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ENVIRONMENTAL IMPACT OF AIRPORT LAND USE AND ACTIVITIES ON STORMWATER, GRISSOM AFB, INDIANA

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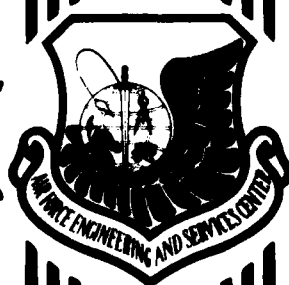KNOXVILLE, TENNESSEE

DECEMBER 1980

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OCTOBER 1978 — JULY 1980

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Computer Model	Stormwater

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Grissom Air Force Base near Bunker Hill, Indiana, was selected for test applying three stormwater simulation models: (1) the U.S. Army Corps of Engineers "STORM," (2) the EPA "SWMM," and (3) a model "AFRUM," developed by the Department of Civil Engineering, of the University of Tennessee for the U.S. Air Force. It was also the objective of the project to identify sources of stormwater runoff pollution, i.e., ground and air.

(Reverse)

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A comparison of the stormwater models was coupled with a review of existing models and recommendations made as to which models should be used under what circumstances. Finally, the ability of AFRUM to be transferred to other Air Force bases was evaluated. The AFRUM computer user's manual is presented in ESL-TR-80-29.

Three small watersheds ranging from 70 to 276 acres were instrumented with continuous rainfall, streamflow, and water quality samplers and dustfall collection samplers. The models were utilized to simulate the observed storm hydrographs and pollutographs. A survey of ground and air sources coupled with air quality modeling was utilized to identify and delineate the relative contribution of ground and air sources.

STORM and SWMM simulated hydrographs and pollutographs were significantly different from the observed. Since there were no prediction schemes for the model parameters provided in the user's manuals, default values were utilized. AFRUM simulations were accurate for the two watersheds without extensive storm sewers, but were in error for the one watershed having extensive storm sewers. The analysis phase of AFRUM, i.e., the TVA Double Triangle Model (DTM), was called thereby calibrating the model to the storms and the results were incorporated back into AFRUM. The Grissom runoff quality is substantially better than the urban areas of Chicago, Knoxville, or Durham.
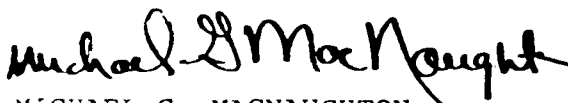
PREFACE

This report culminates a 3 1/2-year technical effort by the Department of Civil Engineering at the University of Tennessee, Knoxville. The efforts of the first year were devoted to model development under contract number F08635-76-C-0247 entitled, "Development of a Regional Mathematical Model for Predicting Changes in Streamflow Quantity and Quality as a Function of Land Use, Soil Type and Rainfall Characteristics." The efforts of the next year and a half were devoted to test applying the developed models at Grissom Air Force Base near Bunker Hill, Indiana, under contract number F08635-77-C-0254. Due to severe weather, equipment malfunction and liaison problems, little usable data were obtained. The contract was extended for one year for the purpose of collecting representative data for test,applying the models and developing criteria for transferring the models to other Air Force bases which, for the most part, have no recording rain gages, streamflow gages, or stormwater quality samplers. This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

1. EFFECTS OF LAND USE CHANGES AND ACTIVITY ON RUNOFF

Land use activities are continuing with an increasing intensity.
Assessment of the environmental impact of these activities is of
great concern before and after the fact. Urbanization, agri-
cultural practices, coal strip mining, and logging operations are
examples of land use activities that have allegedly contributed
to flooding and stream water quality degradation. To develop
defensible environmental impact statements associated with these
activities, it is essential that the most scientifically based
methodology be applied to the problems. Since little hydrologic
data are available on smaller watersheds, it is becoming widely
accepted that mathematical modeling is the only available means
of making reliable predictions of the effects of land use changes
on streamflow quantity and quality.

Recent water quality studies have indicated that treatment of the
wastewater of a community will not be enough to achieve and main-
tain national, state, and local water quality standards. Efforts
must also be made to utilize land resources in such a way as to
minimize adverse effects on water quality. Problems of soil ero-
sion and sedimentation, stormwater runoff, and changes in land-
use patterns have measurable effects on water quality. Any
attempt to provide solutions to problems of water quality must
include an adequate identification of these nonpoint sources.

Solutions to water quality problems have traditionally been faci-
lities for transmitting and treating wastewater yielding point
sources of pollutants. It has been determined that treatment,
even advanced treatment, does not provide the total solution to
water quality problems. Treatment systems must be supplemented
by suitable land development practices and regulations. It
follows that streamflow quality problems cannot be placed in a
realistic perspective without delineating stormwater (nonpoint
source) pollution relative to municipal and industrial (point
source) pollution.

2. PROJECT OBJECTIVES

The objectives of this project are to:

    a. Evaluate stormwater and runoff mathematical models deve-
loped by the University of Tennessee (UT) on data collected
during 1 year at Grissom AFB, Indiana.

    b. Perform an assessment of other available models, and
place the UT models in the context of the present state of the
art.

c. Using the UT models, assess the impact of the air base development and the associated activities on stormwater runoff and its associated quality.

d. Delineate the sources of runoff pollution including air and ground sources.

e. Document the statistical reliability and scope of limitations of the models.

f. Develop an Air Force Runoff Model (AFRUM) to predict the quantity and quality of stormwater runoff from small watersheds on Air Forces bases.

3. EXPERIMENTAL DESIGN

a. Mathematical Modeling

(1) Stormwater - Stormwater is the direct response to rainfall. It is the runoff which enters a ditch, stream, or storm sewer which does not have a significant base-flow component. It has not been assumed that all stormwater reaches an open channel by the overland flow route, although conceptually many of the models do not have an interflow or base-flow component. In urban areas, this should be a realistic approach because of the high degree of imperviousness; however, in some rural watersheds an overland flow component may be nonexistent and direct storm response may be only near the stream and occur as seepage through the banks (References 1 and 2).

As defined herein, stormwater is associated with small upland or headwater sheds where base flow is not a significant proportion of the total flow in the open channel during periods of rainfall. Hence, the attention in this report is directed principally at predicting watershed stormwater discharges as a function of land use and activity rather than predicting the water level along a river. The emphasis herein is upon the storm hydrograph rather than the stage hydrograph.

(2) Mathematical Models - A mathematical model is a quantitative expression of a process or phenomenon being observed, analyzed, or predicted. Since no process can be completely observed, any mathematical expression of a process will involve some element of stochasticism, i.e., uncertainty. Hence, any mathematical model formulated to represent a process or phenomenon will be conceptual to some extent, and the reliability of the model will be based upon the extent to which it can be or has been verified. Model verification is a function of the data available to test scientifically the model and the resources available (time, manpower, and money) to perform the scientific tests. Since time, manpower, and money have finite limits, decisions must be made by planners and engineers as to

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the degree of complexity a model is to have, and the extensiveness of the model verification tests that are to be performed.

The initial task of planners and engineers who use models is to decide which models to use or build, how to verify them and how to determine their statistical reliability in applications, e.g., feasibility, planning, design, or management. This decision-making process is initiated by clearly formulating the objective of the model endeavor and placing it in the context of the available resources on the project for fulfilling the objective.

If the initial model form does not achieve the intended objective, then it becomes a matter of revising the model and repeating the experimental verifications until the project objective is met. Hence, mathematical modeling is by its nature heuristic and iterative. The choice of model revisions as well as the initial model structure will also be heavily affected by the range of choice of modeling concepts available to the modeler, and by the skill which the modeler has or can develop in applying them.

(3) Modeling Approaches - There are two conceptual approaches that have been used in developing stormwater models. An approach often employed in urban planning has been termed deterministic modeling or system simulation. These models have a theoretical structure based upon physical laws and measures of boundary conditions. When conditions are adequately described, the output from such a model should be known with a high degree of certainty. In reality, however, because of the complexity of the stormwater flow process, the number of physical measures required would make a complete model intractable. Simplifications and approximations must therefore be made. This means that the results from usable deterministic models must be verified by being checked against real watershed data wherever such a model is to be applied.

The second conceptual stormwater approach has been termed parametric modeling. In this case, the models are somewhat less rigorously developed and generally simpler in approach. Model parameters are not necessarily defined as measurable physical entities although they are rational. Parameters for these models are determined by fitting the model to hydrologic data usually with an optimization technique.

The two modeling approaches thus appear to be similar, and indeed, for some subcomponent models, the differences are relatively minor. The real difference between the two approaches lies in the number of coefficients or parameters typically involved. The typical deterministic model has more processes included and thus more coefficients to be determined. Because of the inherent interactions among processes in nature, these coefficients become very difficult to determine.

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(4) Complexity of Model - If a highly complex mathematical representation of the system under study is made, either parametric or deterministic, the risk of not representing the system will be minimized, but the difficulty of obtaining a solution will be maximized. Much data will be required, programming effort and computer time will be large, and the general complexity of the mathematical handling may even render the problem formulation intractable. Further, the resource constraints of time, money, and manpower may be exceeded. Hence, the modeler must determine the proper degree of complexity of the mathematical model such that the best problem solution will result and the effort will meet the project constraints. Conversely, if a greatly simplified mathematical model is selected or developed, the risk of not representing the system will be maximized, but the difficulty in obtaining a solution will be minimized. The main point here is that the modeler must make a decision from the range of choice of models available or from the models which could be built.

Figure 1 is called the "trade-off diagram" because it illustrates the consequences of the decision of how complex the model should be. If, after preliminary verification, the initially chosen model is determined to be either too complex or not complex enough, then the modeler may move along the abscissa scale as shown in Figure 1 and try another degree of complexity. This modeling effort should continue until the project obective is attained within the resource constraint.

(5) Model Optimization - Since parametric models are conceptual, a set of unknown coefficients or parameters will appear in the mathematical formulation. The parameter values in the model are experimentally determined in the verification procedure. Intuitively, the proper coefficient values would produce the best fit or linkage between storm rainfall (input) and the stormwater hydrograph (output). An instinctive temptation, which has appeared in modeling literature, is to derive model parameters from observed storms by trial-and-error "eyeballing" best fit procedures. Certain distinct and far reaching disadvantages are associated with this approach to model verification. They are:

(a) If the model is of average complexity, about four or five parameters, a very large number if not an infinite set of coefficients exist which will produce essentially the same fit. Hence, a large operational bias is introduced into the modeling process.

(b) If the goodness of fit between the model and the observed stormwater hydrograph is not quantified, the "eyeballing" technique introduces another operational bias and the same negative effects as above will result.

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RISK OF NOT REPRESENTING THE SYSTEM

DIFFICULTY IN OBTAINING A SOLUTION

COMPLEXITY OF MATHEMATICAL MODEL
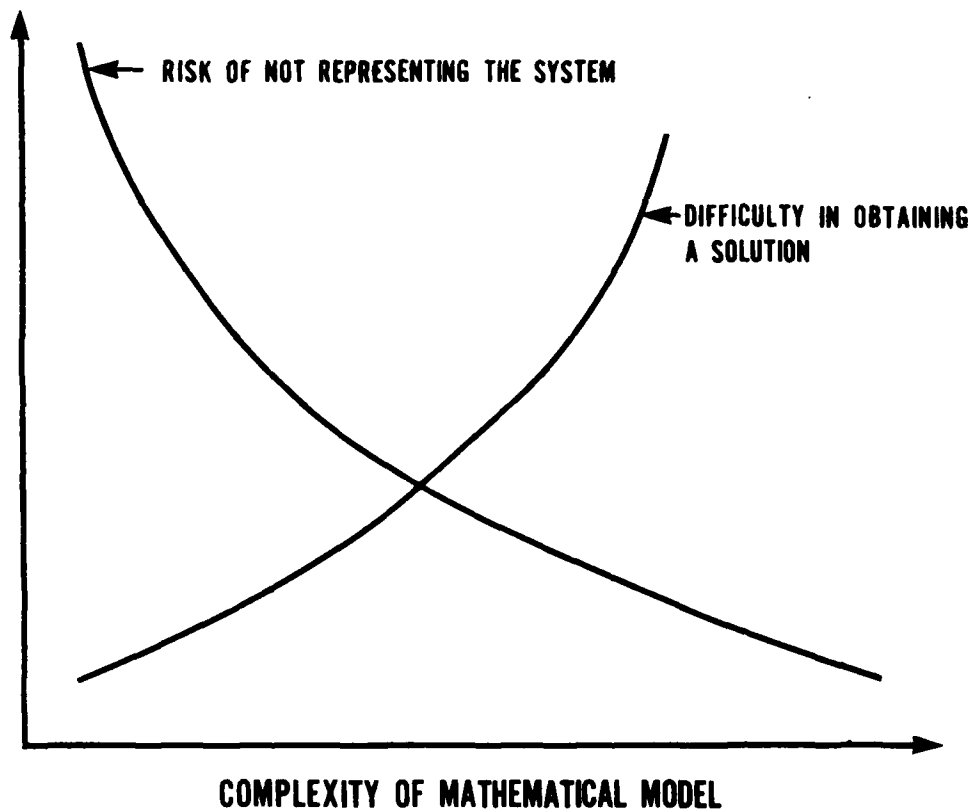
Figure 1.   Trade-off Diagram (After Overton and Meadows [Reference 1]).

(c) The trial-and-error process is very time consuming and inefficient. Time constraints will permit relatively few trials.

The conclusion here is that coefficient optimization in parametric stormwater models is achieved statistically by utilization of objective best fit criteria rather than by trial-and-error "eyeballing" process. However, the size and complexity of a parametric model which can be optimized using an objective best fit criteria has practical limitations.

(6) Sensitivity Analysis - Model verification is not complete without a thorough sensitivity analysis. Once the calibrated parameters are determined by a best fit procedure, sensitivity analysis proceeds by holding all parameters constant but one and perturbating the last one such that variation of the objective function (measure of fit between the observed storm hydrograph and the fitted model) can be examined. If small perturbations of the parameter produce large changes in the objective function, the system is said to be sensitive to that parameter. This gives a measure of how accurately that parameter must be estimated if the model is to be used in prediction. If the objective function is not sensitive to the perturbated parameter, then the parameter need not be accurately estimated in prediction. If the system is extremely insensitive to the perturbated parameter, the parameter and its associated system component may be redundant and could be deleted from the model.

b. Grissom AFB, Indiana

The models used in this study were applied to three small watersheds on Grissom AFB, Indiana. The three areas included residential, airstrip and hangars, and agricultural land uses. Hydrographs and the associated storm rainfall as well as the associated stormwater runoff quality were recorded over a year period. Low flows during nonrainy periods were sampled bi-weekly to develop background runoff water quality data.

Dustfall, i.e., total atmospheric fallout, was collected with one sampler per watershed during rainy and nonrainy periods. Samples were collected monthly.

c. Relation to Other Watershed Experiments

Two other watershed experiments have been underway in the Department of Civil Engineering at the University of Tennessee. The scope of those projects is very similar to this project as each pertains to urbanization (funded by the US Office of Water Resources Technology) and to coal strip mining (funded by the US Department of Energy). The results of this Air Force study will be compared to the results of the two previously mentioned studies. Pooling results will increase the reliability of the models since

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a larger data base will be involved and also will provide a basis for comparing the effects of the various land uses on stormwater runoff.

   d.   Regionalization

   The effectiveness of parametric stormwater models will be measured, in the long run, by the confidence modelers will have in their ability to estimate model parameters on basins which have no hydrologic data for calibrating the model being utilized. A high level of confidence could be achieved if enough bench mark watersheds with hydrologic data were available for analysis. Optimized model parameters for each basin could then be related to physiographic, land use, and climatic characteristics of the study basin. This would permit an interpolation and extrapolation of the results to ungaged basins within the study region at some specified confidence level.

   To regionalize a model means to develop a scientific basis for predicting the model parameters on ungaged watersheds from hydrologic and physiographic characteristics of that watershed. Regionalization can be accomplished if there are enough bench mark watersheds with adequate storm rainfall and stormwater runoff data such that an inference can be drawn.

   Figure 2 indicates the steps involved in parametric modeling; it must be emphasized that the process is heuristic and iterative. After parameter optimization, the conclusion may be drawn that the model has done a poor job of fitting the data, hence, adjustment of the model structure could be made and the experiment repeated. Further, the conclusion could be that, even though the model does a good job of fitting the data, little physical interpretation can be placed on the optimized model parameters. At this point any attempt to regionalize the parameters would be futile; therefore, another adjustment of the model structure would be necessary.

   An objective of this study is to develop a method for transfering the results obtained at Grissom AFB, plus the results from previous modeling studies, to ungaged Air Force bases. There are several component models in AFRUM (i.e., runoff, and water quality), and it will be shown that they may be transferred to ungaged air bases with varying degrees of reliability.

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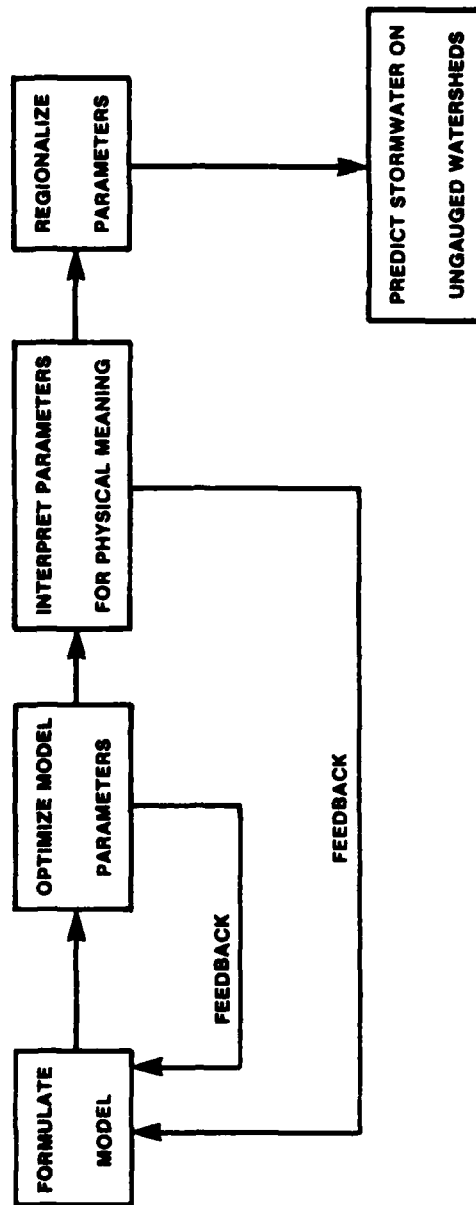
Figure 2. Steps in Parametric Modeling.

The flowchart contains the following boxes connected by arrows:

FORMULATE MODEL → OPTIMIZE MODEL PARAMETERS → INTERPRET PARAMETERS FOR PHYSICAL MEANING → REGIONALIZE PARAMETERS → PREDICT STORMWATER ON UNGAUGED WATERSHEDS

FEEDBACK (from OPTIMIZE MODEL PARAMETERS to FORMULATE MODEL)

FEEDBACK (from INTERPRET PARAMETERS FOR PHYSICAL MEANING to FORMULATE MODEL)

SECTION II

REVIEW OF MATHEMATICAL MODELING APPROACHES

1. ANALYSIS VERSUS SIMULATION

It is essential to the success of any hydrologic assessment to distinguish between analysis and simulation. Analysis is the procedure used to calibrate a model to the data (e.g., input, rainfall; output, runoff). It is an attempt to improve the state of the art and is fundamentally research and development to develop and verify a reliable regionalization scheme for simulating model parameters, data covering a period of years from a number of watersheds or catchments need to be analyzed. Simulation, by contrast, utilizes the results of previous analysis to synthesize runoff quantity and quality form either design or real time rainfall data on ungaged runoff sites. The reliability of the simulated output is a function of the statistical reliability of the mathematical models developed and verified during the analysis phase.

One of the main features of the UT runoff models is that they have an analysis phase and a simulation phase. Either one can be called depending upon the project objective, the data available, and the resource constraints of the project.

2. STORMWATER HYDROGRAPHS AND POLLUTOGRAPHS

a. Brandstetler's Assessment (1976)

(1) Scope of Model Comparisons - Sponsored by the Environmental Protection Agency (EPA), Brandstetler (Reference 3) performed an extensive assessment of mathematical models for the simulation of urban stormwater and combined wastewater flow and quality. The report documents evaluations of 11 models on the basis of information published by the model builders and model users. Seven other models were also tested using both hypothetical and real catchement data.

(2) Summary of Model Comparisons - Extensive tables were reported which compared model structure, including hydrologic simulation capacity for: (a) multiple catchment inflows, (b) dry weather flow, (c) subcatchment precipitation, (d) evaporation, (e) snow accumulation and melt, (f) groundwater simulation, and (g) gutter flow. Input data requirements and computer running times generally decreased with decreasing complexity of the model. Some of the models include options to suppress portions of the simulation if only selected hydrologic phenomena are of interest.

