new" soils and land uses.

When conventional tillage is replaced by chisel plowing (#1), the infiltration components (A and FC) should be increased approximately 20 percent. At the same time, the surface descriptors (HU and N) should be increased by approximately 15 percent. In changing from conventional tillage to minimum tillage techniques (#2), the infiltration and surface parameters should be increased by approximately 25 percent and 20 percent, respectively. The change from conventional to no-till (#3) requires increases of approximately 25 percent for both infiltration and surface parameters.

Table C-1 lists the BMPs which are based on structures or land use changes. Each BMP, its code number, additional descriptors required and any pertinent assumptions are listed.

Table C-1. Structural and Land Use Change BMP Descriptions.

BMP	Code No.	Additional Information	Assumptions
Tile Outlet Terraces	1		Trap efficiency of 90% Only lowermost terraces are described
Sedimentation Pond	2		Trap efficiency of 95% Only ponds in upland areas should be defined, instream structures are treated differently
Grassed Waterways	3	Width	Decreases erodibility
Field Borders	4	Total width	Decreases erodibility

If a terrace or pond exists only in a portion of the element, the assumption is made that **all** incoming flow is influenced by that BMP. Thus, elements which have only a small portion of a practice within their boundaries should not be given credit for that practice. The most effective BMP found in an element should be the one described. As an example, in an element with a pond and a grassed waterway, the pond, with its very effective sediment trapping characteristics, should be chosen for description.

APPENDIX D - ENHANCED SEDIMENT MODEL

General

In order to better understand the complex processes of sediment and nutrient movement on a watershed scale, it is necessary to have a transport model capable of determining not only the magnitude of the material in movement but also the makeup. Since phosphorus transport is highly influenced by the amount of fine material in the sediment load, a model which can predict the actual "enrichment" of fines in the sediment load should be a very positive addition to a total "water quality" model.

An expanded capability sediment transport model is available as part of the ANSWERS package which can produce information on the differential detachment and transport of the various particles which make up the soil surface and sediment load. This model utilizes many of the assumptions that the original detachment/transport model within ANSWERS uses. It is based on the Yalin (1963) model with modifications for multiple particle classes and for varying densities.

The component relationships, additional input information required, and output formats are described in this section. The general release of the ANSWERS model does **not** contain this version of the sediment model. It is significantly slower and requires more computer resources than the original sediment algorithms. A complete discussion of the development and testing of this section of ANSWERS can be found in Dillaha (1981). A modified version of ANSWERS, incorporating this model, can be obtained by contacting the Agricultural Engineering Department, Purdue University, West Lafayette, IN 47907.

Model Development

Sediment transported by overland flow occurs in two related forms: bedload and suspended load. Bedload is that portion of the load which moves along the bottom of the flow by saltation, rolling and sliding. Bedload is generally composed of the larger soil particles (sand, gravel and aggregates). Bedload movement is highly transport dependent. A decrease in transport capacity causes the immediate deposition of the excess bedload.

Suspended load is much more uniformly distributed throughout the flow depth as contrasted with bedload. A decrease in the transport capacity will not result in the immediate deposition of suspended sediment. This delay is the result of the small fall velocities of most suspended particles which prevents them from depositing immediately. Part of the suspended load has such small fall velocities (see Table D-1) that they are effectively permanently suspended, when compared with the larger sediment particles. In this research the smallest particles, primary clay and silt less than 10 microns in diameter, were considered to be washload and were not allowed to deposit unless the overland flow rate was zero. This means that their yield was determined entirely by their weight fraction in the original soil masses and the total amount of detachment.

Table D-1. Typical Sediment Characteristics.

Particle Type	Size (mm)	Specific Gravity	Fall Velocity (mm/s)	Time to Settle 1.0 mm
Primary Clay	0.002	2.65	0.003	5. min
Primary Silt	0.010	2.65	0.080	13. s
Small Aggregate	0.030	1.80	0.349	3. s
Primary Sand	0.200	2.65	24.	.04 s
Large Aggregate	0.500	1.60	40.	.03 s

The fraction of particles larger than 10 microns which were deposited when there was a transport capacity deficit was defined as:

$$RE_i = FV_i * \frac{AREA}{Q} \quad \text{(if } RE_i > 1\text{, then } RE_i = 1\text{)} \tag{D-1}$$

where: RE_i = fraction of particles of particle size class i depositing,
FV_i = fall velocity of particle i, m/s,
AREA = area of an overland flow or channel element, m^2,
Q = flow rate, m^3/sec.

