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Infiltration Characteristics and Hydrologic Modeling of Disturbed Land, Moshannon, Pennsylvania

A Thesis in

Geology

by

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ABSTRACT

A series of 97 infiltration tests were conducted on a 120 ha disturbed watershed (a reclaimed mine site), under variable surface age (1,2,3,4,8, and 9 years), rainfall intensity (2-11 cm/hr), and antecedent moisture conditions (4-40% by volume). Infiltration characteristics of the minesoils were determined, and the effects of rainfall intensity and change in infiltration with age were explored through qualitative and statistical analyses.

Rainfall intensity is an important control on infiltration rate. As intensity increases, initial and final infiltration rate, the 30-minute infiltrated volume, and the saturated wetting depth increase. The strength of the relationship between rainfall intensity and the infiltration parameters increase with minesoil age, up to age 4.

Several soil/surface properties of minesoil change with minesoil age, including the grain size distribution, vegetation, and surface roughness. The infiltration characteristics final infiltration rate, 30-minute infiltrated volume, time to first runoff, sorptivity, and Horton's exponent also change as the soil/surface properties change. The result is an overall increase in infiltration rate as minesoil age increases. The changes in the soil/surface properties and infiltration

characteristics are rapid over the first three years, but the rate of change dramatically decreases by age 4. This may be an indication that a quasi-equilibrium has been obtained between soil/surface properties, weathering, and erosion.

Multiple regression equations were developed to describe the influence of rainfall intensity and soil/surface properties on each infiltration parameter for each surface age. The significant independent variables and coefficients in the regression equations change with age for each infiltration variable.

The ANSWERS hydrologic model was used to simulate infiltration and runoff characteristics of a small disturbed watershed. Input parameters for the model were determined from data collected during infiltration tests and from regression equations developed for the infiltration parameters. The runoff hydrograph predicted by ANSWERS was found to be very sensitive to topography, infiltration parameters, and Manning's roughness coefficient. Simulation of a high intensity storm (4.0 cm/hr) was calibrated against observed runoff. The calibrated parameters were then applied to a higher intensity storm (5.7 cm/hr), and three lower intensity storms (2.9, 2.3, and 1.0 cm/hr). Predicted peak runoff was 106% of observed for the high intensity storm (5.7 cm/hr), but the accuracy of the predicted peak decreased with rainfall intensity (at an intensity of 1.0 cm/hr, ANSWERS predicted only 35% of observed peak runoff). For each storm, total runoff volume and time to peak runoff were underpredicted.

CHAPTER III

RUNOFF MODELING

ANSWERS Runoff Model

ANSWERS (Beasley and Huggins, 1980) is an acronym for Areal Non-point Source Watershed Environmental Response Simulation. The model is a deterministic, distributed parameter event model, developed to estimate and control non-point source pollution from agricultural land. The model simulates a given rainfall event, and uses a description of the topography, soils, vegetation and channel network to predict runoff and sediment detachment and transport. In this study, only the runoff generation subroutine is used to model surface hydrology of the Moshannon watershed. A generalized flow chart of the ANSWERS program is given in Figure 13.

The modeled watershed is initially divided into square elements, which for the Moshannon watershed are 10 m on a side (see Figure 19b). Several input parameters are specified by the user for each element: average slope of the land surface (S1), the direction of maximum surface slope (ANG), soil type, crop type, and if applicable, channel type. Soil type specifies the infiltration parameters and crop type specifies vegetation and roughness parameters (Table 9).