Model testing with hypothetical data showed that computer running time was governed more by efficient formulations

of the overall model logic than by the basic equations used for specific phenomena. Various models stood out due to their completeness in hydrologic and hydraulic formulations, the ease of input data preparation, the efficiency of computational algorithms, and the accuracy of the program output.

(3) Recommendations - The following models were recommended for routine applications:

(a) Batelle Urban Wastewater Management Model

(b) Corps of Engineers "STORM" Model

(c) Dorsch Consult Hydrograph Volume Method

(d) EPA Stormwater ("SWMM")

(e) Hydrocomp Simulation Program

(f) M.I.T. Simulation Program

(g) Seattle Computer Augmented Treatment and Disposal System

(h) SOGREAH Looped Sewer Model

(i) Water Resources Engineers SWMM

(4) Assessment of Brandstetler's Assessment - The models which Brandstetler assessed were simulation models, not analysis models. The models were also developed for urban areas with heavy emphasis on storm and combined sewer flow. Most of the models assume that sheet surface runoff is pervasive. This is true in various degrees in urban areas, but the assumption breaks down in rural areas where studies have shown that surface runoff may not occur and that the entire watershed may not contribute to channel flow (References 1 and 2).

There are three significant limitations which apply to all of the models evaluated by Brandstetler. First, very few of the models have been extensively tested with results reported in open literature. Second, the models do not have analysis phases whereby coefficients can be readily optimized. Third, most of the models are not applicable to rural areas. The models have not been evaluated on rural data because the fundamental assumptions of sheet surface runoff do no apply to rural areas.

b. University of Tennessee (UT) and Tennessee Valley Authority (TVA) Models (1973-79).

(1) Relation to Brandstetler's Assessment - The models developed by UT and TVA were not reviewed by Brandstetler. The

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TVA model documentation was not reported until 1973 (Reference 4) and it was evaluated on rural data only. This model, called the TVA Double Triangle Model (DTM), was extended to urban data in a 1976 report (Reference 5). Hence, there was no opportunity for Brandstetler's review. Further, the model is parametric and has no present capability for simulating combined sewer overflows which was of interest to Brandstetler.

(2) Hydrograph Analysis (TVA DTM) - The DTM has two basic components: the US Soil Conservation Service Curve Number (SCS-CN) model for generating rainfall excess from rainfall, and it has a unit response function (URF) or unit hydrograph which is composed of the sum of two triangles. The model structure is summarized below:

(a) Rainfall Excess - The model used for distributing rainfall excess over the duration of the storm is the SCS-CN model (Reference 6). This method relates accumulated values of rainfall, direct runoff volume, and infiltration plus initial abstraction (depression storage and vegetation interceptor). The curve number method assumes that

$$\frac{F}{S} = \frac{SRO}{P_e} \tag{1}$$

where F is the infiltration occurring after runoff begins in inches, S is the potential abstraction in inches, SRO is the actual direct runoff in inches, i.e., the storm rainfall minus the initial abstraction, IA, and P_e is the potential runoff or effective storm runoff in inches. Since infiltration can be expressed as

$$F = P_e - SRO \tag{2}$$

Equation (1) can be expressed as

$$SRO = \frac{P_e^2}{P_e + S} \tag{3}$$

The IA has been estimated by SCS from an empirical relation based on data from small watersheds to be

$$IA = 0.2(S) \tag{4}$$

Thus

$$P_e = P - IA = P - 0.2(S) \tag{5}$$

where P is the total storm rainfall in inches. Substituting Equation (5) into Equation (3) gives the following relation for accumulated runoff

$$SRO = \frac{(P-0.2\ S)^2}{P + 0.8S} \qquad (6)$$

Potential abstraction (maximum potential retention), S, is related to the SCS curve number, CN, by definition as,

$$CN = \frac{1000}{S + 10} \qquad (7)$$

for which $\quad S = \dfrac{1000}{CN} - 10 \qquad (8)$

For a time distribution Equation (6) becomes

$$SRO_i = \frac{(P_i - 0.2\ S)^2}{(P_i + 0.8\ S)} \qquad (9)$$

where SRO_i is the total storm runoff to time i and P_i is the accumulated rainfall to time i. The distribution of rainfall excess over time is then determined by the following equation

$$P_{e_i} = SRO_i - SRO_{i-1} \qquad (10)$$

where P_{e_i} is the rainfall excess from time i-1 to i. CN for each storm analyzed is first calculated by computing S from Equation (6) and then computing CN from Equation (7). These variables are illustrated in Figure 3.

     (b) Unit Response Function (URF) - Ardis (Reference 4) has found that many URF shapes varied considerably among and within watersheds and that a quadrilateral URF was based on the concept of partial area runoff which assumes that the initial or quick response from a watershed comes from the riparian areas. As other areas of the watershed become saturated, they too begin to contribute to runoff in the form of a delayed response. This concept has been recognized and explored by Betson (Reference 2), Dunne and Black (Reference 7), and Betson and Marius (Reference 8).

     Ardis (Reference 4) assumed that these two responses could be simulated by two separate triangle response functions. When added together, these two triangles form a quadrilateral URF for the storm as shown in Figure 4.

     Symbols used in the figures are:

I = Precipitation excess intensity in inches per hour. Since the volume of input is one basin-inch I = 1/DT.

DT = Time interval used in abstracting rainfall and discharge record in hours.

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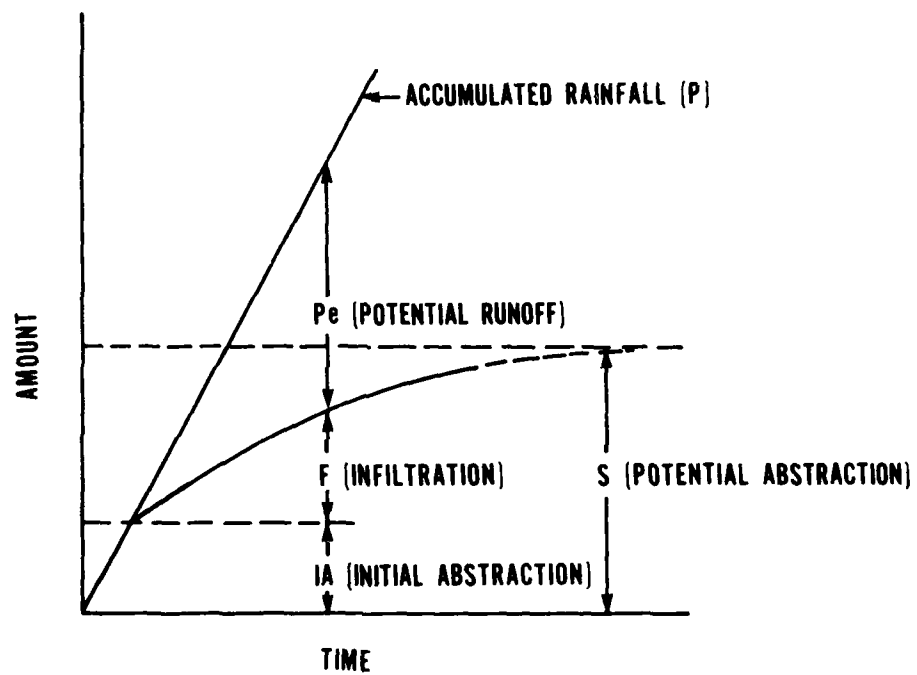
Figure 3. Schematic Relating Rainfall, Potential Rainfall, Infiltration, and Initial Abstraction.

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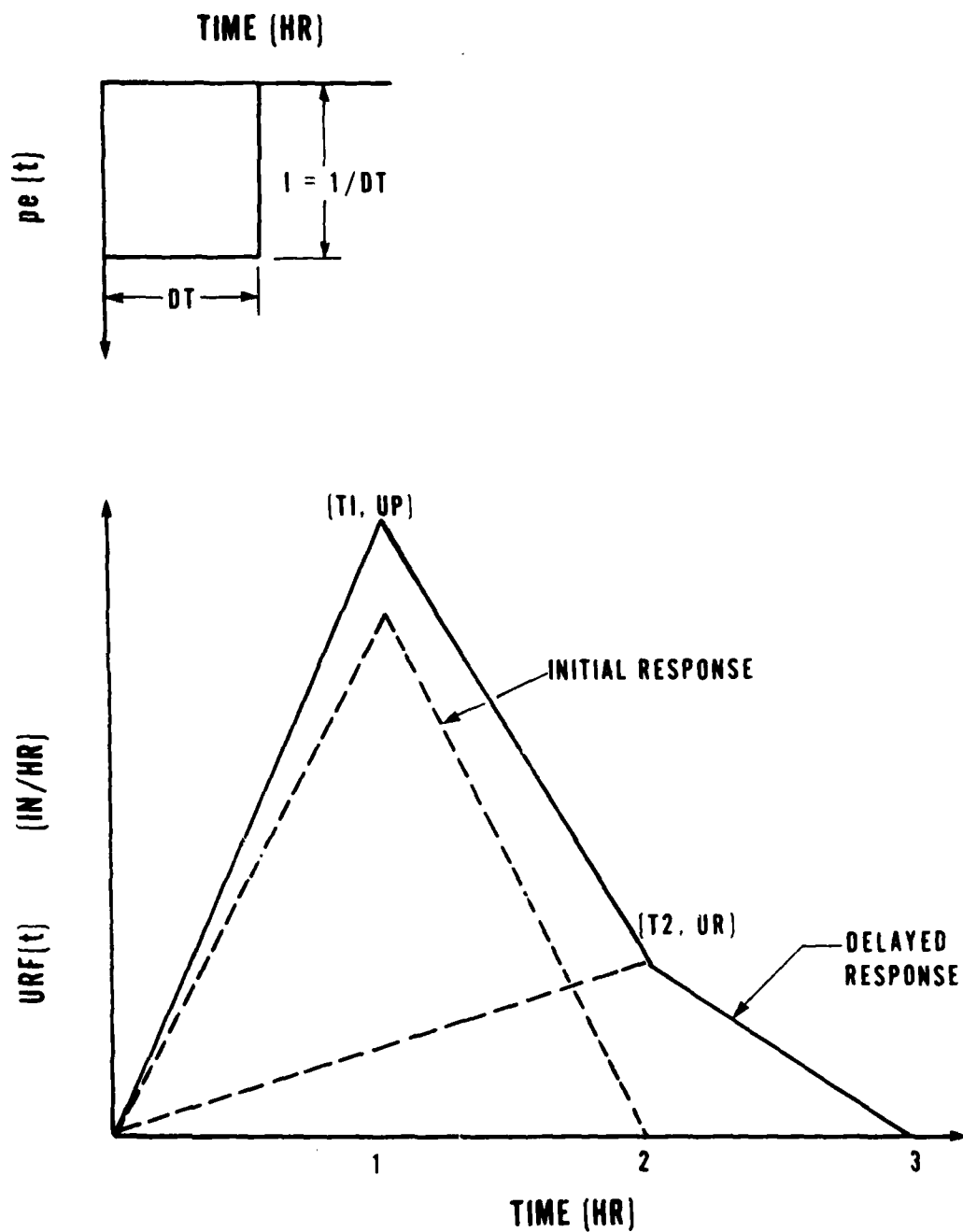
Figure 4. Double Triangle Model for Unit Response Function.

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UP = peak of URF at T1

UR = peak of delayed response at T2

T1 = Time to peak of initial response, hours

T2 = Time base of initial response and equal to the time of peak delayed response, hours

T3 = Time to end of delayed response, hours

pe(t) = precipitation excess as a function of time, t, in inches per hour

urf(t) = URF ordinate as a function of time, t, in inches per hour.

In deriving the URF, it was assumed that (a) the peak of the delayed response (UR) occurs at the end of the initial response (T2), and (b) the time bases of both responses and the time to peak of the initial response (T1) must be integer multiples of DT. No assumption was made concerning the relative volumes contained in the initial and delayed responses or concerning the relative magnitudes of the peaks of the initial responses. The URF is defined by five parameters UP, UR, T1, T2 and T3.

T3 is determined by:

$$T3 = (NOBS - NRAIN + 1)*DT \qquad (11)$$

where NOBS = number of storm hydrograph ordinates in multiples of DT and NRAIN = number of rainfall increments in multiples of DT. By maintaining a unit volume, UR is calculated from Figure 4:

$$UR = (2 - (UP*T2))/(T3-T1) \qquad (12)$$

Defining a storm URF therefore involves determining values of UP, T1, and T2.

(c) Model Optimization - The parameters UP, T1, and T2 were optimized using the pattern search technique developed by Green (Reference 9). The objective function was the minimization of the sum-of-squares of errors between observed and simulated discharges. Since all five parameters describing the model were allowed to vary from storm to storm, the model is considered nonlinear. Rainfall excess, P_e, was optimized using the SCS-CN model after setting it equal to the observed direct runoff volume.

(3) Analysis of Watersheds - Ardis (Reference 4) analyzed 140 storms from 11 watersheds within the Tennessee Valley

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and determined optimum values for each of the parameters of the DTM hydrograph. The model was then regionalized by using step-wise multiple regression to relate the storm hydrograph model parameters to watershed characteristics and storm variables. Betson (Reference 5) modified the regionalization scheme utilizing 13 additional watersheds. His data set included 18 rural and 6 urban watersheds. The watershed characteristics and storm variables used by Betson in his regionalization scheme were: drainage area, length of main stream squared divided by drainage area, main channel slope, drainage density, sinuosity, percent forest, SCS-CN, and an index of the extent of storm sewers in the watershed. An attempt to incorporate nonlinearity was made by including storm rainfall and duration as independent variables in the regionalization scheme.

The analysis was extended to 42 additional storms in 2 of the urban watersheds (Reference 10) and to 54 storms in 4 small watersheds in New River, Tennessee (Reference 11). Three of the New River watersheds have undergone coal strip mining and one is 100 percent forested. Hence, to date 455 storms have been analyzed using the TVA DTM. These latter two studies were performed in the Department of Civil Engineering at the University of Tennessee.

(4) Parameter Regionalization - In the latter two studies mentioned in the above section (References 10 and 11) a regionalization scheme was developed which relates the model parameters to watershed physical and land use characteristics and storm rainfall characteristics. The watershed and land use characteristics involved are:

      (a) Percent of surface area in forest (PF)

      (b) Percent of surface area in imperviousness (PI)

      (c) Percent of surface area in strip mining (PS)

      (d) Surface area in square miles (AREA)

      (e) Soil type

      (f) Land use (agricultural, forested, ubran or strip mined)

3. HYDROGRAPH SIMULATION (TENN-1)

a. Nonlinearity of Runoff Response

Using the results of the hydrograph analysis, a storm-water runoff simulation model was developed. The model is called the University of Tennessee Hydrograph Simulation Model or TENN-I. The shapes of the optimized URFs for the same watersheds exhibited wide variation from storm to storm. If the URF was constant from storm to storm, holding land use constant, the

system would be linear. Since this is not so, the system is nonlinear and its response varies with the associated storm rainfall characteristics (Reference 1).

This nonlinear response variation can be explained by the variation in the hydrograph lag time, TL. TL is defined as the time lapse between the occurrence of 50 percent of the rainfall excess and 50 percent of the runoff volume. It is assumed, and generally found to be true, that TL does not significantly vary within a storm. The quantification of the variation of the optimized URFs within and among the study watersheds will be explained in the following section.

b. Analogy with Sheet Surface Runoff

(1) Kinematic Wave Model - The state of the art in modeling sheet surface runoff is highly advanced. The runoff response of overland flow is known to be highly nonlinear and is well understood. Overland flow and catchment flow can be accurately simulated using the one dimensional equations of conservation of mass and momentum (Reference 1). It is also known that overland flow under most conditions encountered in nature is kinematic rather than dynamic. This means that flows are essentially unsteady, but uniform. Hence, there is no significant backwater effect and the fluid is not appreciably accelerating (Reference 1).

Lag time for overland flow and for idealized surface runoff systems can be derived from the kinematic wave equations. Further, variation in the URFs is accurately explained by the associated lag time.

(2) Normalized URF (NURF) - Lag time is shortest for the URF with the highest peak flow and longest for the URF with the lowest peak flow. Hence, normalized unit response functions (NURF) were derived for each watershed studied by dividing the time scales of the optimized URFs with its associated lag time and multiplying the the ordinate scale by its associated lag time (References 10 and 11). This operation was originally performed for overland flow (Reference 15).

NURFs for each study watershed were derived, and their variations were examined. Attempts were made to relate the coordinates of the NURFs to watershed characteristics. By far, the best relations were found by simply averaging the coordinates for (a) the 8 watersheds in the 100 percent forested condition, (b) the 6 urban watersheds, (c) the 12 agricultural watersheds, and (d) the 3 strip mined watersheds. None of the aforementioned models tried could explain more than 20 percent of the variations of the NURF within each of the four watershed groups. Further, the average NURF for the agricultural group was nearly identical to that obtained from the average NURF for the urban group.

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To offer some perspective to these results, the NURF for the four groups are plotted in Figure 5 with the NURF for sheet surface runoff derived by Overton (Reference 15). For sheet runoff from a uniform plane and V-shaped watershed, the NURF has no delayed response (DR) and a much higher peak than the watershed NURFs. This comparison reinforces the idea of the watershed being a heavily damped system. It is reasonable that 100 percent forested areas would produce a DR larger than urban and agricultural wastesheds. The urban watershed, on the average, produced a higher DR than the agricultural watersheds perhaps due to the drainage retention in the urban stormwater drainage systems.

(3) Lag Modulus - Variation of lag time (in minutes) within and among plane surfaces has been derived from the kinematic wave equations as:

$$TL = \frac{0.58}{i_e^{0.4}} \cdot \left[\frac{nL}{S_o}\right]^{0.6} \tag{13}$$

where:

n = Manning resistance coefficient

L = length of plane

S_o = slope of plane, and

i_e = rainfall excess rate, (inches/hr.)

Equation (13) can be written as:

$$TL = \mu/i_e^{0.4} \tag{14}$$

Where μ is the lag modulus (Reference 16) and is equal to the lag time of a runoff system for a unit input intensity. Hence, lag modulus is a catchment characteristic and independent of storm characteristics. The variation of runoff response among watersheds, therefore, can be explained by relating lag modulus to watershed characteristics.

(4) Regionalization of Watershed Lag Modulus - Lag modulus for each of the watersheds was optimized by least squares, by relating lag time for each storm to the associated storm weighted rainfall excess intensity, REI.

$$TL = \mu/REI^{0.4} \tag{15}$$

The exponent, n, was set at 0.4 to standardize watershed lag moduli values with sheet surface runoff. REI was weighted to allow large bursts of rain excess to contribute a greater percentage to the uniform weighted rainfall excess. The weighted rainfall excess intensity is defined by the following equation:
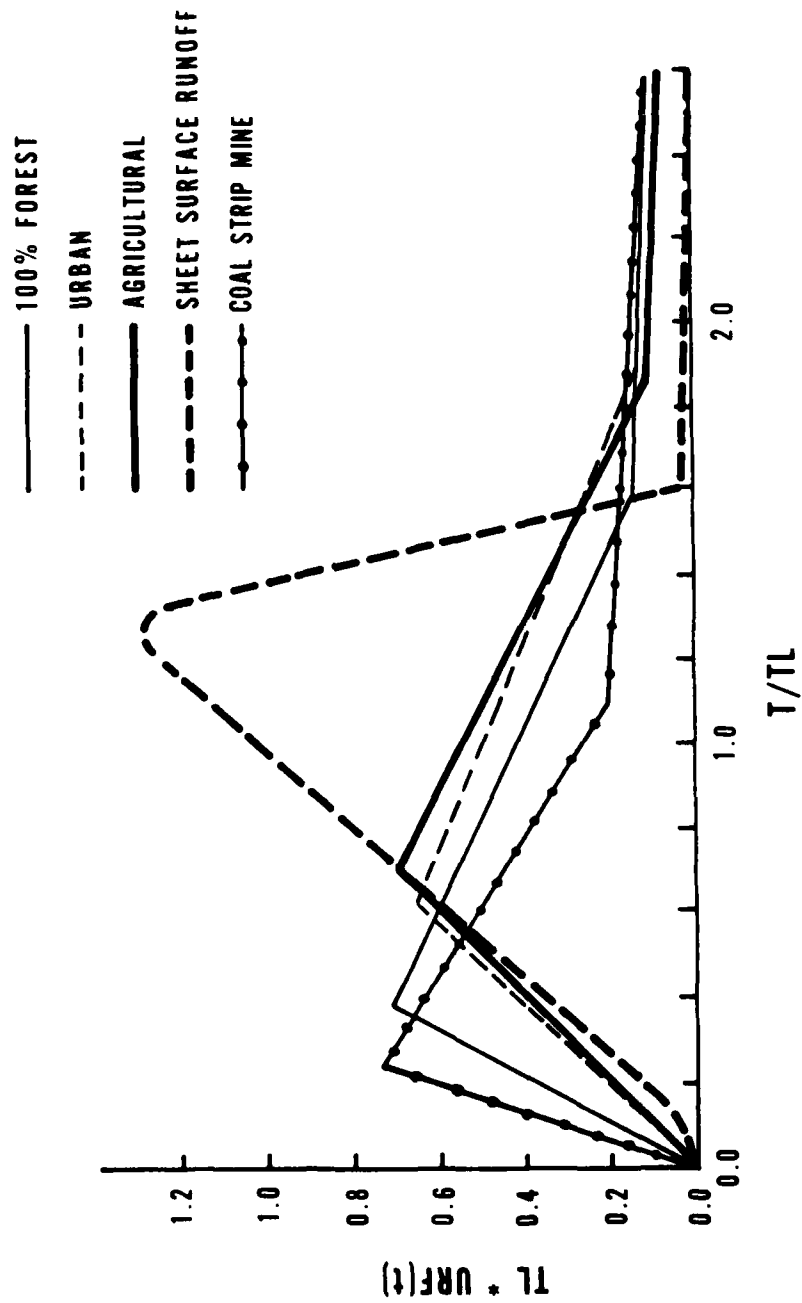
Figure 5. Average Normalized Unit Response Functions (NURFs) for Different Watershed Groups

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$$REI = \sum_{j=1}^{N} (i_{ej}^{2}) / \sum_{j=1}^{N} (i_{ej}) \qquad (16)$$

where i_e is rainfall excess rate at time j and N is the number of increments of i_e.