This is the classic relation describing the settling efficiency of particles in water (Weber, 1972). This equation is not strictly true for the case of overland flow since it was developed assuming that:

1. The settling is occurring under quiescent conditions.
2. Flow is steady and the concentration of suspended particles of each size is initially distributed uniformly throughout the flow.
3. Once the particles are deposited they are not resuspended.

Although overland flow conditions violate some of these assumptions (resulting in a possible overestimation of the removal efficiency), it was decided to use the equation anyway. It was chosen because it is an improvement over the normal procedure which assumes that all excess sediment is deposited immediately and because the overestimation of removal efficiency due to turbulence is potentially offset by the high concentration of the large particles in the lower flow region.

The fall velocity, FV_i, in Equation (D-1) was calculated as (Fair, et al., 1968):

$$FV_i = \left(\frac{4 * AGRAV * (SG-1) * DIA_i}{3 * CD}\right)^{.5} \tag{D-2}$$

where: AGRAV = acceleration due to gravity, m/s^2,
SG_i = particle density, g/cm^3,
DIA_i = diameter of particle class i, mg,
CD = Newton's drag coefficient.

Newton's drag coefficient, CD, is defined as:

$$CD = 18 * VISCOS \qquad \text{for } REYN \leq .1 \tag{D-3a}$$

$$CD = \frac{24}{REYN} + \frac{3}{\sqrt{REYN}} + .34 \qquad \text{for } REYN > .1 \tag{D-3b}$$

where: VISCOS = kinematic viscosity of water, m^2/s,
REYN = Reynolds number = $FV_i * DIA_i * VISCOS$.

For Reynold's numbers less than or equal to 0.1 the fall velocity calculation was direct; but for values greater than 0.1, an iterative solution was required. If experimentally determined fall velocities are available for the actual particle classes being modeled, they should be input directly and the model will not have to estimate the fall velocities.

The rate at which sediment is transported by flow is a function of both the sediment supply rate and the transport capacity of the flow. The net rate of movement is proportional to the lesser of the transport or the rate at which the particles are available for transport.

The selection of a transport equation for the overland flow regime is probably the most critical component of a sediment yield model. It is very difficult because all accepted transport models, developed to date, were developed for streamflow conditions. The differences between deeper channel flows and shallow overland flows are significant. Shallow flow undulates constantly, resulting in flow regime changes; rainfall drastically increases the turbulence of the flow (Barfield, 1968); the ratio of particle diameter to flow may be high; surface tension may affect flow conditions; (Young and Mutchler, 1969); and the slope of the energy gradeline is difficult to estimate (Foster, 1982). In spite of these differences, streamflow transport relations must be used because of the lack of any relations developed from overland flow data.

Foster and Meyer (1972), Davis (1978), Alonso, et al. (1981) and Foster (1982) have done considerable work in studying the use of streamflow equations for modeling the overland flow situation. Their general concensus is that the Yalin (1963) equation best fits experimental overland flow data, especially when one is modeling the particle size distribution of the eroded sediment. Based upon their success with the equation it was decided to use the Yalin equation in this work.

Yalin (1963) developed an expression for the bedload transport of uniform, cohesionless grains over a movable bed for steady, uniform flow of a viscous fluid. His derivation is based upon dimensional analysis and upon the mechanics of the average motion of a grain. The flow was assumed to be turbulent with a laminar sublayer not exceeding the thickness of the grains. Grain motion was assumed to be by saltation and a critical tractive force was assumed. The critical tractive force as a function of the laminar sublayer thickness was assumed to be demonstrated by the Shields' curve.