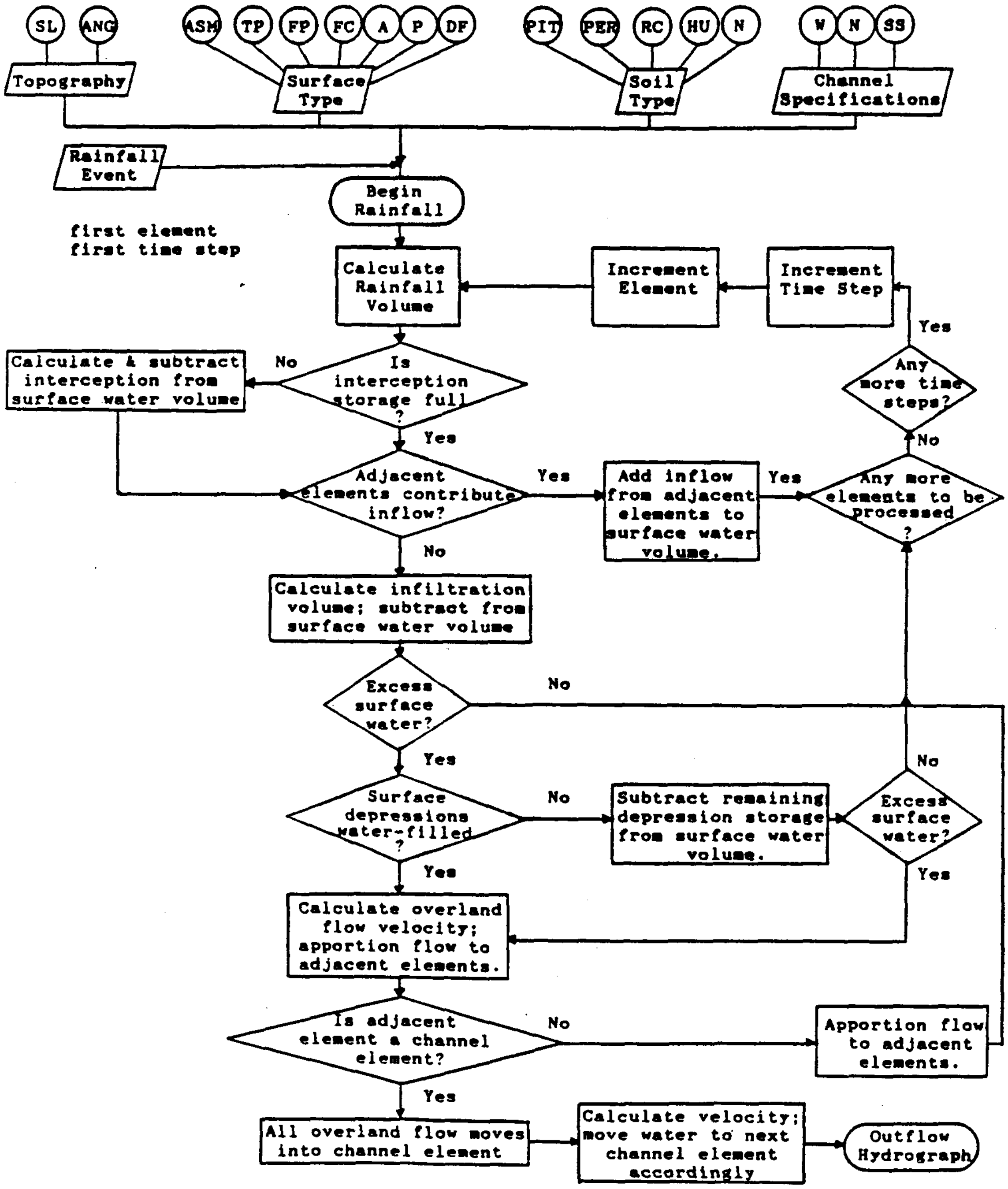


Figure 13. Flow diagram of the ANSWERS program. See Table 7 for explanation of input symbols.

Table 9. Input parameters for the ANSWERS runoff model.

	VARIABLE	DEFINITION	UNITS
RAINFALL VARIABLES:	TIME	Time since beginning of event	minutes
	RF	Rainfall intensity that ended at corresponding time	mm/hr
SOIL TYPE:	TP	Total porosity	% volume
	FP	Field capacity	%
	FC	Steady-state infiltration rate	mm/hr
	So	Holton's a: difference between fc and maximum infiltration rate (eqn. 7)	mm/hr
	P	Holton's P: exponent (eqn. 7)	-
	DF	Infiltration control zone depth	mm
	ASM	Antecedent soil moisture	%
CROP TYPE:	PIT	Potential interception volume	mm
	PER	Percentage of vegetation cover	%
	RC	Roughness coefficient	-
	HU	Maximum roughness height	mm
	n	Manning's "n"	-
CHANNEL DESCRIPTORS	W	Width	m
	n	Manning's "n"	-
	SS	Channel slope	%
TOPOGRAPHY	Sl	Slope steepness for element	%
	ANG	Direction of maximum slope for element	degrees

ANSWERS generates a runoff volume from each element using a mass balance equation

$$RO = (RAIN + FL) - (IT + DEP + F) \qquad (15)$$

where RO = volume of runoff from individual element

RAIN = rainfall volume for element

FL = volume of inflow from adjacent elements

IT = volume of water intercepted by vegetation on element

DEP = surface retention volume for element

F = infiltrated volume for element.

A rainfall event is input into ANSWERS by specifying time periods from the beginning of the storm and rainfall intensity during the corresponding time period. The volume of rainfall over each element at each simulation time step is the calculated RAIN variable.

Interception is treated as a finite volume which is generally satisfied early in the storm. Maximum potential interception volume (PIT), is specified by the user. The amount of interception at each time step is a function of the rainfall rate and the percentage of vegetation cover. Additions to this storage volume continue during each time step until it is full.