The data were grouped into urban and rural land use, and a separate model was optimized for each. Principal components regression was utilized to optimize the rural model, since there were some interrelations among the parameters. The result was:

$$\mu(\text{hours}) = 0.0600 * AREA + 0.0203 * PF + 1.16 \qquad (17)$$

$$R^2 = 0.723; \quad SEE = 1.08 \text{ hr}; \quad N = 20$$

For 100 percent forested watersheds, Equation (17) indicates that lag modulus depends directly on surface drainage area.

For the six urban watersheds, a different form of the lag modulus was optimized. It was placed in the form of lag modulus for a uniform plane. AREA is an index of length of overland flow, PI should be inversely related to basin roughness in urban areas, and the range of average watershed slope in the urban sample was small. Hence, the lag modulus was optimized as

$$\mu(\text{hours}) = 3.24 \, [AREA/PI]^{0.6} \qquad (18)$$

$$R^2 = 0.936; \quad SEE = 0.135; \quad N = 6$$

where PI is percent impervious.

SEE is the standard error of estimate and R is the correlation coefficient.

c. Simulation Procedure

The final form of the storm hydrograph simulation model was completed using the results of the previously described analysis. The model, called TENN-I, proceeds as follows:

(1) READ storm rainfall in intervals of DT, $i(t)$

(2) READ SCS-CN

(3) READ AREA, PF or PI

(4) COMPUTE rainfall excess time distribution $i_e(t)$, using $i(t)$ and CN.

(5) COMPUTE weighted rainfall excess intensity, REI, Equation (16).

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(6) COMPUTE lag modulus, μ, from either Equation (17) or (18).

(7) COMPUTE lag time for the storm, TL, from Equation (15).

(8) Enter TABLE LOOK-UP for the coordinates of the NURF, and COMPUTE coordinates for this storm by dividing the ordinate scale by TL and multiplying the time scale by TL.

(9) CONVOLUTE i_e (t) with URF to obtain the simulated storm hydrograph.

d. Limitation and Reliability

TENN-I has been shown to be an effective simulator of hydrographs in various split data tests (References 10 and 11). The ability of TENN-I to simulate hydrograph shape and timing has been tested. TENN-I should be highly reliable in most of the rural Eastern United States except in flatwoods and plain states, i.e., flatter areas that were not utilized in the samples analyzed.

4. POLLUTOGRAPH ANALYSIS USING UT MASS BALANCE MODEL (TMBM-I)

A pollutant yield model has been developed for small watersheds undergoing coal strip mining (Reference 10) and for urbanization (Reference 11). This analysis model, known as TMBM-I analyzes the pollutograph, i.e., the load rate curve and hydrograph associated with storm hydrographs. The linkage of the pollutograph and the hydrograph is accomplished through the use of a load modulus. This load modulus was derived for the watershed as a function of selected watershed characteristics.

a. Model Structure and Optimization

If the concentration of the pollutant is known, then the instantaneous load rate can be related to the basin hydrograph as follows:

$$SL = \delta_L Q \tag{19}$$

where SL is the instantaneous load rate in units of mass per time, Q is the hydrograph in units of volume per time, and δ_L is a concentration relating mass of sediment to volume of flow. Under conditions of low flow, δ_L varies substantially. But under storm conditions there is evidence that δ_L is constant. Rainulator tests on erosion plots indicate that the concentration is essentially constant for steady rainfall excess (Reference 17). It has been further postulated (Reference 17) that the sediment concentration would approach constant values during high

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storm flows because the flow transport capacity would be approached. The high concentrations and flows are of interest. Using this premise, a study of five urban watersheds in Tennessee and Kentucky during storm conditions has shown that the suspended sediment load appears to be related to storm flow by a constant value (Reference 17). Hence, the suspended sediment yield, SY, model for mined basins was selected to be

$$SY = \mu_W \, Q \tag{20}$$

where μ_W is the watershed load modulus or analogous constant concentration (Reference 18).

The load modulus for the watershed pollutant yield model was formulated from a mass balance of the suspended load within a watershed. Under this concept, it can be reasoned that the watershed suspended load results from the summation of the pollutant loads produced, deposited and stored within the watershed. Hence the watershed suspended load, L_W, for a storm could be expressed as

$$L_W = L_S + L_B - L_D \tag{21}$$

where L_S is the load stored, L_B is the load produced from source areas, and L_D is the load deposited in the watershed.

Further, the watershed load may be represented as

$$L_W = \mu_W \, RD_W \, A_W \tag{22}$$

where μ_W is the watershed load modulus in units of mass per surface area per depth of surface runoff volume, RD_W is the watershed surface runoff volume as depth, and A_W is the watershed drainage area.

The source load was expressed as

$$L_B = \mu_B \, RD_B \, A_B \tag{23}$$

where μ_B is the source load modulus in units of mass per surface area per surface runoff volume as depth, RD_B is the source surface runoff volume as depth, and A_B is the source area of the pollutant.

The deposited load in strip mined watersheds and forested areas can be expressed as

$$L_D = \mu_D \, RD_F \, A_F \tag{24}$$

where L_D is the watershed deposition modulus in units of mass per surface area per surface volume runoff as depth, RD_F is the surface runoff volume in depth from the deposition area, and A_F is

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the deposited area. Combining Equations (21), (22), (23) and (24) results in

$$\mu_W = \left[\mu_B \; (\frac{RD_B}{RD_W}) \cdot (\frac{A_B}{A_W}) \right] - \left[\mu_D \; (\frac{RD_F}{RD_W}) + \frac{L_S}{RD_W \, A_W} \right] \quad (25)$$

The surface runoff ratios in Equation (25), RD_B/RD_W and RD_F/RD_W, are considered storm constants. The area ratios can further be expressed as percentages using the following:

$$PF = 100 \left(\frac{A_F}{A_W} \right) \quad (26)$$

$$PS = 100 \left(\frac{A_B}{A_W} \right) \quad (27)$$

where PF is the percent of watershed forested or in which the pollutant was deposited, and PS is the percentage of watershed mined or in which source erosion occurs. This allows Equation (25) to be represented as

$$\mu_W = C_1 \, PS - C_2 \; PF + C_3 \quad (28)$$

where $\quad C_1 = \mu_B \; RD_B/(100*RD_W) \quad (29a)$

$$C_2 = \mu_d \; RD_f/(100*RD_W) \quad (29b)$$

and $\quad C_3 = L_S/RD_W A_W \quad (29c)$

In equation (29b), it has been assumed that μ_d is proportional to the lag modulus, μ. To illustrate, if the area for deposition were paved, μ would decrease as would μ_d.

C_1 is an index of source load generated per percent watershed mined or impervious. C_2 is an index of the load stored in the watershed that is available for transport when the transport capability of the flow has not been filled, e.g., an average background level of suspended sediment.

Equation (28) provides a model for simulating load modulus as a function of three constants and two measurable basin quantities, percent forest and percent mined. The coefficients C_1, C_2, and C_3 were optimized from observed watershed data. These constants were related to strip mining practice, i.e., changing land use, overburden characteristics, and physiographic measures of a watershed.

Once μ_B has been determined the suspended yield may be determined by convoluting the load modulus with the hydrograph to

produce the loadograph. The total storm load may be determined
by integrating the loadograph over time.

b. Analysis of Urban and Coal Strip Mined Watersheds

TMBM-I was optimized on six small watersheds in New
River, Tennessee (five undergoing coal strip mining (Reference
10) and one 100 percent forested and five small urban watersheds
(four in Knoxville, TN, and one in Durham, NC) (Reference 11).
Lag modulus for each watershed was optimized from the storm data
and served as input to TMBM-I. Two distinct sets of coefficients
were obtained for strip mining and urbanization.

c. Parameter Regionalization

The results of the previously mentioned analyses
(References 10 and 11) are in themselves a regionalization. Lag
modulus has been regionalized and PF, PS, or PI are also regional
input. The optimized source, storage, and deposition coef-
ficients should be reliable in much of the Appalachian strip
mining and perhaps in associated urban areas also.

In similar analyses, magnesium, manganese, calcium and
iron have been found to be strongly correlated ($R^2>.90$) with
either PS or PI. This indicates very high delivery ratios since
the deposition and storage coefficients were negligibly small as
compared to the source term in both mined and urban watersheds.

5. POLLUTOGRAPH SIMULATION (LOAD-I)

a. Simulation Procedure

The simulation phase of TMBM-I is LOAD-I. Presently
LOAD-I simulates the storm pollutograph, loadograph, and total
load for urban, 100 percent forested, and coal strip mined
watersheds. The following water quality constituents are
simulated:

(1) Total suspended solids

(2) Total iron

(3) Total manganese

(4) Total calcium

(5) Total magnesium

(6) Total alkalinity

(7) Total sulfate

(8) pH

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The simulation procedures is as follows:

    (1)   Input (a) PS or PI (percent)

                (b) PF (percent)

                (c) specify land use

                (d) watershed area (square miles)

    (2)   Predict lag modulus (hour)

    (3)   Predict load modulus (pound/acre-in runoff)

    (4)   Multiply load modulus by the TENN-I hydrograph to obtain pollutograph (pound/second)

    (5)   Integrate pollutograph to obtain loadograph and total load.

b.   Limitations and Reliability

LOAD-I is most reliable in Appalachian coal regions and urban areas. Additional data sets from other regions would extend the reliability to TENN-1 and LOAD-I.

6. EPA STORMWATER MANAGEMENT MODEL (SWMM)

a.   Runoff Block

There are four major blocks in the SWMM model (Reference 21) runoff, transport, storage/treatment, and receiving water. The latter two blocks are not relevant to this project and they will not be reviewed. The runoff block simulates surface runoff from rainfall hyetographs, antecedent conditions, land use, and topography. This block also simulates dry weather flow based on land use, population density, and other factors. Infiltration into the sewer system is simulated based on available groundwater and sewer conditions.

    (1)   Rainfall Excess - In order to simulate infiltration and direct runoff, rainfall is converted to water depths at the watershed surface. The depth of flow may be expressed as:

$$D_1 = D_t + R\Delta t \tag{30}$$

where D_1 = water depth after waterfall

        D_t = water depth of the subcatchment at time, t

R_t = intensity of rainfall in time interval, Δt.

Infiltration is simulated by Horton's exponential function, which may be written as

$$I_t = f_o + (f_i - f_o) e^{-at} \qquad (31)$$

where I_t is infiltration at time t and f_o, f_i, and a are coefficients in Horton's model (Reference 21).

Excess runoff, or depth of flow, is computed by the following equation:

$$D_2 = D_1 - I_t \Delta t \qquad (32)$$

where D_2 is water depth after accounting for infiltration and D_1 is water depth before accounting for infiltration.

(2) Runoff Response - SWMM has the capability of dividing a watershed into subcatchments and computing runoff from each of the subcatchments. Overland, gutter, and pipe flows are simulated by Manning's equation, or:

$$V = \frac{1.49}{n} (D_t)^{2/3} S^{1/2} \qquad (33)$$

and

$$Q_W = V\ W\ D_t \qquad (34)$$

where V = velocity of flow

n = Manning's resistance coefficient

S = ground slope

W = width

Q_W = outflow rate

Inflow to a gutter or main channel is computed by summing all outflow rates from upstream subcatchments and flow rates of immediate upstream gutters. This flow becomes the discharge hydrograph at the outlet of the watershed.

(3) Water Quality Response - SWMM simulates the amount of contaminants allowed to accumulate on the ground prior to the storm, and then, taking into account rainfall intensity, major land use, and land slope, the washed off pollutants are routed through any gutter or pipes to generate pollutographs at inlet manholes. The constituents simulated are: 5-day Biochemical Oxygen Demand (BOD), total suspended solids (TSS), total

coliforms (represented as a conservative pollutant), and dissolved oxygen (DO). Erosion is simulated by the Universal Soil Loss Equation (Reference 22).

b. Transport Block

Routing of hydrographs and pollutographs through the sewer system is performed in the transport block. Transport accepts as inputs outputs from the runoff block. The hydrograph routing is performed by the kinematic wave model adapted for pipe flow. The model involves a solution of the conservation of mass equation and Manning's equation. Essentially this is the same routing procedure as in runoff block.

c. Simulation Procedure

Two major steps are involved in simulating storm hydrographs using SWMM: (a) determining the geometric representation of the drainage basin and (b) estimating the coefficients used in the model. If coefficients for the drainage basin are not known, default values are available in SWMM.

(1) Input Requirements - In this study, none of the model coefficients were known, thus only default values were used. Thus, the inputs to SWMM were limited to physical and hydraulic descriptions of the watersheds.

The inputs were: average width of overland flow, percent impervious, slopes of overland flow, gutters, pipes and open channels, and land use, i.e., single family residential, multi-family residential, commercial, industrial, and undeveloped or parklands.

(2) Discretization - SWMM is capable of representing the watershed as a network of hydraulic elements such as subcatchments, gutters, and pipes. Watershed geometry may be described by one of two approaches: (a) a coarse or (b) fine discretization. A fine discretization may result in the drainage area being broken down into several subcatchments containing all major transport systems within the watershed. A coarse discretization is a more unrestrained approach for describing the watershed, thereby reducing the number of transport systems used in simulation. Both fine and coarse discretizations were utilized in simulating stormwater on the three Grissom AFB watersheds.

7. CORPS OF ENGINEERS MODEL (STORM)

STORM was developed by Water Resources Engineers, Inc. for the US Army Corp of Engineers (Reference 23). This model uses three methods to simulate precipitation excess; a runoff coefficient, a SCS-CN method, and a combination of the first two methods. The resulting direct runoff is convoluted with the SCS single triangle URF to produce the simulated storm hydrograph.

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STORM is a continuous simulation package capable of predicting flows for long durations. Therefore, precipitation data are read in at hourly time steps for any time period to be modeled. For this study, all recorded rainfall data, which cover approximately 6 continuous months, were read into STORM.

a. Model Structure

(1) Rainfall Excess - STORM simulates rainfall excess by one of three methods: the coefficient method, the SCS-CN technique, or a combination of the two. The coefficient method assumes a certain fraction of rainfall becomes runoff. The SCS-CN technique, as previously described, is based upon a curvilinear relationship between rainfall and runoff. The third method uses the coefficient method on impervious areas and the SCS-CN on pervious areas, weighting the sum according to the percent impervious of the entire watershed.

(2) Runoff Response - The triangular shaped unit hydrograph, developed by the SCS (Reference 6), shown in Figure 15, is used in STORM to route rainfall excess to the outfall. Only two additional variables are required to use this procedure: (1) the time of concentration of the basin and (2) the ratio of time to recession to time of peak of the unit hydrograph. The equations which describe the characteristics of the unit hydrograph are:

$$T_p = 0.5 + 0.6 \, T_c \tag{35}$$

$$K = 2/(1 + T_r/T_p) \tag{36}$$

$$Q_p = [1.00833 \, (KAQ)]/T_p \tag{37}$$

where T_p = time to peak of the unit hydrograph in hours,

T_c = time of concentration of the subbasin in hours,

T_r = time of recession of the unit hydrograph in hours,

A = drainage area,

Q = one inch of surface runoff, and

Q_p = unit hydrograph peak in cubic feet per second.

For this study, the value read into STORM for the ratio of time to recession to time of peak was 1.67; the value read in for the time of concentration was 1.5. These values are suggested by the builders of STORM when unit hydrograph characteristics of the watershed are unknown. Once the SCS unit hydrograph is defined, rainfall excess is convoluted at one hour time steps to obtain the simulated stormwater hydrograph.

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(3) Continuous Simulation - The SCS-CN method is based upon the relationship previously described, and may be written as Equation (6). Since STORM is a continuous simulation model, losses such as evapotranspiration, infiltration, and percolation during periods of no rain are simulated. The model computes soil moisture capacity (deficit) at the beginning of each time increment by the following equation:

$$S_t = S_{t-1} - IN * \Delta t + A * EV * \Delta t + B * MP * \Delta t \qquad (38)$$

where $A = 0.7 \ [(SM-S_{t-1})/SM]^v$

$B = [(SM-S_{t-1})/SM]^p$

S = soil moisture capacity for storage of water in inches

IN = maximum infiltration rate from initial abstraction in inches/hour

EV = pan evaporation rate in inches/hour

MP = maximum soil percolation rate in inches/hour

SM = maximum soil capacity for storage of water in inches

v = exponent regulating evapotranspiration

p = exponent regulating percolation.

Default values for these parameters were suggested by the builders of STORM for different land uses in order to account for rainfall losses to the soil. Soil properties and percent imperviousness for each land use are used by the model to simulate total rainfall losses. Infiltration values for soil properties suggested by the model builders for different land uses in this study were read into STORM. Pan evaporation rates were obtained from the National Weather Service.

(4) Water Quality Response - Water quality simulations in STORM are very similar to those of SWMM, and the constituents simulated are also essentially the same as for SWMM. But as with SWMM, the models and associated coefficients are only based upon a study in Chicago on street surface contaminants and not on watershed production. All default values in the model were utilized in simulating pollutographs.

b. Simulation Procedure

With the exception of the default values, the input requirements to STORM are storm rainfall at one hour time intervals, land use, and the percentages of range, commercial, unimproved land, and single and multiple use residential areas.

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Since STORM is a lumped rather than distributed system model, the land use characteristics are lumped together after being weighted. As can be seen from these descriptions, there are similarities between TENN-I and STORM.

SECTION III

APPLICATION OF MODELS TO GRISSOM AFB, INDIANA

1. DESCRIPTION OF BASE

a. Location

Three watersheds located at Grissom Air Force Base were used as the study basins. Grissom Air Force Base is located in north central Indiana and within the Wabash River watershed. Land use on the watersheds remained constant during the study period.

Land use varied from watershed to watershed. McDowell Ditch watershed is the largest of the three and contains the main runway, aircraft and maintenance buildings, and land used for pasture. Cline Ditch watershed contains a large residential area, a wooded area, and commerical buildings. East Ditch watershed contains apron space for aircraft, commercial buildings, and land used for agricultural activities. The base has extensive storm sewers.

b. Soils and Geology

Two types of soil exist at Grissom Air Force Base, Brookston silty clay loam and Fincastle silt loam. Brookston silty clay loam is a deep, poorly drained soil with a high available water capacity and organic matter content. This soil is usually located in valleys or on broad flats. Fincastle silt loam is a deep, somewhat poorly drained soil with a high available water capacity and a moderate organic content. It is usually located on gentle slopes. Both types of soil have low permeability.

c. Climate

Climate at Grissom Air Force Base is moderate. The average temperature is 50°F and the mean annual rainfall is 35 inches. The majority of the precipitation occurs in late spring and early summer. Historically, the maximum rainfall to occur in 24 hours was 4.5 inches, which is comparable to a 26 year return period storm. Snowfall, which occurs the heaviest in January and February, averages 28 inches annually.

2. EXPERIMENTAL DESIGN

a. Watersheds Sampled

Physical characteristics of the three watersheds instrumented are shown in Table 1. Each watershed has a high degree of imperviousness (20 to 25 percent) which is characteristic of

urban areas. McDowell Ditch and East Ditch watersheds have extensive drainage ditches excavated with some storm sewers, while the Cline Ditch watershed has extensive storm sewers.