The Yalin equation is:

$$\mathrm{TF} = \mathrm{PS} * \mathrm{SG} * \rho_w * \mathrm{DIA} * \mathrm{VSTAR} * \mathrm{AGRAV} \qquad \text{(D-4a)}$$

where:

$$\mathrm{PS} = \mathrm{YALCON} * \mathrm{DELTA} * \left(1 - \frac{\ln\,(1 + \mathrm{SIGMA})}{\mathrm{SIGMA}}\right) \qquad \text{(D-4b)}$$

$$\mathrm{SIGMA} = 2.45 * \mathrm{SG}^{-.4} * Y_{CR}^{.5} * \mathrm{DELTA} \qquad \text{(D-4c)}$$

$$\mathrm{DELTA} = \frac{Y}{Y_{CR}} - 1 \qquad (\text{when } Y < Y_{CR},\ \mathrm{DELTA} = 0) \qquad \text{(D-4d)}$$

$$Y = \frac{\mathrm{VSTAR}^2}{(\mathrm{SG} - 1) * \mathrm{AGRAV} * \mathrm{DIA}} \qquad \text{(D-4e)}$$

$$\text{VSTAR} = (\text{AGRAV} * r * \text{SL})^{.5} \tag{D-4f}$$

TF = transport capacity,
ρ_w = mass density of fluid,
VSTAR = shear velocity,
Y_{CR} = critical shear stress from Shield's diagram,
SL = slope of the energy gradeline,
r = hydraulic radius,
YALCON = an empirically derived factor = 0.635.

In the new sediment model, the hydraulic radius, r, was assumed to be equal to the flow depth (actually depth of stored water less the depth of retention storage).

Foster and Meyer (1972) developed a method by which Yalin's equation could be used to predict the transport capacity of each particle size class in a mixed sediment. Yalin assumed that the number of particles in transport was equal to DELTA. Foster and Meyer, therefore, assumed that for a mixture, the number of particles of a size i is proportional to DELTA_i. Values of DELTA_i for each particle class were summed to give the total transportability, SDEL:

$$\text{SDEL} = \sum_{i=1}^{\text{NPART}} \text{DELTA}_i \tag{D-5}$$

where: NPART = number of particle size classes,
DELTA_i = DELTA as defined by Equation (D-4d) for particle class.

The number of transported particles of class i in a mixture, $(N_e)_i$ was taken to be:

$$(N_e)_i = \frac{N_i * \text{DELTA}_i}{\text{SDEL}} \tag{D-6}$$

where: N_i = the number of particles transported in a uniform sediment for DELTA_i.

In a similar manner, PS was assumed to be proportional to DELTA, so:

$$(P_e)_i = \frac{\text{PS}_i * \text{DELTA}_i}{\text{SDEL}} \tag{D-7}$$

where: $(P_e)_i$ = the effective PS for particle class i in a mixture,
PS_i = the PS calculated for a uniform sediment of class i.

The actual transport rate TF_i of each particle class in a mixture can then be expressed as:

$$TF_i = (P_e)_i * SG_i * \rho_w * AGRAV * DIA_i * VSTAR \qquad \text{(D-8)}$$

Yalin's method, as originally derived, was developed from laboratory flume studies of the transport of sand and gravel with flows much deeper than those encountered in overland flow. The constant 0.635 was determined from these flume studies. Davis (1978) found that 0.88 was a better value for sand with a diameter of 342 microns and that 0.47 was better for coal particles with diameters of 156 microns and 342 microns and specific gravities of 1.67 and 1.60 respectively. No other information is available concerning the value to use for YALCON unless one determines it by calibration. It was decided to leave it fixed at 0.635 in this study.

The original Shields' diagram used by Yalin was not developed for sediment particles of low specific gravity and small size. Fortunately, the Shields' diagram was extended for small particles by Mantz (1977) and Figure D-1 can be used to estimate YCR. In the model, Shields' diagram, as extended by Mantz, was broken down into the 5 regions listed in Table D-2.