TABLE 1. PHYSICAL CHARACTERISTICS OF STUDY WATERSHEDS

Watershed	Area (areas)	PI[1]	PF[2]	Slope (ft/ft)	Width of Overland Flow (ft)
McDowell Ditch	276	20	0	0.0014	3200
East Ditch	70	25	0	0.0043	1800
Cline Ditch	76	21	5	0.0190	1800

[1]Percent Imperviousness

[2]Percent Forest

These three watersheds had automatic rainfall, streamflow, and water samplers installed. Two other drainage areas were sampled. They were (1) Manhole No. 55 which is a storm sewer and drains about 80 acres mostly involving barracks, Bachelor Officer's Quarters, officer's club and base exchange; (2) about 20 acres which contain the coal pile storage for the power plant. Only grab samples of water quality were taken at these two sites. A wet/dry dustfall monitor was installed in each of the three watersheds to measure dry and wet dustfall.

    b. Instrumentation

    (1) Rainfall-Runoff - Streamflow gages were located at the outlet of each watershed, and rainfall gages were located within each study basin. Continuous rainfall records were obtained from early May, 1978 to middle December, 1978, and from late March, 1979 to late August, 1979. Due to mechanical failures, some rainfall records were not obtained. In such cases, rainfall data from the remaining rainfall gages were utilized to fill in the missing records. The rain gages were manufactured by the Belfort Instrument Company. The streamflow gages (Stevens W-2) were set to trip at a predetermined water level, thereby recording only the larger stormwater events.

    Rainfall and streamflow records were abstracted in 15-minute time intervals, thus establishing the basic time step for the input data into the simulation programs. Gage heights were converted to discharge by hydraulic rating curves developed at each site. These rating curves are not very reliable at low flows.

(2) Runoff Quality - Stormwater quality samplers were located at the streamflow gages and were triggered by the water level recorders. The water level recorders, i.e., streamflow gages, were triggered by the water level reaching a predetermined elevation. The samplers were battery powered Sigma Motor Units (WM-2-24) set to pump a sample from the ditches over a 15-minute period. A total of 24 samples could be taken over a continuous 6-hour period.

Low flow samples during non-rainy periods, were scheduled to be taken daily, but due to the low variability of the water quality the grab sampling was changed to bi-weekly.

(3) Dustfall Monitors - During the project, dustfall was monitored at selected locations. Four dustfall monitors were located on the base in the three watersheds in December 1977. A fifth monitor was placed off-base in June 1978 to serve as a background station. Each dustfall monitor consisted of three polypropylene straight-sided buckets. One dustfall bucket was used to measure the total deposition (wet and dry) for a one month consecutive monitoring period. The other two were operated to collect the dry deposition and wet deposition, respectively. During dry periods, the dry deposition bucket was exposed to the atmosphere, and the wet bucket was covered by a canopy, pre-venting deposition into this bucket. The canopy, activated by precipitation, was automatically removed from the wet bucket and covered the dry bucket during precipitation periods.

To the extent possible, the wet and dry buckets were replaced after each wet and dry with new buckets. In this manner the total deposition for each dry period and wet period was determined. The buckets, which were 7.75 inches in diameter and 8 inches deep, were located four feet above ground-level. To prevent excessive re-entrainment of deposited dust, 200 ml of distilled water was placed in each bucket. During the colder months, the mixture was changed to 100 ml distilled H_2O and 100 ml of isopropyl alcohol to prevent freezing.

c. Summary of Data Collected

(1) Storm Rainfall and Runoff - A total of 17 storm rainfall-runoff events were of sufficient quality to analyze. Seven were on McDowell Ditch watershed, six on East Ditch watershed and four on Cline Ditch watershed. The storm charac-teristics are listed in Table 2.

Only two of the storms were extreme events. The storms of August 2, 1978 and July 8, 1978 had periods of about 2 years (note these storms were of different durations). The remainder of the storms had return periods of less than one year.

(2) Runoff Quality Samples - A total of 24 storm pollu-tographs were collected. Nine were on McDowell Ditch watershed,

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TABLE 2. STORM CHARACTERISTICS

GRISSOM AFB, BUNKER HILL, INDIANA

Watershed	Date	Rainfall (in)	Runoff (in)	Rainfall Duration (hrs)
McDowell Ditch	8-02-78	1.40	0.166	7.5
	8-27-78	0.50	0.066	12.0
	9-14-78	0.50	0.052	0.5
	11-14-78	1.49	0.309	11.5
	12-03-78	1.53	0.581	10.2
	4-11-79	1.07	0.112	18.0
	7-08-79	2.80	0.568	18.0
East Ditch	11-14-78	1.22	0.130	12.0
	11-17-78	0.42	0.063	5.5
	12-03-78	1.20	0.264	8.0
	12-07-78	0.60	0.058	14.5
	4-11-79	1.22	0.277	20.0
	7-08-79	2.80	0.834	18.0
Cline Ditch	8-02-78	1.30	0.014	7.0
	8-27-78	1.10	0.013	15.5
	9-14-78	0.50	0.011	0.5
	12-03-78	1.05	0.021	12.0

nine on East Ditch watershed, and six on Cline Ditch watershed. Due to instrument malfunctions, associated hydrographs were not measured for all pollutographs. Grab samples during nonrainy periods were collected almost every day between July 15 and September 30, 1978. After September 30, samples were collected about twice weekly during nonrainy periods.

Prior to October 1, 1978, the following quality constituents were determined from the pollutograph water samples: Fe, Zn, Na, Mg, Ca, suspended solids (SS), chemical oxygen demand (COD), alkalinity (ALK), and pH. After October 1, 1978, the following constituent concentrations were analyzed: Pb, NO_3, PO_4, NH_3, TSS, oil and grease (OG), biochemical oxygen demand (BOD), COD, ALK, and pH. Occassional total organic carbon measurements were made. Continued instrument malfunction prevented routine determinations.

(3) Dustfall Samples - A total of 26 dry samples were successfully collected. The samples were analyzed for the mass of insoluble and soluble dustfall, and insoluble and soluble lead. The data were then converted to deposition velocities by dividing the mass by the collection area and the exposure period, and reported in grams/meter^2-month.

d. Problems in Data Collection

The principle problems associated with data collection were (1) logistics between UT at Knoxville and Grissom AFB, and (2) an extremely cold winter during 1977-78 which caused breakdown and freezing of the instruments. The dustfall monitor at the flight line monitoring site was used frequently as a perch for birds. As a result, several samples were contaminated. Also, several dustfall samples were destroyed during shipment between Grissom AFB and the University of Tennessee laboratory.

3. MODEL CALIBRATION AND SIMULATIONS

a. Storm Rainfall and Runoff

TENN-I has an analysis phase, previously mentioned, called the double triangle model (DTM). If in the course of evaluating the simulation capabilities of TENN-I it is found that the model does not produce a reasonably good fit to available observed hydrographs, the DTM of TENN-I may be called. The observed hydrographs can then be incorporated into TENN-I for the purpose of expanding the simulation capabilities of the model.

(1) TENN-I - The procedure described in Section II was utilized for simulating the stormwater hydrographs referred to in Table 2. The simulated hydrographs agreed very favorably with the observed hydrographs on McDowell Ditch and East Ditch watersheds but were grossly in error on the Cline Ditch

(residential) watershed. The land use of McDowell Ditch and East
Ditch watersheds was similar to that of many watersheds included
in the data base utilized in developing TENN-I. (Cline Ditch
watershed, however, has an extensive storm sewer system which
drains essentially 100 percent of its surface drainage area. DTM
was called to analyze the Cline watershed storms.)

Generally, TENN-I simulations produced storm
hydrographs which had significantly lower peak flows which peaked
much later than the observed flows. The four optimized NURFs for
each associated storm on Cline Ditch watershed were used to
define the watershed NURF. Using the DTM, the storms were ana-
lyzed and T1, T2, T3, UP, and UR were determined for each storm.
(The results are tabulated in Table 3.) The NURFs for each storm
were derived by dividing the ordinate scale and multiplying the
time scale by the associated lag time. The average NURF for the
storm sewered Cline Ditch watershed is superimposed upon the NURF
diagram as shown in Figure 6. After this analysis, the Cline
Ditch NURF was included into TENN-I as an additional simulation
option. McDowell Ditch and East Ditch watershed NURFs correspond
to the urban NURF in Figure 6.

TABLE 3.   CLINE WATERSHED OPTIMIZED URF's

Storm Date	T1	T2	T3	UP	UR	TL
8-2-78	0.940	3.008	61.00	0.524	0.0071	1.374
8-27-78	1.992	3.180	50.00	0.457	0.0114	1.969
9-15-78	3.040	4.332	38.00	0.462	0.00005	2.442
12-3-78	2.900	6.880	48.00	0.259	0.00489	3.288

All of the NURFs in Figure 6 can be placed into the
context of an initial response (IR) and delayed response (DR).
The highest IR is from sheet surface runoff (nearly 100 percent),
and the lowest IR is 100 percent forested watershed, with agri-
cultural and urban watersheds being somewhere between. The IR of
an extensive urban storm sewer system such as Cline Ditch should
be greater than the IR of an urban area with a limited storm
sewer system and less than the IR from sheet surface runoff.

IR and DR were calculated for each NURF shown in
Figure 6. Both IR and DR are constant for a given land use,
i.e., a given NURF. DR can be calculated as

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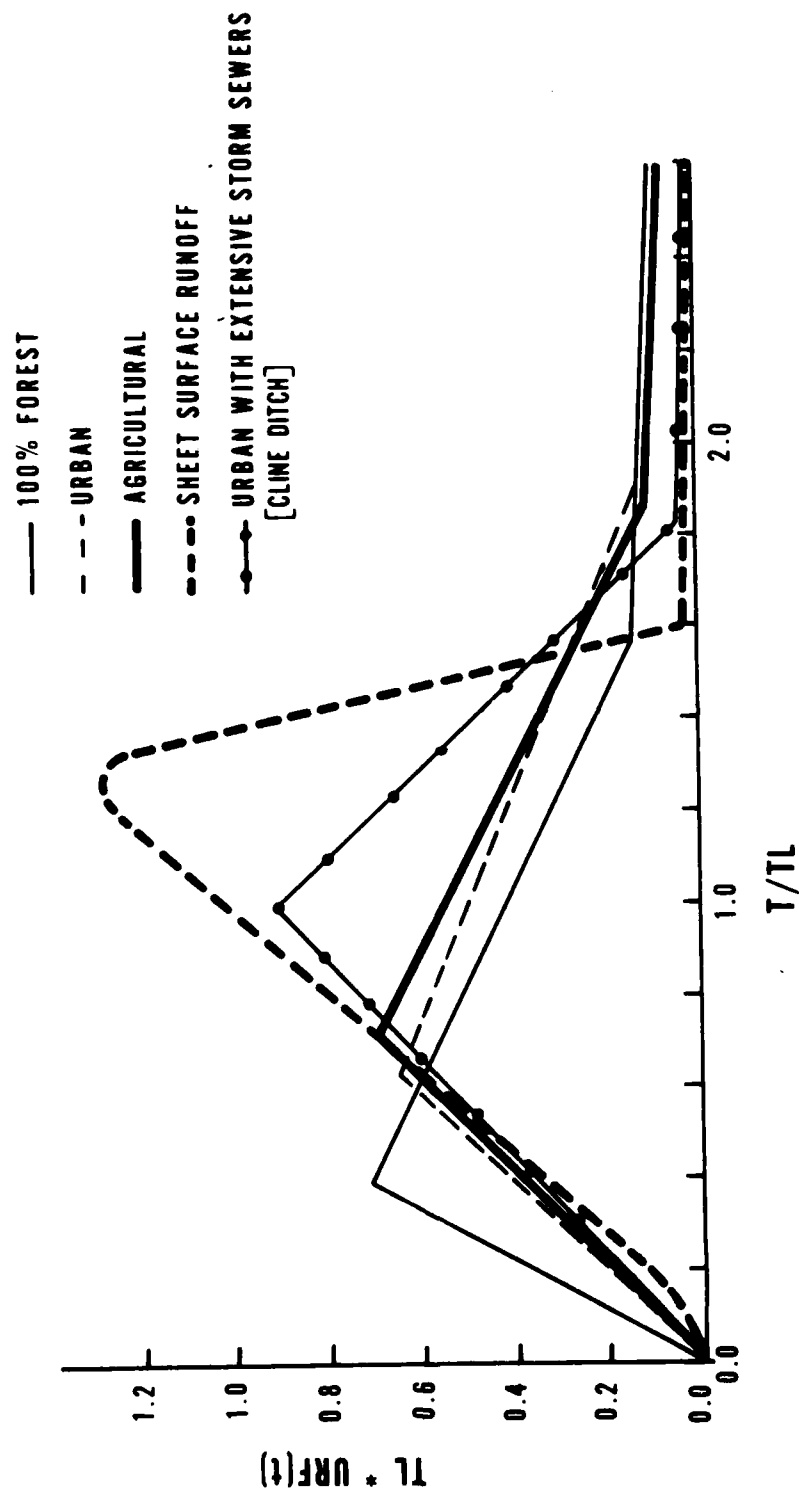
Figure 6. Normalized Unit Response Functions for Different Land Uses.

Legend:
— 100% FOREST
– – – URBAN
— AGRICULTURAL
▪▪▪▪ SHEET SURFACE RUNOFF
•—• URBAN WITH EXTENSIVE STORM SEWERS [CLINE DITCH]

X-axis: T/TL

Y-axis: TL • URF(t)

$$DR = 1/2 *(TL*UR)*(T3/TL) \tag{50}$$

$$\text{or} \quad DR = 1/2 *UR*T3 \tag{51}$$

Since the volume under the URF or NURF is unity, it follows that

$$IR = 1 - DR \tag{52}$$

Using the coordinates in Figure 6, IR and DR for each NURF are shown in Table 4. As can be seen in Table 4, the effect of storm sewers has significantly increased IR which is attributed to an increase in surface runoff.

TABLE 4.   INITIAL AND DELAYED RESPONSE OF
LAND USES ILLUSTRATED IN FIGURE 6

Land Use	IR (percent)	DR (percent)
Sheet Surface Runoff	97	3
Urban Storm Sewers	86	14
Urban	65	35
Agriculture	62	38
100 Percent Forested	46	54
Contour Strip Mining	48	52

(2)   SWMM - Default values recommended by the builders of SWMM were used for Manning's resistance factors and Horton's infiltration coefficients. The SWMM User's Guide (Reference 21) outlines the procedure for estimating the width of overland flow of the subcatchment, while the remaining parameters used in SWMM were estimated from maps of the study basins. Table 5 tabulates the input values of the parameters used by SWMM.

(3)   STORM - Default values recommended by builders of STORM were used for the moisture accounting system between storms. These values are tabulated in Table 6 and correspond to Equation (38). The land use percentages for the three study watersheds are shown in Table 7.

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b. Stormwater Runoff Water Quality

(1) TMBM-I - Attempts were made to optimize TMBM-I on the metals Fe, Zn, Na, Mg, Ca, and Pb; and on total solids, total alkalinity and PO_4. No attempt was made to optimize the model on pH, oil and grease or any of the non-conservative constituents. Non-conservative substances were not analyzed because TMBM-I does not have a decay component. Only storm load moduli were fed into TMBM-I, but the results were compared with low (grab or daily) flow concentration. Comparisons were also made with runoff quality data from urban and coal strip mined projects.

TABLE 5. INPUT VALUES FOR PARAMETERS USED BY SWMM

Watershed	Width (ft)[1]	PII[2]	PI[3]	Slope (ft/ft)
McDowell Ditch	3200	10	20	0.001
East Ditch	1800	11	24	0.0004
Cline Ditch	1900	10	15	0.002

[1]Refers to width of overland flow

[2]Refers to the percent impervious with zero detention

[3]Percent Impervious

Interpretations of the results from TMBM-I were made in view of the relatively short hydrologic record (1 year) and in view of the fact that only three watersheds comprised the data sample. TMBM-I has two independent variables (PI and *PF).

(2) SWMM and STORM - Since SWMM does not have a data analysis phase, the simulation phase was used to generate pollu-tographs and the results were compared with the observed pollutographs. In all cases default values were used. As with SWMM, STORM default values were used to simulate pollutographs. The simulated pollutographs were compared with the observed pollutographs.

TABLE 6. INPUT VALUES FOR PARAMETERS USED BY STORM

Land Use	IN (in/hr)	SM (in)	MP (in/hr)	V	P
Pasture	0.03	3.3	0.02	1.0	2.0
Commercial	0.01	1.1	0.03	1.0	2.0
Unimproved	0.02	1.8	0.02	1.0	2.0
Single	0.02	1.8	0.02	1.0	2.0
Multiple	0.01	1.1	0.03	1.0	2.0

TABLE 7. LAND USES FOR THE STUDY WATERSHEDS

	Land Use	Percent Area	Percent Imperviousness
McDowell Ditch	Range	70	2
	Commercial	25	80
	Unimproved	5	0
East Ditch	Range	65	2
	Commercial	25	75
	Multiple	10	25
Cline Ditch	Park	5	0
	Single	70	25
	Multiple	25	15

SECTION IV

RESULTS

1. STORM HYDROGRAPHS

The major objective of this report is to evaluate the ability of three stormwater models to simulate real storm events at Grissom AFB, Indiana. Appendix A contains the figures and tables of the individual results of the evaluations and Table 8 summarizes those results. In addition, sensitivity analysis was performed on each of the models to determine the parameters which chiefly affected the simulated hydrographs. Three characteristics of the simulated hydrographs were used to evaluate the models: peak discharge (Qp), time to peak (tp), and the volume of direct runoff. Shape, a more qualitative characteristic, was also used to judge the model's ability to simulate.

   a. TENN-I

To determine how well TENN-I simulated peak discharge, time to peak, and shape of the storm hydrograph, the CN were optimized to allow the volumes of the observed and simulated hydrographs to be equal. As a result of the runoff volume simulation phase of TENN-I the CN were estimated using the SCS Hydrology Handbook (Reference 6). The antecedent moisture condition (AMC) is divided into three categories. AMC-I is the lower limit of moisture of the upper limit of S; AMC-II is the average moisture content; AMC-III is the upper limit of moisture or the lower limit of S. The AMC was determined by the total amount of rainfall which occurred in the 5-day period preceding a storm. The results are tabulated in Table 9.

For an average AMC (i.e., AMC-II) close agreement exists between the optimized and estimated CN. Otherwise, estimated CN were lower than optimized CN for storms with AMC-I and higher than optimized CN for storms with AMC-III. Equation (9) used in TENN-I, assumes an AMC-II when simulating rainfall excess. Therefore, the CN were optimized for AMC-II, which may explain the variation in the estimated CN and optimized CN for AMC-I and AMC-III.

According to Overton, Troxler and Crosby (Reference 10), TENN-I was developed based upon three assumptions about the watershed's response to rainfall: it is lumped, time-invariant, and linear. Since the study watersheds are small and since large portions of these watersheds were comprised of one type of land use, these assumptions could be made with a fair degree of confidence. This is evident by comparing the simulated peak discharges with the associated observed peak discharges.

For high rainfall volume storms, TENN-I simulated hydrographs were in close agreement with the observed

TABLE 8. VOLUME SIMULATION RESULTS

Watershed	Storm Date (M-D-Y)	Rainfall (inch)	Observed Runoff (inch)	TENN-I Runoff (inch)	STORM Runoff (inch)	SWMM Runoff (inch)
McDowell Ditch	8-03-78	1.4	0.166	0.178	0.451	0.110
	8-27-78	0.5	0.066	0.067	0.059	0.080
	9-15-78	0.5	0.052	0.054	0.058	0.150
	11-14-78	1.49	0.309	0.320	0.485	0.440
	12-03-78	1.53	0.581	0.568	0.484	0.510
	4-11-79	1.07	0.112	0.112	0.180	0.275
	7-08-79	2.80	0.568	0.568	0.950	4.410
East Ditch	11-14-78	1.22	0.130	0.127	0.220	0.450
	11-17-78	0.42	0.063	0.060	0.045	0.060
	12-03-78	1.20	0.264	0.266	0.341	0.070
	12-07-78	0.60	0.058	0.055	0.045	0.350
	4-11-79	1.22	0.277	0.277	0.200	0.357
	7-08-79	2.80	0.834	0.834	0.850	1.700
Cline Ditch	8-02-78	1.30	0.014	0.015	0.525	0.190
	8-27-78	1.10	0.013	0.013	0.269	0.180
	9-14-78	0.50	0.011	0.011	0.098	0.070
	12-03-78	1.05	0.021	0.021	0.198	0.110

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TABLE 9. OPTIMIZED CN's VERSUS ESTIMATED CN's

Location	Storm Date (M-D-Y)	Rainfall (inches)	Runoff (inches)	AMC	Opt CN	Est. CN	Estimated Runoff (inches)	Error of Runoff (inches)
McDowell Ditch	8-03-78	1.40	0.180	III	77	89	0.55	- 205
	8-27-78	0.50	0.067	I	91	70	0.01	85
	9-15-78	0.50	0.054	I	90	67	0.01	81
	11-14-78	1.49	0.32	III	81	83	0.33	- 3.1
	12-03-78	1.53	0.568	I	87	73	0.10	82
	4-11-79	1.07	0.112	II	80	89	0.31	- 176
	7-08-79	2.80	0.568	II	70	76	0.88	- 55
East Ditch	11-14-78	1.22	0.127	I	78	60	0.01	92
	11-17-78	0.42	0.060	II	93	88	0.05	16
	12-03-78	1.20	0.266	I	85	70	0.03	88
	12-07-78	0.60	0.055	II	87	85	0.03	45
	4-11-79	1.22	0.277	III	85	89	0.43	- 55
	7-08-79	2.80	0.834	II	75	76	0.88	- 5.5
Cline Ditch	8-02-78	1.30	0.014	I	68	45	0.01	28
	8-27-78	1.10	0.012	III	70	85	0.20	-1566
	9-14-78	0.50	0.011	III	85	95	0.18	-1536
	12-03-78	1.05	0.019	II	72	70	0.01	47

hydrographs. For multi-peak, long duration storms TENN-I simulations were not in good agreement with the observed stormwater hydrographs. The storm of August 27, 1978, at McDowell Ditch had two definite peaks, but the TENN-I hydrograph simulated only one. Fortunately, the high rainfall volume storms are considered most important to hydrologic studies for design; therefore, TENN-I is able to simulate storms of hydrologic significance accurately.

In addition, the NURF used to simulate the McDowell Ditch and East Ditch storms were optimized for storms in the Tennessee Valley. This may explain why some of the TENN-I simulated hydrograph shapes were poor. Had NURF been derived for these watersheds as for Cline Ditch watershed, the shapes may have been closer to the observed shapes.

b. STORM

STORM and TENN-I have certain similarities. They both utilize the same rainfall excess simulation and both utilize a URF to convolute the rainfall excess. However, STORM specifies a URF for a watershed, whereas TENN-I specifies a NURF for a watershed. Given rainfall excess, a storm URF is simulated in TENN-I. Since TENN-I considers watershed response to be linear within a storm, but nonlinear from storm to storm, a family of URFs is produced for each watershed. Unlike TENN-I, however, STORM is a continuous model which performs a soil moisture accounting between rainfall events.

All input parameters to STORM used in the simulations were estimated by considering the examples displayed in the user's manual (Reference 23). This was necessary because the STORM user's manual did not include a prediction scheme for the model parameters. All STORM simulated peak discharges and volumes for the Cline Ditch runoff events were considerably higher than the observed peak discharges and volumes. This could be due in part to errors in predicting the input parameters.

In addition, due to the lack of a nonlinear URF in STORM (i.e., the SCS model), the shapes of the simulated storm hydrographs were only fair. Some storm events, such as the one at McDowell Ditch on August 8, 1978, were poor while others, such as the one at McDowell Ditch on September 9, 1978, were good. STORM also seemed to simulate well for short, intense storms, but poor for storms of longer duration.

STORM was not effective in simulating the time to peak. The time increment (DT) used by STORM to input rainfall and to convolute a hydrograph is fixed at one hour. For this reason, peak discharges are limited to hourly increments from the beginning of the storm, and this may create errors when simulating the time to peak. Also, errors in simulating time to peak may be induced by the technique used in STORM to continually

account for the soil moisture capacity value in Equation (38). For example, for the storm of August 27, 1978, at McDowell Ditch, STORM simulated the peak discharge to be 7 hours from the beginning of the storm which was 4 1/2 hours earlier than the observed peak discharge. Since no large storms had occurred preceding this storm, the AMC for this storm event may have been condition I, thereby causing the simulated hydrograph to peak earlier than the observed.

c. SWMM

SWMM is a deterministic model; therefore, when input parameters are known with a high degree of certainty, storm simulations should be modeled accurately. Unfortunately, little work has been reported for defining the input parameters. Since default values suggested in the user's manual were used in this study, SWMM simulations for the watersheds at Grissom Air Force Base were very poor.

The peak discharges simulated by SWMM were consistently higher than those observed for all three study watersheds. This is true especially for the storms simulated at Cline Ditch. In addition, the accuracy of SWMM might increase as the watershed is divided into subcatchments. Also, since no predictive scheme for the parameters was provided in the user's manual, default values would have to be used for all subcatchments.

The alternatives to physically describe the watershed by SWMM are infinite. They range from a detailed or "fine" discretization of the basin to a simplified or "coarse" discretization of the basin. Therefore, a fine and coarse discretization plan for each study watershed was input into SWMM to evaluate the effects on the stormwater hydrographs.

The first set of simulations for the watershed utilized a coarse plan. Each basin was represented by one subcatchment with no gutter or pipe network. The second set of simulations for the watersheds utilized a fine plan. Cline Ditch was represented by three subcatchments with each subcatchment containing a pipe. East Ditch was represented by three subcatchments with each subcatchment containing a ditch.

The SWMM stormwater hydrograph simulations show little variation between the discretization methods in terms of peak discharge, time to peak, and shape with the exception of two storms in East Ditch as shown in Table 10. Table 10 tabulates the results of the simulations.

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TABLE 10. SWMM SIMULATIONS:
FINE DISCRETIZATION VERSUS COARSE DISCRETIZATION

Watershed	Storm Date (M-D-Y)	Coarse Discretization		Fine Discretization	
		Q_p (cfs)	t_p (hrs)	Q_p (cfs)	st_p (hrs)
East Ditch	11-14-78	5.8	3.5	23.2	8.75
	11-17-78	1.8	4.5	1.7	4.5
	12-03-78	1.8	3.0	2.0	3.25
	12-07-78	2.0	6.5	23.5	6.25
Cline Ditch	08-28-78	24.4	1.0	23.3	1.0
	08-27-78	15.8	1.0	14.5	0.75
	09-15-78	7.2	1.0	7.1	1.00
	12-03-78	5.8	4.0	5.4	4.00

Generally, SWMM simulated peak discharges higher than the observed peak discharges, but for some storms the shape of the simulated hydrographs paralleled the observed hydrographs. The Cline Ditch storm of August 27, 1978, shows SWMM overpredicting, but it simulated both peaks and the associated times to peak correctly. For the remaining storms, though, the shapes of the simulated hydrographs were poor with regard to the observed hydrographs. For example, consider the storm of November 14, 1978, at McDowell Ditch. The simulated peak discharge occurred two hours earlier than the observed. This may be due to a large burst of rainfall occurring at a time when Horton's infiltration model had simulated saturation conditions in the soil. Therefore, this large burst of rainfall may have contributed heavily to the SWMM simulation of rainfall excess.

The discharges simulated by SWMM tended to be "flashy." Sharp rises in the hydrograph were predicted after intense bursts of rainfall. This may have been due to the percent imperviousness parameter which corresponds to zero detention. The parameter value used in this study may have been considerably higher than the actual basin characteristics indicated.

d. Sensitivity Analysis

To determine the input parameters of most significance a sensitivity analysis was performed on the three stormwater

models. This was done by perturbating one parameter and holding the remainder constant for a simulation. The storm used for the sensitivity analysis was the McDowell Ditch storm of December 3, 1978.

The input parameters of STORM describing the watershed characteristics were all individually perturbated ± 10 percent of their true values for the purpose of evaluating their sensitivity on peak discharge and the associated time to peak. The simulations showed that the parameters which were used to simulate soil moisture capacity in Equation (38) have a negligible effect on the peak discharge or its associated timing. The results of the sensitivity analysis for STORM are shown in Table 11. As seen in this table, the two parameters which determine the shape of the URF (time of concentration, and ratio of time of recession to time to peak) have a sensitive effect on the peak discharge but not on the timing of the peak discharge. The land use parameters in STORM were also varied to evaluate the effect of the peak discharge and time to peak. The percent of range land use were perturbated and showed very little effect on the stormwater characteristics.

The input parameters used in SWMM to simulate the storm hydrograph may be divided into three categories: (1) parameters used to describe the watershed characteristics, (2) parameters used in Manning's equation, and (3) parameters used in Horton's infiltration equation. All parameters were perturbated ± 10 percent of their true values. The sensitivity analysis showed that no parameter effected the time to peak characteristic. The results of the sensitivity analysis for SWMM are shown in Table 12.

Varying the parameters used in Horton's infiltration equation had a little effect on the simulated peak discharge. Percent imperviousness had a substantial effect on the peak discharge. Also, parameters used in Manning's equation produced a sensitive effect on peak discharge, in order of their importance, were: percent imperviousness, slope, width of overland flow, and Manning n-value.

Sensitivity analysis of the TENN-I model was performed in two parts. First, the NURF parameters used were perturbated ± 10 percent to evaluate their sensitivity on peak discharge. Table 13 tabulates these results.

e. Comparison of Three Models

The results of all sensitivity analyses performed must be qualified in the context of the ± 10 percent perturbations performed. In all of the sensitivity perturbations, only one simulation error was greater than ± 10 percent (KUP in TENN-I). Hence, all parameters in STORM and SWMM and all but one in TENN-I

TABLE 11. SENSITIVITY ANALYSIS RESULTS - STORM,
STORM OF DECEMBER 3, 1978, MCDOWELL DITCH

Parameter	True Parameter Value	True Discharge (cfs)	Perturbated Discharge (cfs)	Simulation Error %
TSUB	1.50	58.8		
			53.0	-5.0
			58.3	+4.4
TRTP	1.67	55.8		
			58.4	+4.6
			53.2	-4.6
EERC	2.0	55.8		
			54.9	-1.6
			56.2	+0.7
EPRC	1.0	55.8		
			61.4	+10.0
			54.8	-1.8
DEPR	0.20	55.8		
			55.2	-1.1
			56.5	+1.3
SACT	1.50	55.8		
			55.2	-1.1
			55.2	-1.1
SMAX	3.30	55.8		
			57.3	+2.7
			53.3	-4.5
FIMP*	2.0	55.8		
			55.8	0
			55.8	0

TSUB = Time of concentration in hours
TRTP = Ratio of time of recession to time to peak
EERC = Exponent in evaporation component model
EPRC = Exponent in percolation component model
DEPR = Maximum depression storage capacity (inches)
SACT = Starting soil moisture retention capacity (inches)
SMAX = Maximum soil moisture
FIMP = Percent imperviousness

TABLE 12. SENSIVITY ANALYSIS RESULTS - SWMM,
STORM OF DECEMBER 3, 1978, MCDOWELL DITCH

Parameter	True Parameter Value	Correct/Perturbated Discharge (cfs)	Simulation Error %
Infiltration Rate (Min)	0.52	$\overline{\dfrac{74.1}{74.1}}$ 74.1	0 0
Infiltration (Rate	3.00	$\overline{\dfrac{74.1}{74.1}}$ 74.3	0 +0.2
Surface Storage Impervious- ness	0.062	$\overline{\dfrac{74.1}{74.1}}$ 74.1	0 0
Surface Storage Perviousness	0.184	$\overline{\dfrac{74.1}{74.1}}$ 74.1	0
Percent Imperviousness	20.0	$\overline{\dfrac{74.1}{79.3}}$ 68.5	+7.0 -7.6
Manning's n-IMP	0.012	$\overline{\dfrac{74.1}{75.6}}$ 72.5	+2.0 -2.2
Manning's n-PER	0.25	$\overline{\dfrac{74.1}{74.1}}$ 74.1	0 0
Width of flow	3200	$\overline{\dfrac{74.1}{75.9}}$ 71.8	+2.4 -3.1
Slope	0.001	$\overline{\dfrac{74.1}{79.9}}$ 73.2	+7.8 -1.2

TABLE 13.   SENSITIVITY ANALYSIS RESULTS - TENN-I,
      STORM OF DECEMBER 3, 1978, MCDOWELL DITCH

Parameter	True Parameter Value	Correct/Perturbated Discharge (cfs)	Simulation Error %
KUP	0.677	42.2	
		48.7	+15.4
		40.3	- 4.5
KT1	0.390	42.2	
		44.7	+ 5.9
		44.9	- 6.4
KT2	1.469	42.2	
		44.0	+ 4.3
		44.3	+ 5.0
PF	5.0	42.2	
		41.8	- 0.9
		41.8	- 0.9
PI	20.0	42.2	
		41.8	- 0.9
		41.8	- 0.9

appear not to have a very sensitive effect upon peak discharge. The sensitivity effect appears to be distributed among several parameters in each associated model.

TENN-I simulated high rainfall volume storms with a fair degree of accuracy with the exception of multi-burst, low intensity and short duration storms. STORM, for most cases, overpredicted peak discharges and simulated the hydrographs poorly in terms of shape. This could be due to the fact that default values were used for several input parameters. SWMM also failed to simulate the storm event accurately. This model generally overpredicted peak discharges and simulated the shapes poorly. Since SWMM also used default values for several input parameters, this may have caused the poor simulations.

The results of SWMM also show that a coarse discretization of a watershed simulates the stormwater hydrograph as well as a fine discretization. SWMM simulates the stormwater hydrograph by kinematic flow; therefore, two facts may explain these results. First, since the storms used in the simulations had relatively low rainfall volumes, the pipes and gutters used in fine discretizations had no appreciable backwater effects. Second, the pipe and gutter network made a negligible contribution to the stormwater hydrograph in terms of direct stormwater volume and timing. This can be seen by comparing the lag modulus for overland flow to the lag modulus for channel flow. Lag modulus is the surface runoff response in terms of geometry and roughness for a unit rainfall excess intensity. The lag modulus for overland flow at Cline Ditch was computed to be 186 minutes while the lag modulus for pipe flow at Cline Ditch was computed to be 21 minutes. The pipe flows may attenuate the stormwater hydrograph peak but should not make a major contribution relative to overland flow.

A sensitivity analysis was performed on each model to determine the parameter which should be accurately defined. The results of this indicate that all parameters in STORM and SWMM, and all but one in TENN-I, appear not to have a very sensitive effect upon peak discharge. The sensitivity effect appears to be distributed among several parameters in each associated model.

In comparing models it should be understood that models are developed to fulfill specific objectives. Their structures are different, and their application procedures are different. TENN-I can be distinguished from STORM and SWMM mainly on the basis that it has an analysis as well as a simulation phase, and its runoff quality simulations are based upon watershed pollutant loads rather than simply on street surface contaminants.

2. POLLUTOGRAPHS

Because of the relatively small number of runoff quality samples as compared to the urban samples used to develop LOAD-I,

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(Reference 10), it was decided not to apply TMBM-I to the Grissom storm data. Instead, it was decided to utilize LOAD-I, SWMM and STORM for simulating the average of the concentrations for the Grissom storms by using McDowell Ditch watershed for illustration.

A comparison of the LOAD-I, SWMM and STORM simulations with the storm and non-rainy period data is shown in Table 14. It is clearly shown that the model concentration simulations are substantially higher than the concentrations observed at McDowell Ditch. (This was true also for the other two watersheds.) In comparing the model simulations, it should be recalled that the SWMM and STORM simulations are based upon street surface pollutants in Chicago, Illinois. LOAD-I is based upon stormwater runoff quality of watersheds in Knoxville, Tennessee, and Durham, North Carolina. It should be expected that solids from the total watersheds will be higher than solids from street surfaces. Further, during the sample periods in Knoxville and Durham, construction was continuous on all watersheds; whereas, there appeared to be little or no construction or denuded areas during the sampling period at Grissom.

TABLE 14. COMPARISON OF SWMM/STORM AND LOAD-I RUNOFF QUALITY
MODELS WITH GRISSOM AFB DATA, MCDOWELL DITCH

Model	Total Solids mg/l	Pb mg/l	BOD mg/l	PO_4 mg/l
SWMM/STORM	282	**	82	****
LOAD-I	1750	0.348	*	2.2
Sample Average				
Storms	215	0.005	***	0.067
Dry Periods	70	0.003	5	0.063

*No BOD prediction component

**No pb prediction component

***No BOD storm samples

****No PO_4 prediction component

Further analysis of Pb in Knoxville shows a substantial drop in Pb since the introduction of no lead gasoline. The sample

period in the urban watersheds occurred prior to the pervasive use of no lead gasoline. The traffic levels in the urban watersheds greatly exceed those of Grissom.

The runoff quality data for McDowell Ditch, Cline Ditch and East Ditch watersheds are shown in Appendix B. The stormwater concentrations for many constituents are not greatly different among the watersheds. Notable exceptions are: (a) suspended solids in East Ditch watershed is about twice that of the other two watersheds because of agricultural practices, and (b) lead from Cline Ditch watershed is about one third of what it was from the other two watersheds.

3. SOURCES OF POLLUTION

From the records at McDowell Ditch, the amount of lead discharged was found to be 7.40 gm/acre/yr. The power plant and residential area generated about 420 kg of lead per year in 1978-79. If it is assumed that the lead is deposited uniformly over the base (8 square miles), the source would be approximately 82 gm/acre/yr as compared to 4.3 gm/acre/yr which was the measured deposition using the dust collectors. The power plant produces 99 percent of deposited lead. Hence, it can be concluded that the power plant produced enough lead to account for all of the lead found in the dustfall, and the deposited lead accounts for about 50 percent of the lead in the runoff. Other sources of lead are vehicular traffic and the jet aircraft; however, jet aircraft have been eliminated as a significant source. The question which could not be reliably answered is, how much of the lead from the power plant is deposited on the base?

Total measured solids deposition from the air was 139 kg/acre/yr. The suspended solids in the McDowell Ditch runoff was 220 kg/acre/yr. This indicates dustfall accounts for about 60 percent of the solids in the runoff. This is realistic given the fact that the runoff conveyance systems (channels and sewers) are stable and are not eroding and that no construction was underway during the sampling period. As shown in Table 14, the 1750 mg/1 of solids predicted for Grissom by LOAD-I translates to 2700 kg/acre/yr. Hence, if erosion associated with any future construction on the base is not controlled at the site, the solids in the runoff could increase many times over.

The following conclusions have been reached:

a. The runoff quality at Grissom is very good as compared to a dynamic urban watershed.

b. Dustfall could account for 50 percent of the lead and 60 percent of solids in the runoff.

c. The power plant could account for all of the lead in the dustfall but it was not possible to determine the relative contributions of off-base and on-base sources in this study.

In conclusion, the Grissom runoff quality is substantially better than Chicago, Knoxville, or Durham. In fact, the E.P.A. effluent criteria on solids of 70 mg/liter would not be violated often at Grissom whereas in the urban areas the standard is greatly exceeded almost on a continuous basis. An additional comparison is shown in Table 15 between the concentrations of several constitutents of the Durham watershed and McDowell Ditch. This shows that only calcium and zinc are higher at Grissom.

TABLE 15.   COMPARISON OF STORMWATER QUALITY AT MCDOWELL DITCH, GRISSOM AFB, WITH THIRD FORK CREEK IN DURHAM, N.C.

Quality Constituent	(Sample average) Grissom AFB (mg/l)	(Sample average) Third Fork Creek (mg/l)
COD	50	131
Phosphorous	0.065	0.85
Calcium	37	11
Iron	0.54	6.0
Magnesium	8.3	11
Zinc	0.88	0.28

SECTION V

DISCUSSION OF AFRUM

1. DEVELOPMENT OF AIR FORCE RUNOFF MODEL (AFRUM)

    a. Integration of TENN-I and LOAD-I

    TENN-1 and LOAD-I have been combined to form AFRUM. Storm
hydrographs and pollutographs are simulated from storm rainfall,
watershed soils, land use, and physical characteristics. AFRUM
is a parametric model; hence all of the model input is lumped.
The model cannot simulate the effects of alternate land use
scenarios for given percentages of land use.

    b. Input Requirements

    AFRUM accepts the following input:

    (1) Accumulated storm rainfall at equal time intervals, DT.

    (2) Stormwater discharge hydrograph at equal time
        intervals, DT (if available).

    (3) Watershed characteristics:

        (a) Curve Number (CN) (can be optimized if observed
            hydrograph read in)

        (b) Drainage area in square miles

        (c) Precent forest

        (d) Percent impervious

        (e) Percent denuded (construction site)

        (f) Land use:

            <u>1</u> Urban without extensive storm sewers

            <u>2</u> Urban with extensive storm sewers

            <u>3</u> Coal strip mined

            <u>4</u> Virgin (100 percent) forested

            <u>5</u> Agricultural

    c. Output

    (1) Simulated storm hydrograph

(2) Observed storm hydrograph (if read in)

(3) Rainfall and rainfall excess time distributions

(4) Pollutographs and total loads for the following constituents:

    (a) total solids

    (b) iron

    (c) manganese

    (d) magnesium

    (e) calcium

    (f) lead

    (g) total alkalinity

    (h) total sulfate

    (i) total phosphate

2. AFRUM APPLICATION

AFRUM may be transferred to other Air Force bases with varying degrees of reliability. The most reliable component of the model is its hydrograph simulations. This is attributed to the extensive development and verification associated with TENN-I as reported in Section II.

By contrast, the pollutant simulation component has a lesser degree of reliability attributable to a substantially smaller data base than that of TENN-I. Suspended solids is the most reliable component and is related primarily to construction (denudation) and stream channel scour. The primary sources of suspended solids are easily identifiable, whereas the source of dissolved constituents such as lead and other metals is not at all clear. AFRUM does not simulate non-conservative pollutants, such as BOD, because of the very small data base available for analysis and the high degree of complexity of the process.

3. MODEL SENSITIVITY

As shown in the previous chapter, the most sensitive parameter in TENN-I is the peak on the storm URF, i.e., UP. This is also the most reliable model parameter. UP is a function of storm lag time, and lag time is a function of watershed lag modulus and rainfall excess intensity. As shown in Section II and in

the present study, lag modulus is reliably predicted in urban areas by drainage area and percent imperviousness. Rainall excess, however, is a function of storm rainfall and SCS-CN. Therefore, the reliability of TENN-I is directly a function of the confidence modelers will have in their ability to determine watershed average rainfall and SCS-CN.