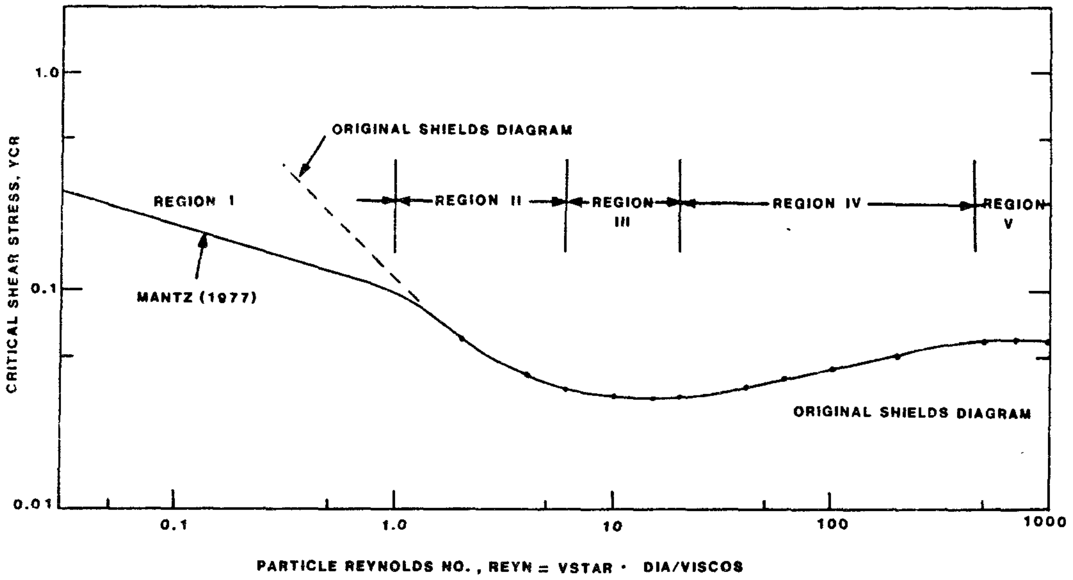

Figure D-1. Shield's Diagram as Extended by Mantz (1977).

Table D-2. Critical Shear Stress Relations Used in Transport Model.

Region	Reynolds number	Critical shear stress relation
I	$0.03 \leq REYN \leq 1.0$	$YCR = 0.1 * REYN^{-0.3}$
II	$1.0 < REYN \leq 6.0$	$YCR = EXP\ (-2.3026 - .5546 * \log_e (REYN))$
III	$6.0 < REYN \leq 20.$	$YCR = 0.033$
IV	$20. < REYN \leq 450.$	$YCR = EXP\ (-3.9793 + .19212 * \log_e (REYN))$
V	$REYN > 450.$	$YCR = 0.06$

A flow diagram of the model is presented in Figure D-2 which gives an overall picture of the interactions between the various parts of the model.