The most sensitive parameters in LOAD-I are percent imperviousness (PI) and percent denuded (PS). In urban areas, the results of the urban study (Reference 10) and the results of the present study have indicated that the delivery ratios for pollutant loads is nearly 100 percent and is directly related to PI and PS. These parameters are by far the easiest to estimate of all watershed characteristics.

4. MODEL UTILITY

AFRUM has utility as a simulator of storm runoff and associated pollutographs under a wide variety of land uses and soils. The model inputs are readily obtainable, and their complexity is low. In addition, AFRUM allows for varying degrees of surface runoff depending on land use and drainage patterns. The model also has the capability of simulating stormwater associated with land use conditions prior to Air Force base construction, e.g., agricultural to urban.

5. MODEL LIMITATIONS AND RELIABILITY

TENN-I is most reliable in urban areas in general but specifically in the Appalachian region. Caution should be exercised in applying TENN-I in flatwoods and generally west of the Mississippi River. Although some judgement will be required in applying TENN-I in some regions, a basis has been developed for exercising said judgement. As shown in the NURF diagrams, Figures 5 and 6, there are defined limits for the variation of a wateshed NURF. The variation of a watershed NURF should be between the NURFs of sheet surface runoff and 100 percent forested areas since these land uses represent the extremes of initial response and delayed response.

LOAD-I has more stringent limitations primarily because of data limitations and lack of understanding of pollutant sources including to what degree they contribute. The limitations and reliability of TENN-I also apply to LOAD-I. Further, LOAD-I reliability will depend upon the ability of the modeler to identify the pollutant sources.

SECTION VI

CONCLUSIONS

1. RUNOFF RESPONSE

The storm rainfall-runoff for Grissom AFB are very similar to
those of any urban area. Generally, imperviousness increases
runoff volume and peak runoff rate and decreases time to peak.
AFRUM is fully capable of simulating these effects, i.e., before
and after development of the urban areas.

2. RUNOFF QUALITY

Effects of Grissom AFB operations on runoff quality can be
compared with prior agricultural use and with other urban areas
where sediment control measures are not applied. Several studies
(Reference 1) have shown that suspended solids in storm runoff
from cultivated land range from about 100 to 600 mg/l and average
about 1000 mg/l. The average concentration at Grissom AFB was
185 mg/l. Pastured alfalfa and brome grass watersheds average
40 mg/l. Hence, Grissom AFB has greatly reduced solids from
cultivated land use. Lead, however, has increased from essen-
tially zero to 0.005 mg/l; yet, this is still not in violation of
EPA drinking water standards. Generally, stormwater pollution at
Grissom is low as compared to that of urban watersheds.

3. SOURCE OF RUNOFF POLLUTION

Dustfall which occurred during the months sampled could
account for 50 percent of the lead and 60 percent of the solids
found in the water runoff. It is also possible that the power
plant was the primary contributor of lead. The accumulation of
solids during cold winter months, when no runoff occurred, may
have accounted for the other 50 percent of the lead found in the
runoff. Vehicular traffic possibly could account for the
remainder of the lead and pervious (grassed) areas could account
for the remainder of the solids. The jet aircraft do not appear
to be a major pollution source of solids or lead in the runoff.

4. DEVELOPMENT OF AFRUM

The Air Force Runoff Model (AFRUM) has been developed by com-
bining the University of Tennessee hydrograph simulation model
(TENN-I) with the University of Tennessee pollutograph model
(LOAD-I). Hydrographs and pollutographs are simulated from storm
rainfall, watershed soils, land use, and physical characteristics.

AFRUM is a parametric model, hence all model input is lumped.
The model cannot simulate the effects of distributed land use
scenarios for given percentages of land use. AFRUM can, however,
simulate the effects of extensive storm sewer systems,
urbanization, forest cover, and agricultural practices.

5. COMPARISON OF RUNOFF MODELS

The three stormwater models evaluated in the present study
(1) AFRUM, (2) STORM, and (3) SWMM were compared theoretically,
computationally, and analytically as to their ability to accura-
tely simulate stormwater hydrographs and pollutographs. AFRUM
provided accurate simulations of the shapes and timing of most of
the 17 storms observed. However, the volume simulations were
limited by the SCS-CN model. STORM and SWMM simulated discharges
were generally much higher than the observed. These models are
limited by their default values.

SECTION VII

RECOMMENDATIONS

1. ANALYSIS VERSUS SIMULATION

In future modeling endeavors undertaken by the US Air Force, it is strongly recommended that the probability of success will be maximized by keeping a sharp distinction between analysis versus simulation. Analysis is an attempt to improve the state of the art, whereas simulation is a prediction or prognostication which utilizes the state of the art. Both analysis and simulation utilize mathematical models, but they are contrasted by having different objectives, and perhaps different project resource constraints.

2. FUTURE ANALYSES

a. Future analyses should concentrate on expanding the stormwater quality data base and improving the pollutograph component of AFRUM (i.e., LOAD-I).

b. It is recommended that future runoff analyses concentrate upon improving the SCS-CN model as it is applied to Air Force bases.

c. Future analyses could be undertaken to better identify and quantify ground sources of pollution. Sampling of these ground sources at control outfalls under storm conditions could greatly advance the state of the art.

d. AFRUM is recommended for use as a simulation and prediction tool for the characterization of stormwater runoff from Air Force bases as long as the objective and available resources are compatible.

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TABLE A-1. MCDOWELL DITCH SIMULATION RESULTS

Storm Date	Observed Qp (cfs)	Observed tp (hours)	TENN-I		STORM		SWMM	
			Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)
8-03-78	15.0	2.00	18.6	2.50	58.2	2.00	8.07	7.00
8-27-78	6.7	11.50	2.7	9.25	7.2	7.00	10.45	4.25
9-15-78	6.6	2.25	4.7	1.75	7.6	2.00	55.42	0.50
11-14-78	13.0	10.75	9.0	10.50	30.0	8.00	74.61	8.50
12-03-78	22.0	6.50	42.2	6.50	55.8	6.00	74.05	8.50
4-11-79	0.92	5.00	2.4	9.00	6.3	3.00	25.00	3.00
7-08-79	9.2	2.00	17.5	4.00	66.4	3.00	12.90	3.50

TABLE A-2. EAST DITCH SIMULATION RESULTS

Storm Date	Observed Qp (cfs)	Observed tp (hours)	TENN-I		STORM		SWMM	
			Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)
11-14-78	1.38	10.50	0.64	11.00	4.8	9.00	23.5	8.75
11-17-78	0.59	7.50	0.63	7.50	1.0	6.00	1.69	4.50
12-03-78	4.03	4.75	3.63	4.75	8.6	7.00	2.04	3.25
12-07-78	0.65	7.25	0.45	9.00	0.7	4.00	23.51	6.25
4-11-79	1.05	3.00	0.90	12.00	2.5	5.00	4.50	3.00
7-08-79	2.10	3.00	5.90	5.00	19.9	3.00	12.90	1.50

TABLE A-3. CLINE DITCH SIMULATION RESULTS

Storm Date	Observed Qp (cfs)	Observed tp (hours)	TENN-I		STORM		SWMM	
			Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)	Qp (cfs)	tp (hours)
8-02-78	2.02	0.75	0.88	1.25	18.6	2.00	23.33	1.00
8-27-78	1.70	2.25	1.20	2.25	6.2	2.00	14.48	0.75
9-14-78	1.90	1.25	1.04	1.00	3.2	2.00	7.11	1.00
12-03-78	1.90	5.75	2.12	5.50	6.0	4.00	5.41	4.00

C-1,MCDOWELL DITCH
12-03-78

OBSERVED HYDROGRAPH
TENN1 HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH

RUNOFF (CFS)

TIME FROM BEGINNING OF STORM (HOURS)
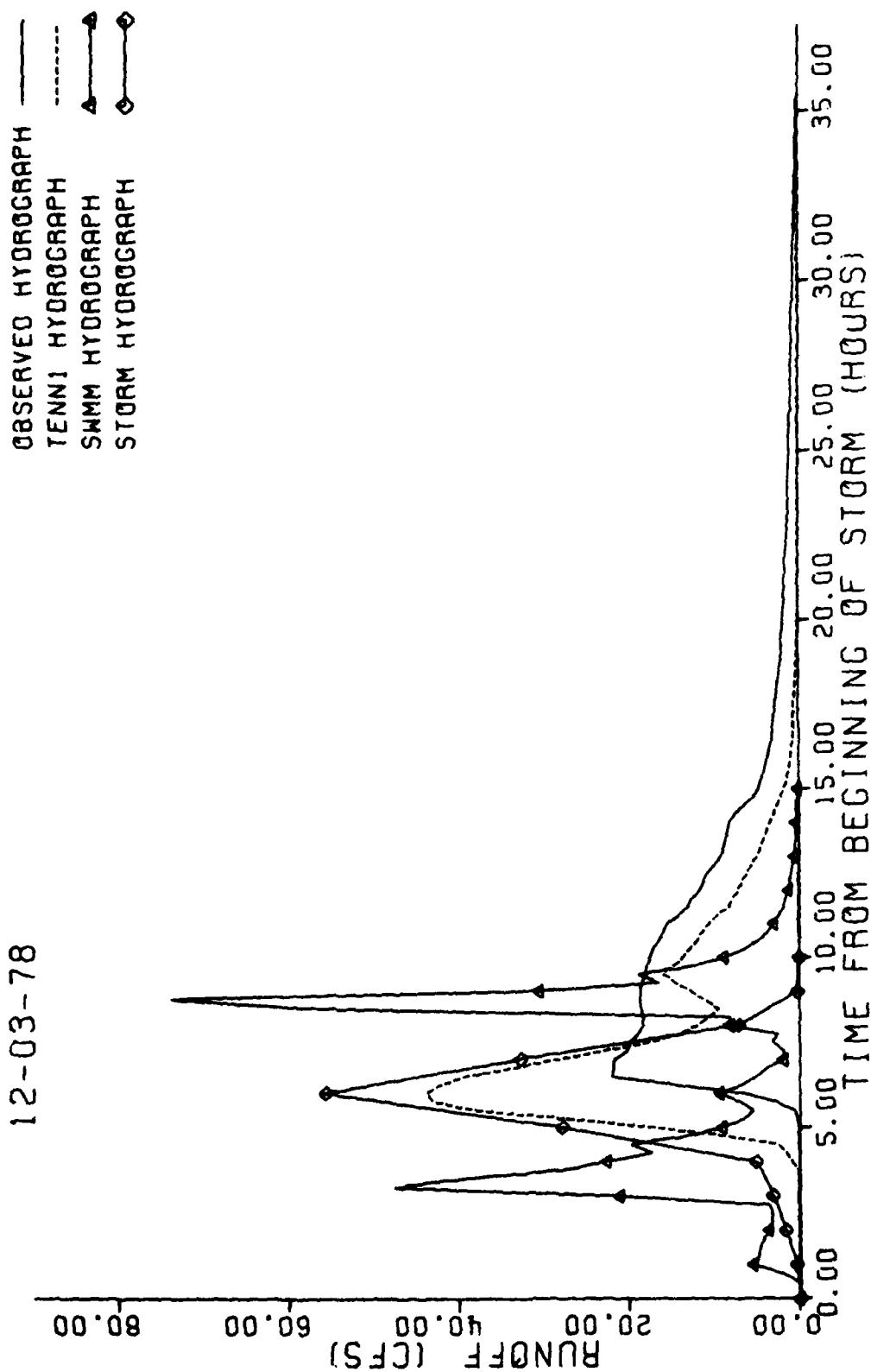
Figure A-1. Hydrograph Simulations, McDowell Ditch, 12/3/78
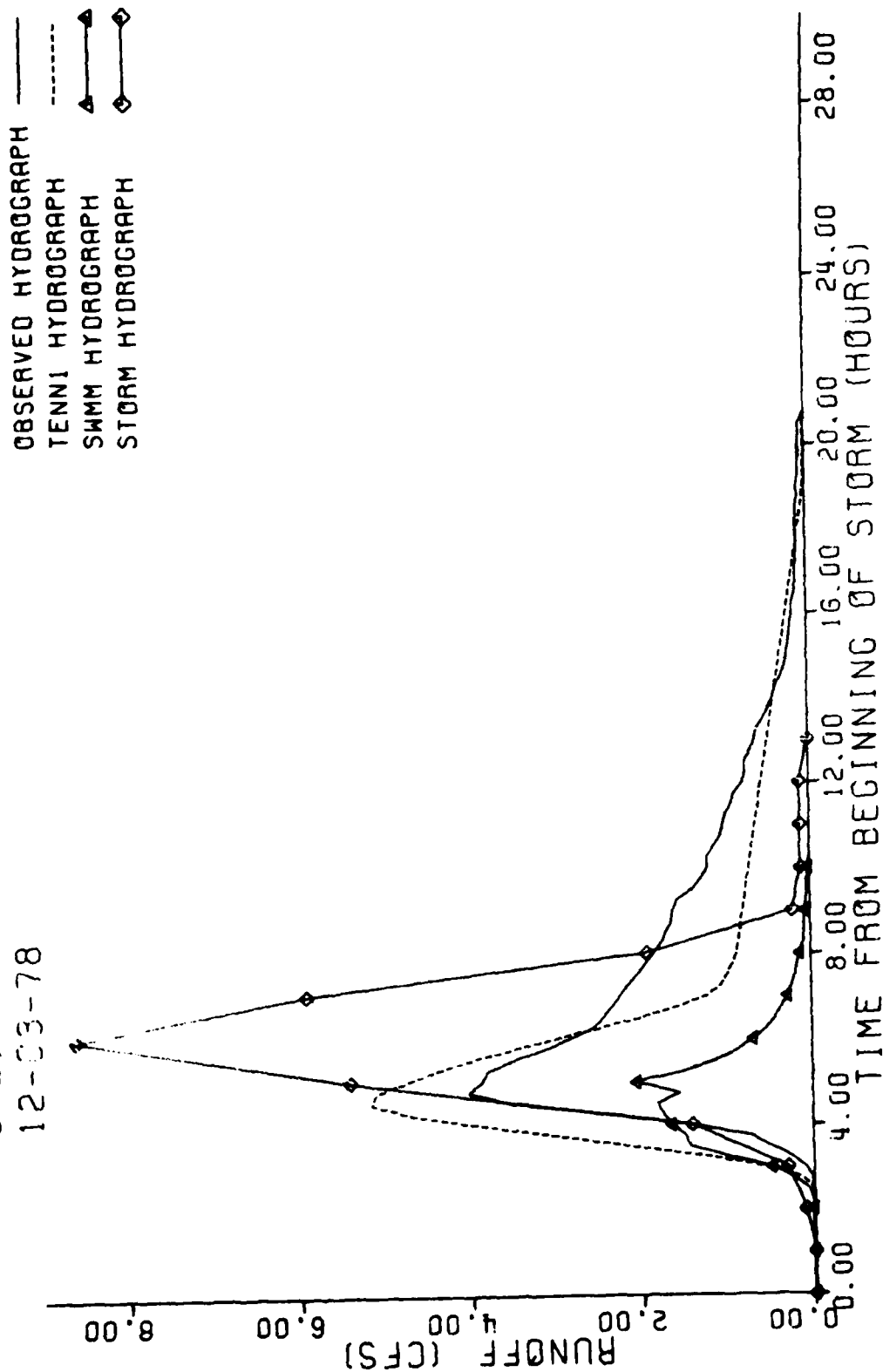
Figure A-2. Hydrograph Simulations, East Ditch, 12/3/78

M-1, CLINE DITCH
12-03-78

OBSERVED HYDROGRAPH
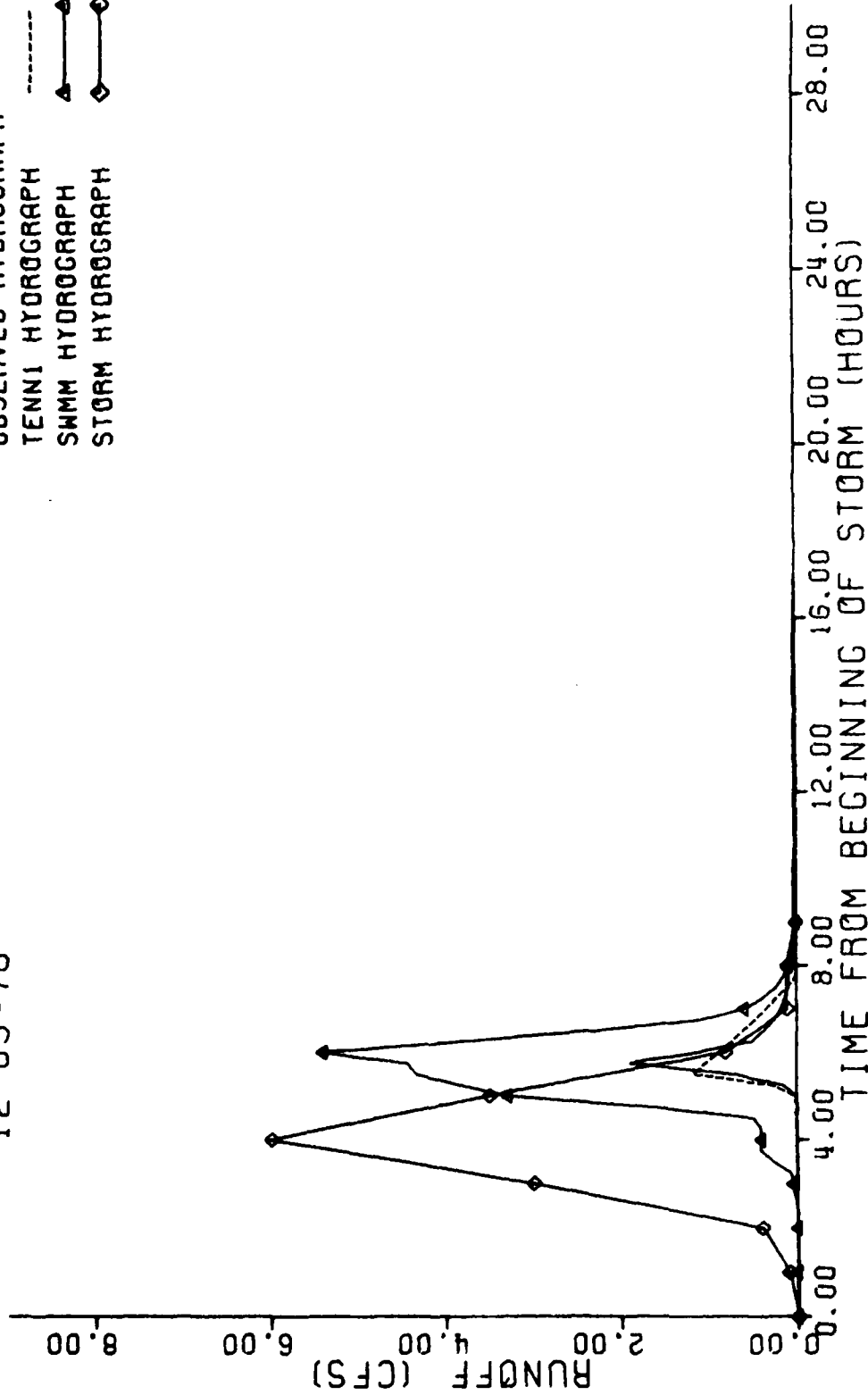TENNI HYDROGRAPH
SWMM HYDROGRAPH
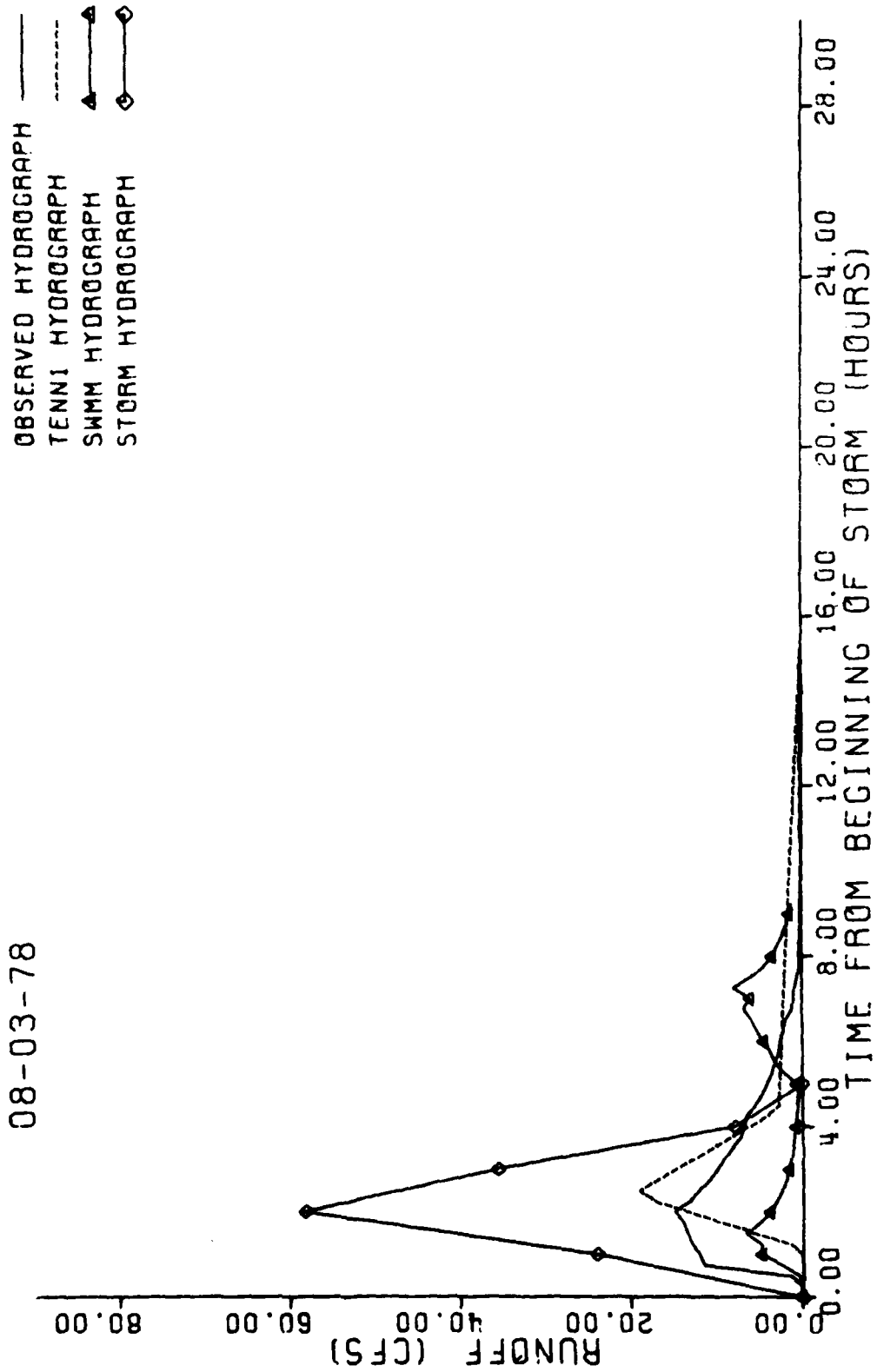STORM HYDROGRAPH

RUNOFF (CFS)

TIME FROM BEGINNING OF STORM (HOURS)

Figure A-3. Hydrograph Simulations, Cline Ditch, 12/3/78

C-1, MCDOWELL DITCH
08-03-78

OBSERVED HYDROGRAPH
TENN1 HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH

Figure A-4. Hydrograph Simulations, McDowell Ditch, 8/3/78
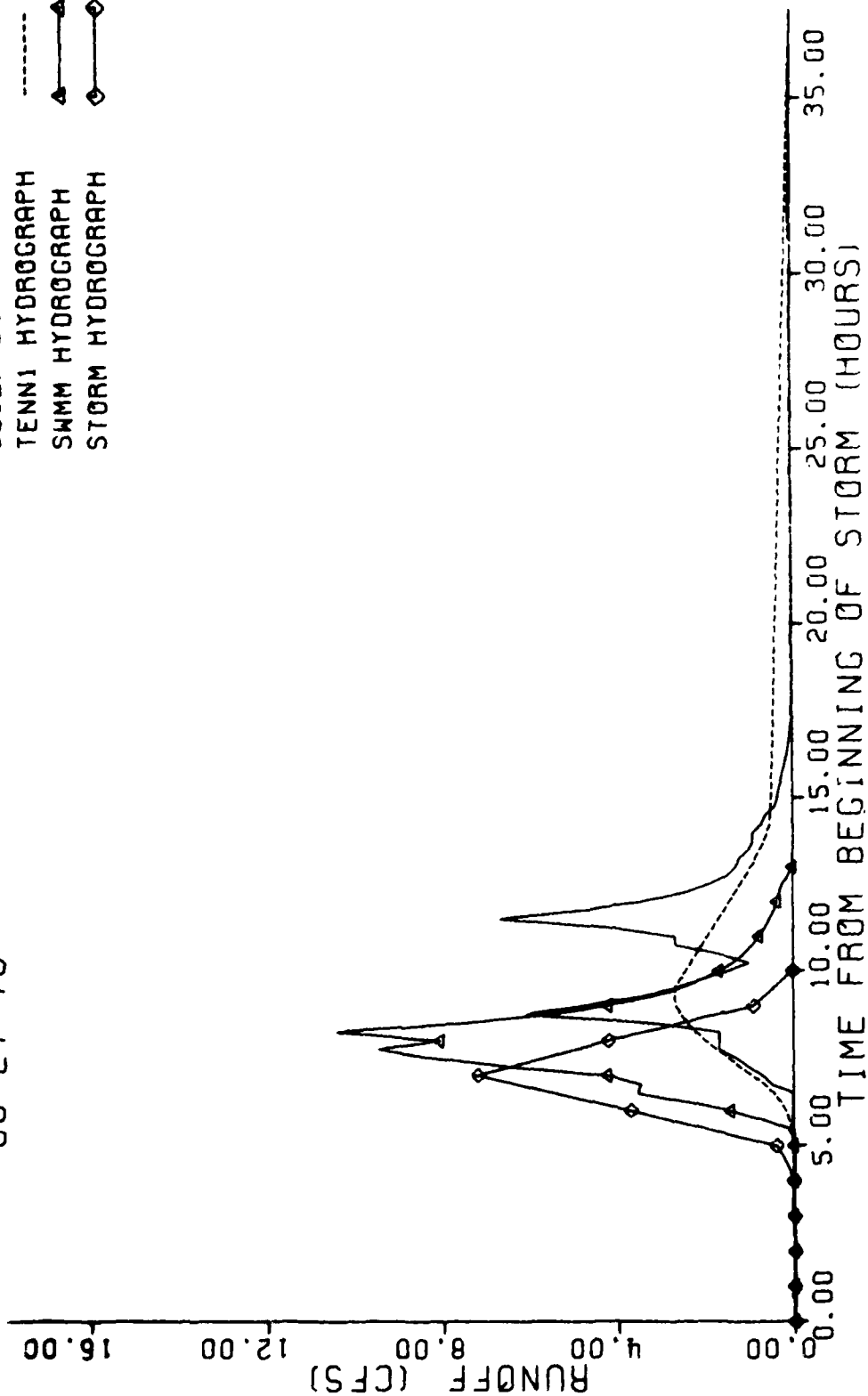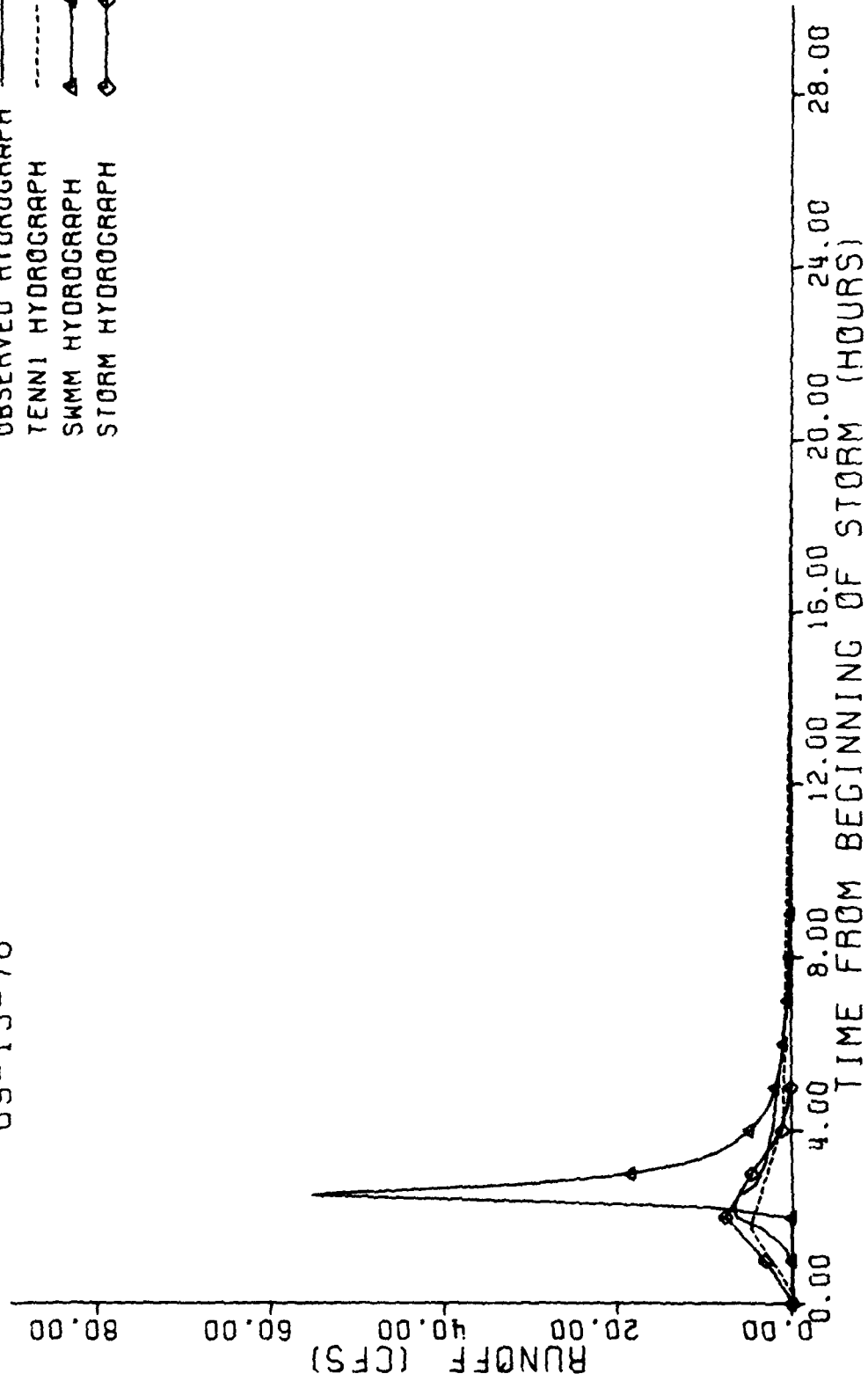
Figure A-5. Hydrograph Simulations, McDowell Ditch, 8/27/78

Figure A-6. Hydrograph Simulations, McDowell Ditch, 9/15/78

C-1,MCDOWELL DITCH
11-14-78

OBSERVED HYDROGRAPH
TENNI HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH

RUNOFF (CFS)
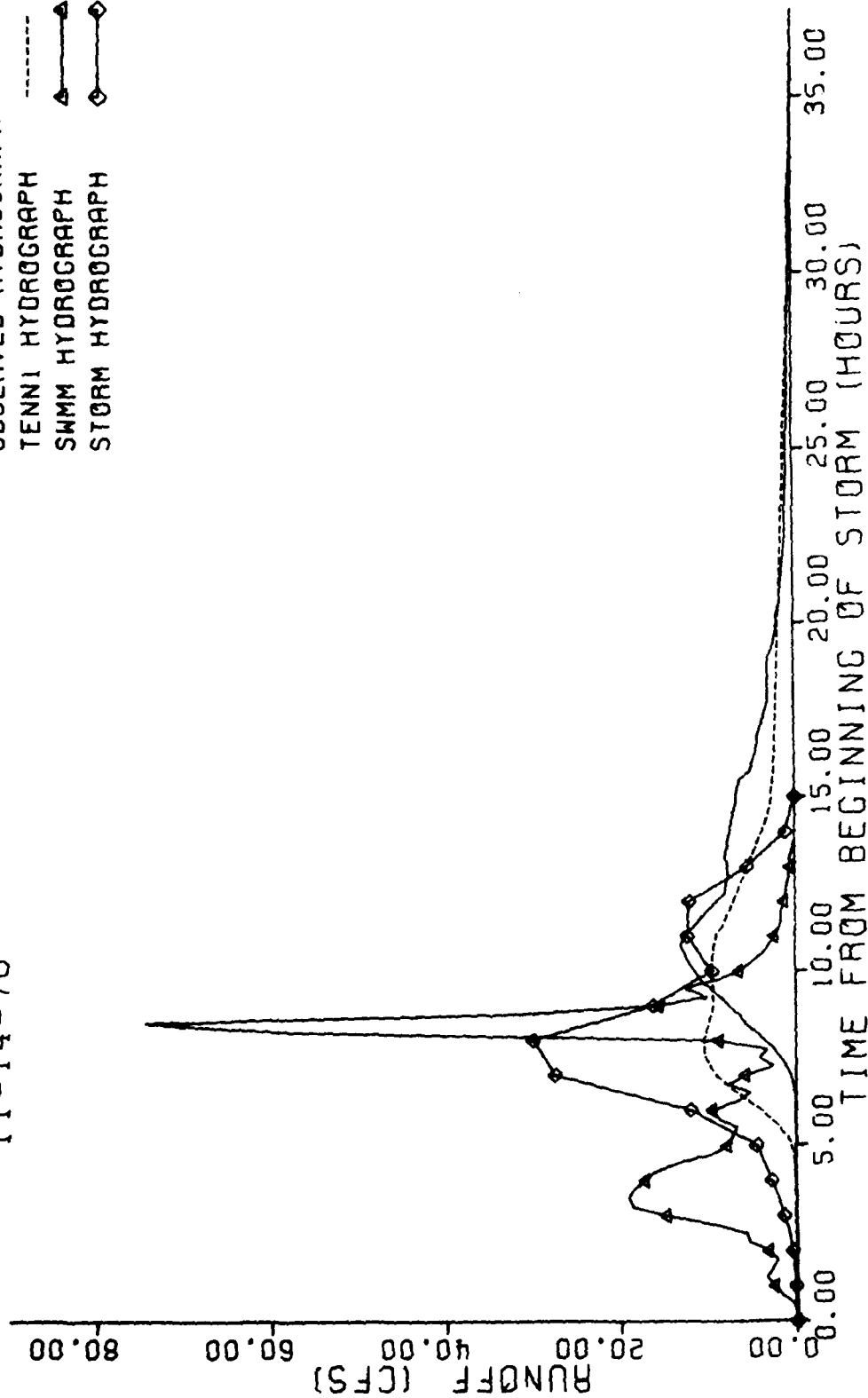
TIME FROM BEGINNING OF STORM (HOURS)

Figure A-7. Hydrograph Simulations, McDowell Ditch, 11/14/78
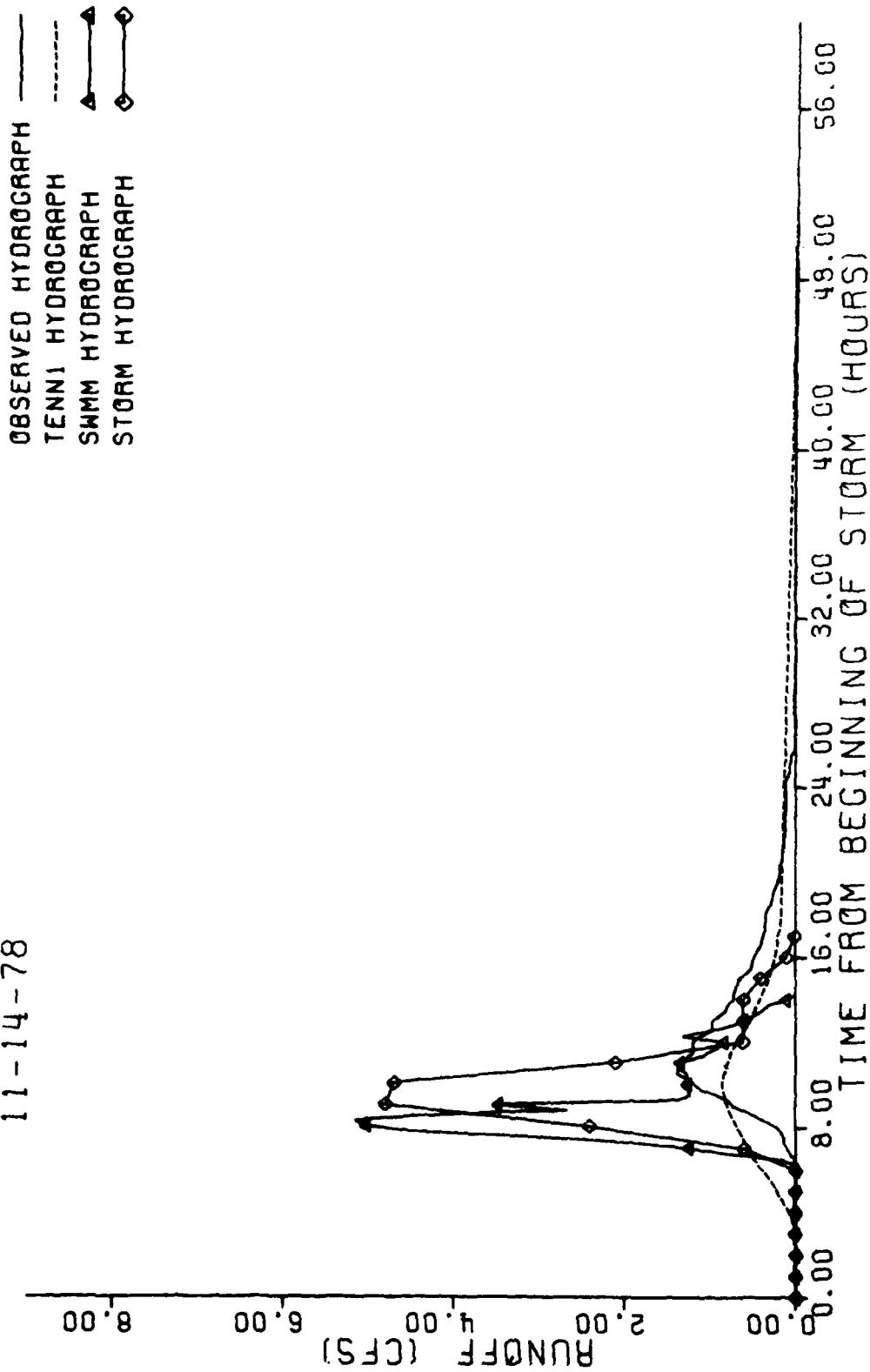
Figure A-8. Hydrograph Simulations, East Ditch, 11/14/78

75

C-2, EAST DITCH
11-17-78

Legend:
OBSERVED HYDROGRAPH
TENN1 HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH

RUNOFF (CFS)

TIME FROM BEGINNING OF STORM (HOURS)
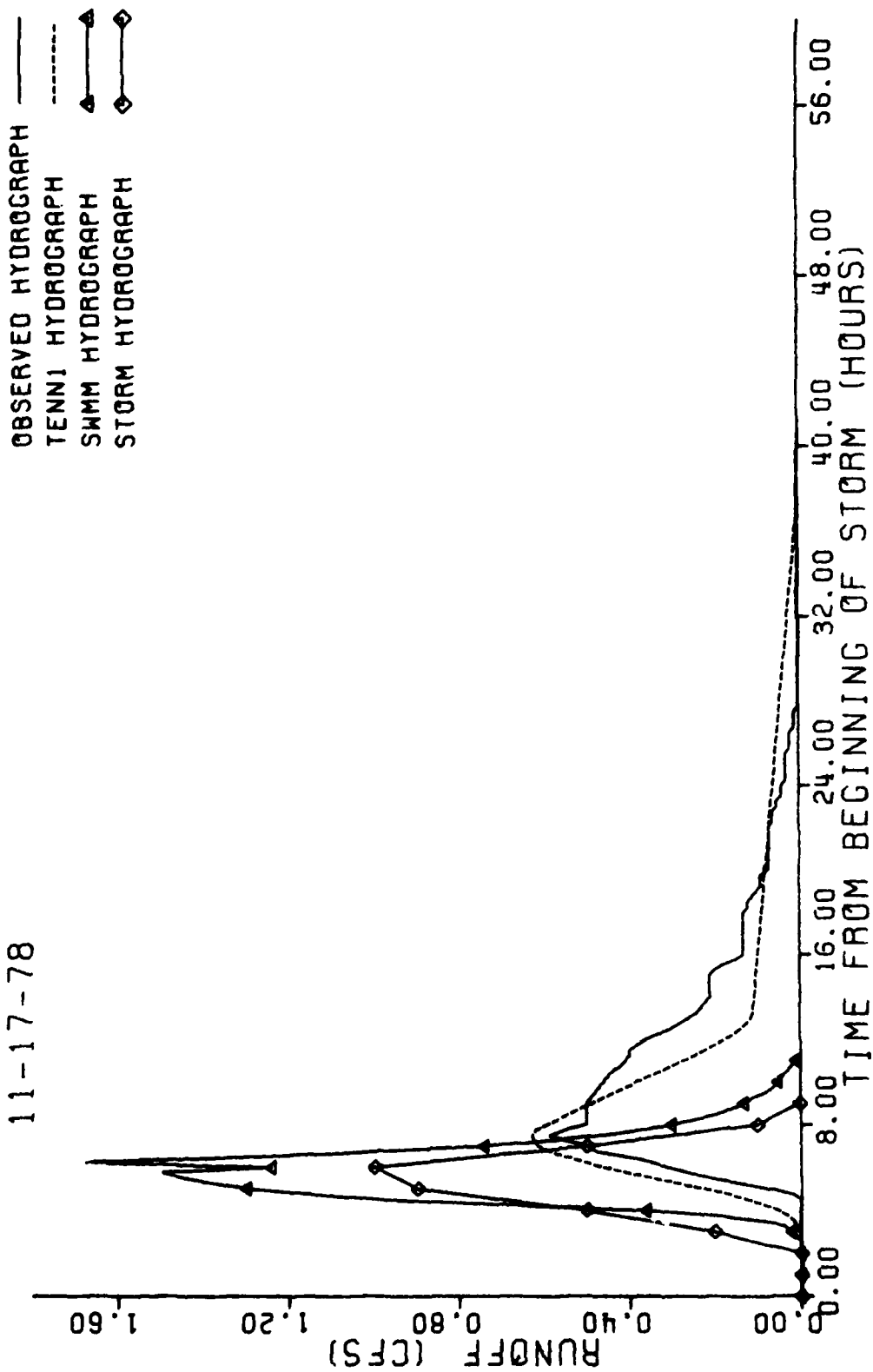
Figure A-9. Hydrograph Simulations, East Ditch, 11/17/78