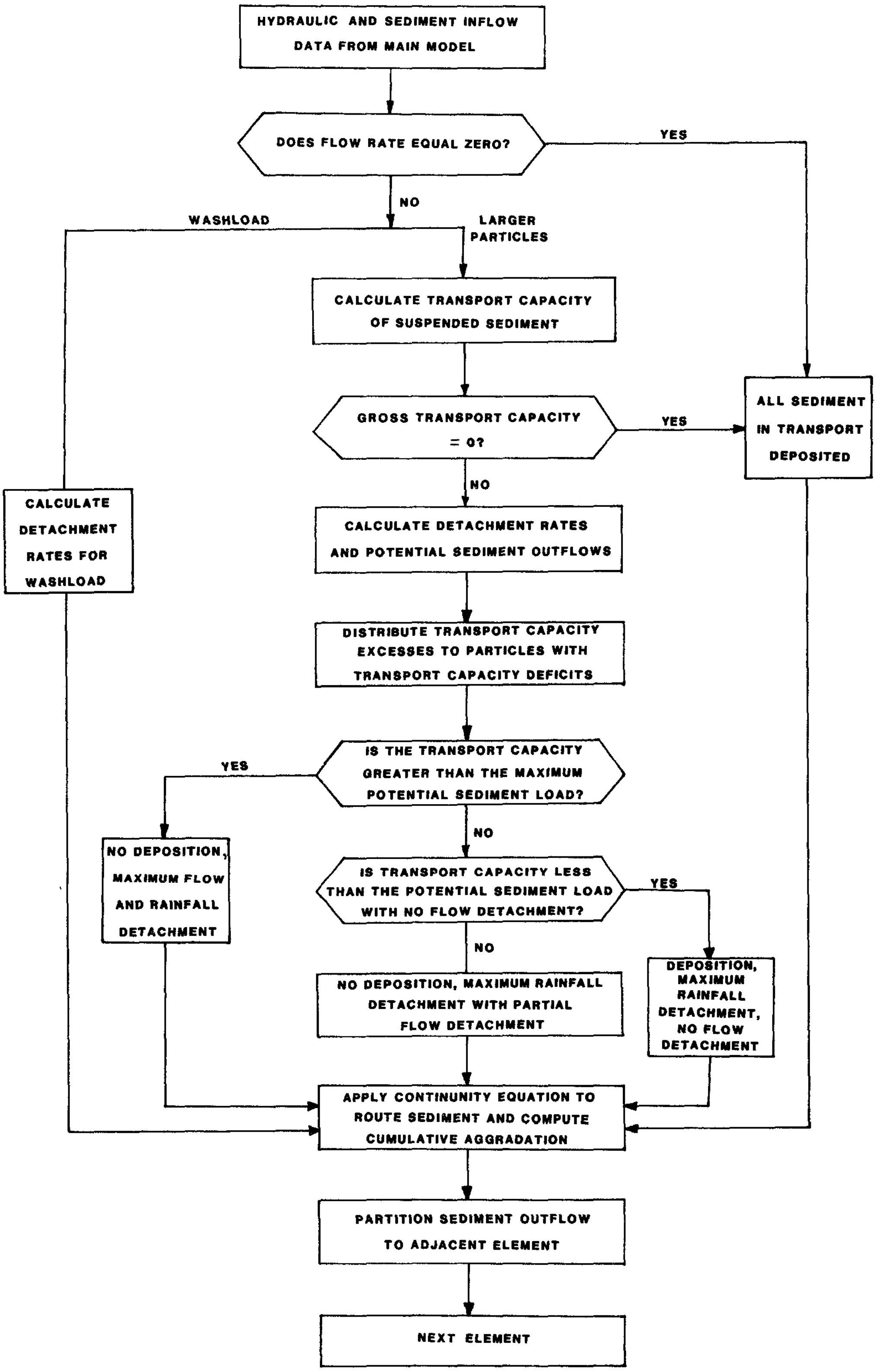

Figure D-2. Flow Diagram.

A brief summary of the basic assumptions on which the model is based follows:

1. The particle size distribution of detached sediment is the same as the weight fractions of the soil particles in the original soil mass (no enrichment during detachment).
2. Rainfall detachment is not limited by the transport capacity of the flow.
3. Flow detachment occurs only if there is excess transport capacity and can never exceed the transport capacity excess.
4. Deposition and flow detachment never occur at the same time for the same particle.
5. Washload transport is independent of the transport capacity of the flow and does not influence the transport of the larger particles.
6. Deposited sediment requires the same amount of energy as in the original detachment to become redetached.
7. Enrichment is controlled by the deposition process.
8. The rate at which a particle will deposit is proportional to its fall velocity.
9. Channel erosion does not occur.
10. Subsurface or tile drainage produces no sediment.

Input and Output Format Changes

Figure D-3 depicts the additional information required to run the expanded version of the ANSWERS sediment model. The data block is inserted just after the soils information and before the drainage and groundwater release information. It includes a description of each particle class (size, specific gravity, and fall velocity — if known) and the make-up (in terms of the defined size classes) of each of the listed soil types. In this example, there were five total size classes with two (the first two) defined as washload classes. Additionally, there were ten soil types. Soil number three was composed of the following percentages of the five size classes:

1. 10 percent of class 1 (.002 mm),
2. 18 percent of class 2 (.010 mm),
3. 50 percent of class 3 (.030 mm),
4. 17 percent of class 4 (.500 mm),
5. 5 percent of class 5 (.200 mm).

```
 PARTICLE SIZE AND TRANSPORT DATA FOLLOWS
NUMBER OF PARTICLE SIZE CLASSES    = 5
NUMBER OF WASH LOAD CLASSES        = 2
  SIZE  SPECIFIC GRAVITY  FALL VELOCITY
0.002            2.65             0.0
0.010            2.65             0.0
0.030            1.80             0.0
0.50             1.60             0.0
0.20             2.65             0.0
 .100  .180  .500  .170  .050
 .100  .180  .500  .170  .050
 .160  .160  .530  .110  .040
 .080  .120  .350  .150  .300
 .160  .160  .530  .110  .040
 .100  .180  .500  .170  .050
 .160  .160  .530  .110  .040
 .024  .031  .240  .239  .466
 .200  .200  .200  .200  .200
 .200  .200  .200  .200  .200
```

3a

```
DRAINAGE COEFFICIENT FOR TILE DRAINS = 6.35 MM/24HR
GROUNDWATER RELEASE FRACTION =    .001
```

Figure D-3. Additional Input Information.