Figure A-10. Hydrograph Simulations, East Ditch, 12/7/78

M-1,CLINE DITCH
08-02-78

OBSERVED HYDROGRAPH
TENNI HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH
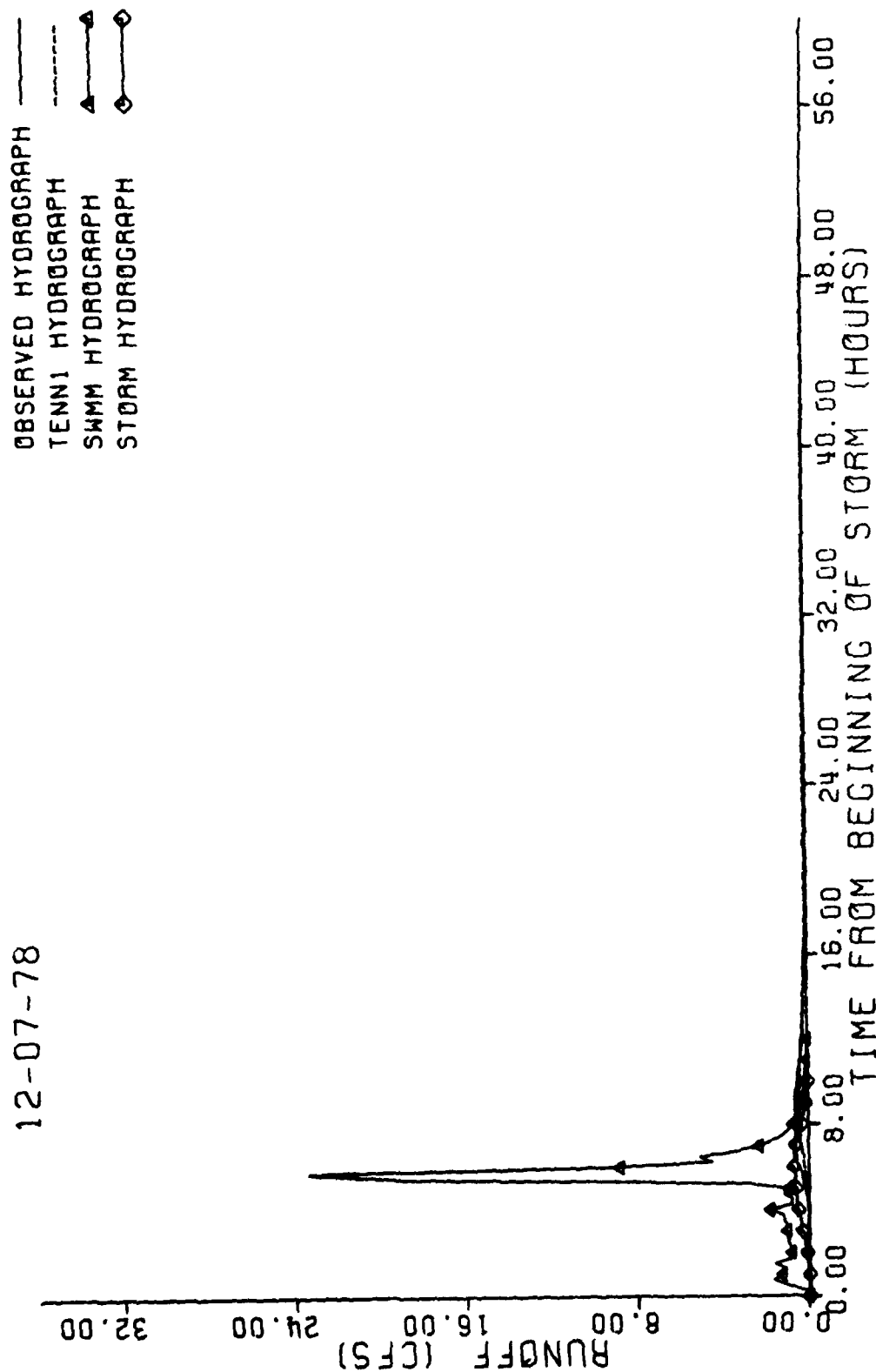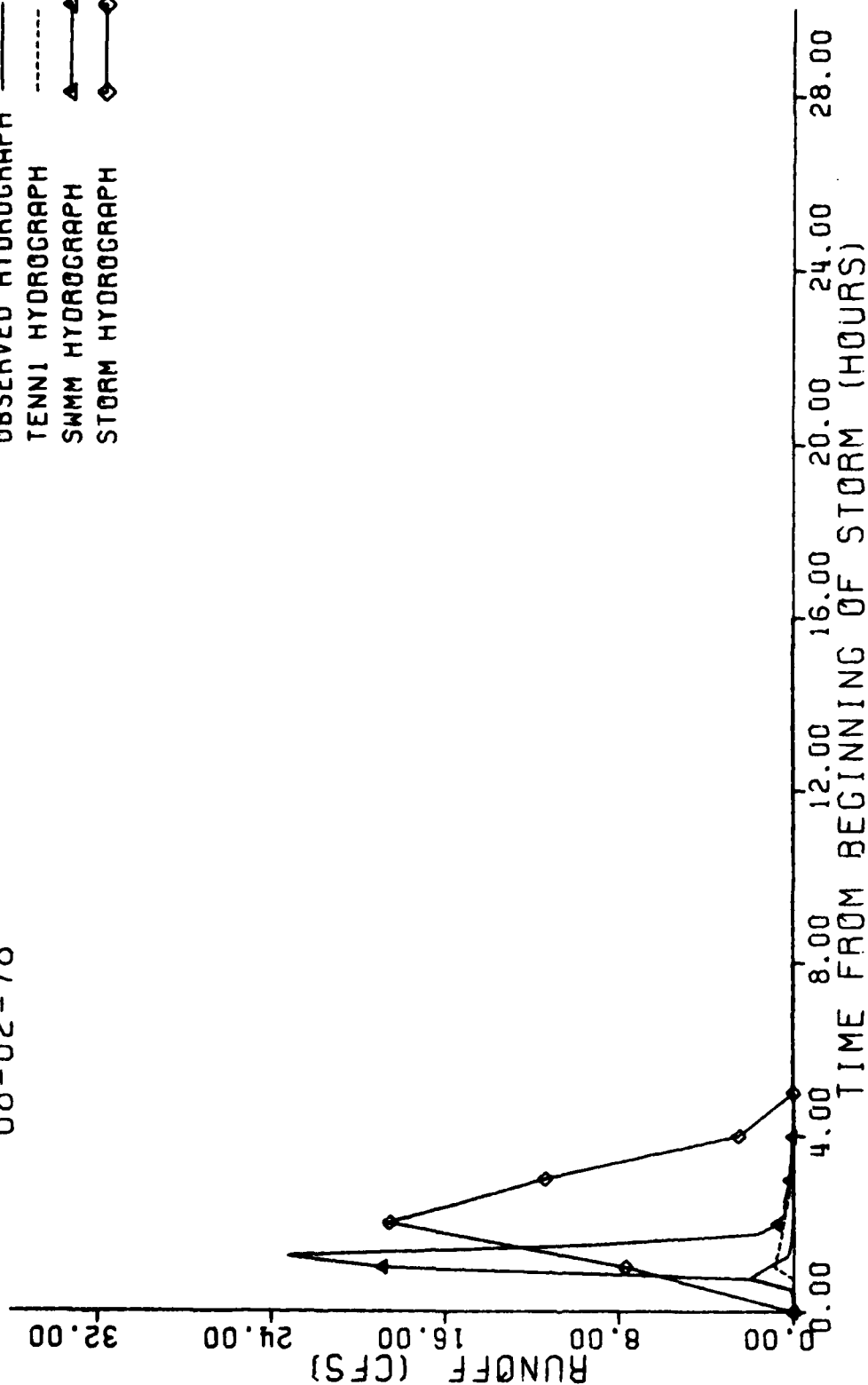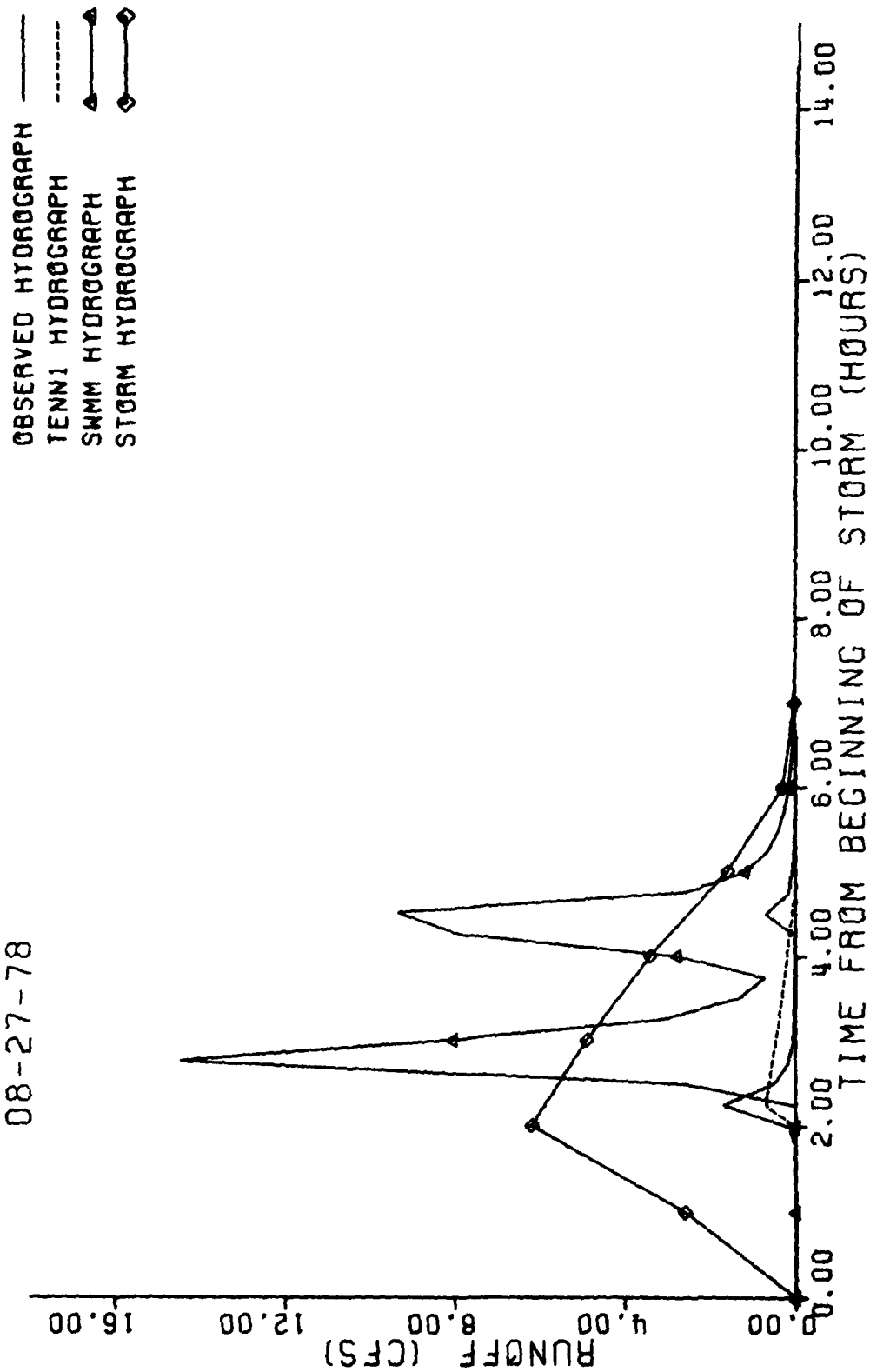
Figure A-11. Hydrograph Simulations, Cline Ditch, 8/2/78

Figure A-12. Hydrograph Simulations, Cline Ditch, 8/27/78

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M-1,CLINE DITCH
09-14-78

OBSERVED HYDROGRAPH
TENN1 HYDROGRAPH
SWMM HYDROGRAPH
STORM HYDROGRAPH

RUNOFF (CFS)

TIME FROM BEGINNING OF STORM (HOURS)
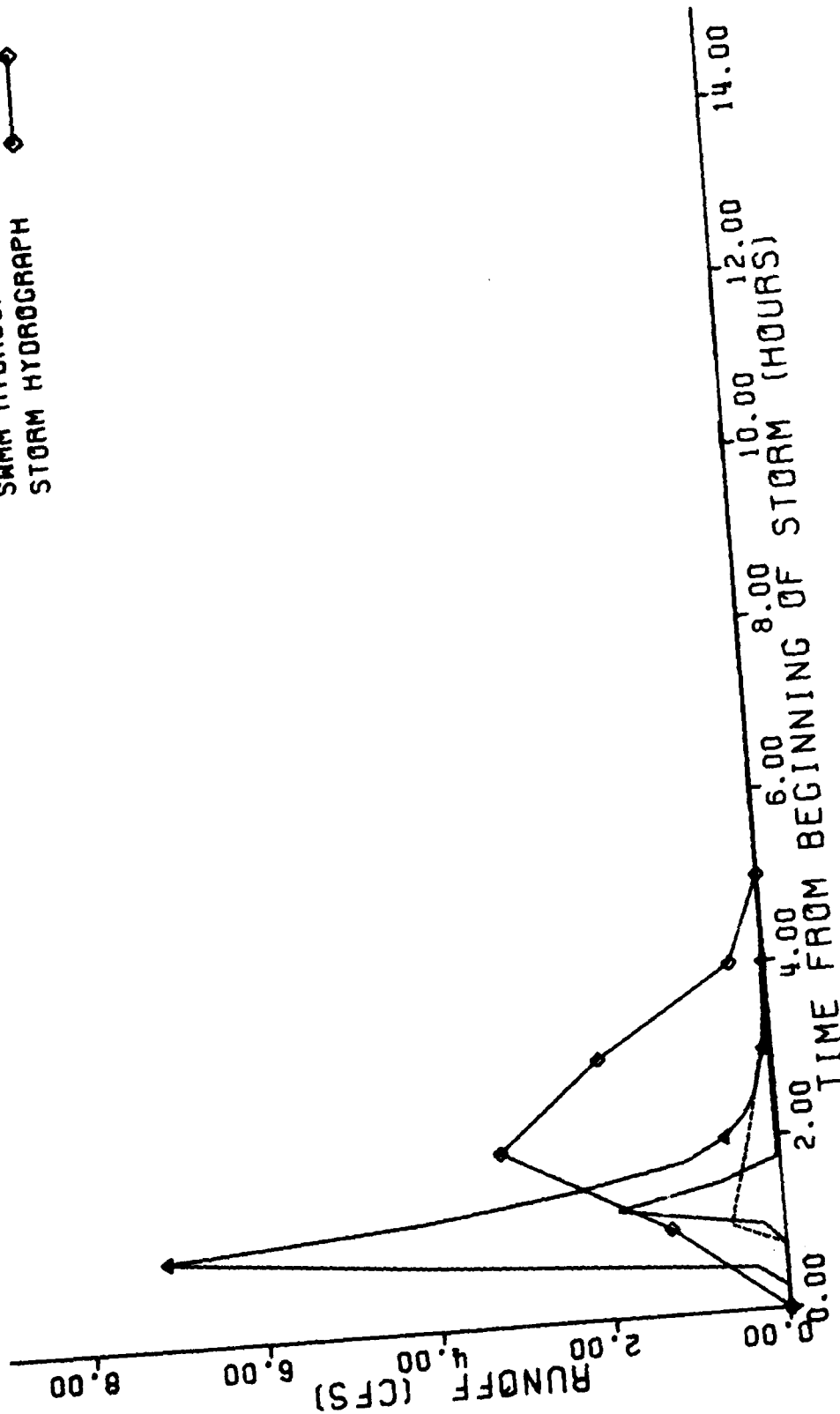
Figure A-13.   Hydrograph Simulations, Cline Ditch, 9/14/78

APPENDIX B
RUNOFF QUALITY DATA

TABLE B-1. SUMMARY OF MCDOWELL DITCH WATERSHED RUNOFF QUALITY

Pollutant (mg/l)	Stormwater Runoff			Runoff During Dry Periods		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
Fe	0.54	0.55	184	0.42	0.46	110
Zn	0.88	0.52	123	0.69	1.96	50
Na	2.80	2.45	76	9.3	2.4	26
Mg	8.3	7.2	118	22.7	12.4	76
Ca	37.0	23.0	119	69.3	15.8	47
Pb	0.005	0.003	124	0.017	0.110	53
Mn	0.06	0.01	5	0.071	0.039	10
NO_3	7.00	4.68	115	4.32	4.16	62
NH_3	0.11	0.16	116	10.0	18.8	68
SS	75.3	55	156	48.5	69.1	68
TOC	–	–	0	10.0	8.8	4
Alk	51.8	31.7	138	83.4	45.4	49
PO_4	0.067	0.035	72	0.063	0.034	58
COD	50.0	31.6	153	30.1	29.0	32
O&G	–	–	0	40.7	48.8	11
BOD	–	–	0	4.49	2.85	12
pH	7.64	0.39	7	7.2	0.80	37

TABLE B-2. SUMMARY OF CLINE DITCH WATERSHED RUNOFF QUALITY

Pollutant (mg/l)	Stormwater Runoff			Runoff During Dry Periods		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
Fe	0.60	0.76	142	0.41	0.18	75
Zn	0.55	0.56	120	0.08	0.12	28
Na	4.05	2.05	48	-	-	0
Mg	6.08	3.40	120	37	44	48
Ca	36.6	28.1	120	81.8	37.2	19
Pb	0.00143	0.0143	115	0.0051	0.0101	54
Mn	0.12	0.05	6	0.16	0.23	11
NO_3	5.65	3.30	96	10.7	5.30	69
NH_3	0.13	0.09	96	0.066	0.133	70
SS	87.8	162.9	65	77	92	43
TOC	-	-	0	16.5	13.8	4
Alk	43.0	22.8	66	105	18	43
PO_4	0.228	0.167	120	0.026	0.029	36
COD	30.3	24.2	97	24.7	30.7	23
O&G	-	-	0	68.3	56.5	15
BOD	-	-	0	1.38	0.49	8
pH	-	-	0	7.3	0.9	21

TABLE B-3. SUMMARY OF EAST DITCH WATERSHED RUNOFF QUALITY

Pollutant (mg/l)	Stormwater Runoff			Runoff During Dry Periods		
	Mean	Standard Deviation	No. of Samples	Mean	Standard Deviation	No. of Samples
Fe	0.80	0.62	22	0.38	0.30	22
Zn	0.29	0.89	73	-	-	0
Na	-	-	0	-	-	0
Mg	5.61	3.23	82	-	-	0
Ca	22.9	12.0	88	-	-	0
Pb	0.0060	0.0073	143	0.038	0.155	36
Mn	0.15	0.12	34	0.07	0.02	9
NO_3	5.21	2.83	168	9.21	30.0	51
NH_3	0.071	0.055	168	14.7	36.1	53
SS	166	211	63	66.7	71.8	38
TOC	10.4	4.4	23	14	10.5	4
Alk	60.0	39.8	55	126	52	40
PO_4	0.23	0.14	152	0.075	0.102	48
COD	30.4	27.9	60	28.4	33.7	18
O&G	-	-	0	22.2	23.8	12
BOD	-	-	0	2.07	1.25	9
pH	-	-	0	7.15	0.85	26

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