Classes 1, 2, and 5 are defined as primary clay, silt, and sand, respectively. Classes 3 and 4, as noted by their lower specific gravity and larger sizes, are small and large aggregates, respectively.

The input data "echo" for the expanded model shows the newly calculated fall velocity (unless previously defined) for each size class and the "sand equivalent" diameter of particles with specific gravities less than 2.65. Figure D-4 shows the data "echo" which is displayed immediately following the soils information.

```
   9     55.0       80.0        38.1   127.0    .60   203.0      70.0      .20
  10      1.0      100.0           0    25.4   1.00      .1     100.0        0

                    PARTICLE SIZE DISTRIBUTION DATA

                  NUMBER OF PARTICLE SIZE CLASSES = 5
                  NUMBER OF WASHLOAD CLASSES      = 2
  CLASS    DIA,MM         EQSAND,MM          SG   FALL VELOCITY,  M /S
    1       .002           .002           2.650       .0000036
    2       .010           .010           2.650       .0000896
    3       .030           .021           1.800       .0003910
    4       .500           .278           1.600       .0432082
    5       .200           .200           2.650       .0263375
PARTICLE SIZE DISTRIBUTION OF SOILS AS DETACHED
 CLASS    1     2     3     4     5     6     7     8
SOIL 1  .100  .180  .500  .170  .050
SOIL 2  .100  .180  .500  .170  .050
SOIL 3  .160  .160  .530  .110  .040
SOIL 4  .080  .120  .350  .150  .300
SOIL 5  .160  .160  .530  .110  .040
SOIL 6  .100  .180  .500  .170  .050
SOIL 7  .160  .160  .530  .110  .040
SOIL 8  .024  .031  .240  .239  .466
SOIL 9  .200  .200  .200  .200  .200
SOIL10  .200  .200  .200  .200  .200

TILE DRAINAGE COEFF. = 6.35  MM/24H
GROUNDWATER RELEASE FRACTION =  1.000E-03
```

Figure D-4. Data "Echo" in Output.

Immediately following the statistics on total rainfall and runoff and average sediment yield (at the end of the printed hydrograph), statistics on the composition of the sediment leaving the watershed are presented. Figure D-5 indicates that both of the washload classes (clay and silt) were significantly enriched during this particular event.

```
3487.0        0      .1633    532016.          0.
  RUNOFF VOLUME PREDICTED FROM  63.40  MM OF RAINFALL = 14.708  MM
                AVERAGE SOIL LOSS =   745.   KG/HA
             ----------------------------------------
             |      PARTICLE SIZE DISTRIBUTION      |
             |          OF ERODED SEDIMENT          |
             |                                      |
             |  PARTICLE CLASS 1 = 24.46 PERCENT    |
             |  PARTICLE CLASS 2 = 38.85 PERCENT    |
             |  PARTICLE CLASS 3 = 28.13 PERCENT    |
             |  PARTICLE CLASS 4 =  3.45 PERCENT    |
             |  PARTICLE CLASS 5 =  5.12 PERCENT    |
             ----------------------------------------

                   INDIVIDUAL ELEMENT NET SEDIMENTATION
ELEMENT SEDIMENT  ELEMENT SEDIMENT  ELEMENT SEDIMENT  ELEMENT SEDIMENT
```

Figure D-5. Sediment Sizes Exiting Watershed.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

This report is an expanded and edited version of the Users Manual for the ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) model, first published in September, 1980. ANSWERS is a distributed parameter model capable of predicting the hydrologic and erosion response of primarily agricultural watersheds. Particle-size distributions of the eroded sediment (at all points in the watershed, as well as the outlet) are available. The manual provides insights into model concepts, input requirements, output interpretation, and planning applications.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Water quality model Hydrology Sediment yield Particle-size distributions Best Management Practices Runoff model		

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