Surface retention is calculated from the height of the micro-relief (HU), a shape factor (RC, which describes the spacing of roughness elements), average surface slope (Sl), and the amount of rainfall during each time step (RAIN). Surface retention determines the amount of water ponded on the surface, and influences infiltrated volume, because infiltration takes place only over ponded areas of the element.

Infiltration is calculated using a form of the Holtan equation (7)

$$fmax = fc + So(PIV/TP)^{P} \quad (16)$$

where fmax = infiltration capacity with the surface inundated

fc = steady-state infiltration capacity

So = maximum infiltration in excess of fc

PIV = volume of water that can be stored in the control zone before saturation

TP = total porosity

P = dimensionless coefficient relating rate of decrease in infiltration rate to increasing soil moisture content.

The FC, A, TP, and P parameters are user-specified for each soil type. PIV is calculated using the control zone depth (DF), TP, FP, and the antecedent moisture content (AM) specified with the soil type. The infiltration rate decreases throughout the storm to a steady-state rate, but can increase again if rainfall intensity decreases during a storm.

Calculated runoff volume (eqn. 15) is routed overland through the elements using the Manning equation to determine velocity:

$$V = n^{-1}R^{2/3}Sl^{1/2} \quad (17)$$

where V = flow velocity

n = Manning's roughness coefficient

R = hydraulic radius (for channel elements, R = width, for overland flow elements, R = average surface water detention depth)

Sl = energy gradient or slope.

Outflow from each element is apportioned to adjacent elements according to direction of maximum slope until overland flow reaches a channel element.

Baseflow also contributes inflow to the channel elements. Infiltrating water that percolates through the control zone enters a single groundwater storage reservoir. It is then released evenly to all channel elements at a rate proportional to the volume of accumulated groundwater storage.

Elements containing a channel are treated as "dual elements": The "top" element is an overland flow element. The "bottom" element is the channel element. Overland flow is simulated in the "top" element just as in other overland flow elements, except that all outflow from the element goes into the channel element below. The channel elements constitute a separate flow system, defined by user-specified channel width, slope, and Manning's n. Flow through the channel elements is simulated using the Manning equation (17) and an explicit, backward difference solution of the continuity equation:

$$In - Q = dST/dt \qquad (18)$$

where In = inflow rate to an element (rainfall, baseflow, and overland or channel flow from adjacent elements)

Q = outflow rate

ST = volume of water stored in an element

and t = time from the beginning of the storm.

Ultimately, the model produces a runoff hydrograph for the outlet channel at the mouth of the basin.

The ANSWERS model is sensitive to several input parameters that will be examined in this chapter. Sensitive parameters include topography of the watershed, the infiltration parameters, FC, So, P, and DF; and the roughness parameters, HU, RC, and n (Table 9). These parameters affect the depth of ponding on the surface, the area over which infiltration takes place, and the rate of infiltration and overland flow; thus, they control the volume and timing of runoff from the watershed. Accurate representation of these parameters is therefore necessary for the model to produce meaningful results.

Application of ANSWERS to Central Pennsylvanian Watersheds

ANSWERS has been applied to surface-mined watersheds by Curwick and Jennings (1982) and Jorgensen (1985). Jorgensen applied ANSWERS to two gaged watersheds on reclaimed mines in central Pennsylvania. One watershed, Pine Glen, was a fairly smooth, planar surface that had been reclaimed five years prior to the model simulation. The second watershed, Moshannon (the watershed also used in this study), was a newly reclaimed, more irregular, chisel-plowed surface with diversion channels. Jorgensen used results from a series of high intensity (6 - 8 cm/hr) infiltration tests conducted on 5 reclaimed mines to determine the input parameters for ANSWERS. He modeled both high and low intensity natural rainfall events on the two watersheds. ANSWERS simulated high intensity storms on the older, smoother Pine Glen surface quite well (Figure 14): the predicted runoff was approximately 80% of observed runoff and time to peak runoff was 116% of the observed (Table 10). Simulations of high intensity storms on the younger, more irregular Moshannon surface were less successful (Figure 15): the predicted runoff was 131 % of the observed and time to peak was 43% of observed (Table 10). Runoff from low intensity storms was severely underpredicted on both watersheds (figures 16 & 17), (Table 10).

The ANSWERS model simulated the Pine Glen watershed better than the Moshannon watershed at high intensities. Jorgensen suggests that this may be due to the differences in roughness features on the two watersheds. The Moshannon watershed has a rough surface (average roughness element is 3 cm) with chisel plow furrows, many boulders, and diversion channels. Conversely, Pine Glen has a fairly smooth surface, with lower roughness elements (average = 1

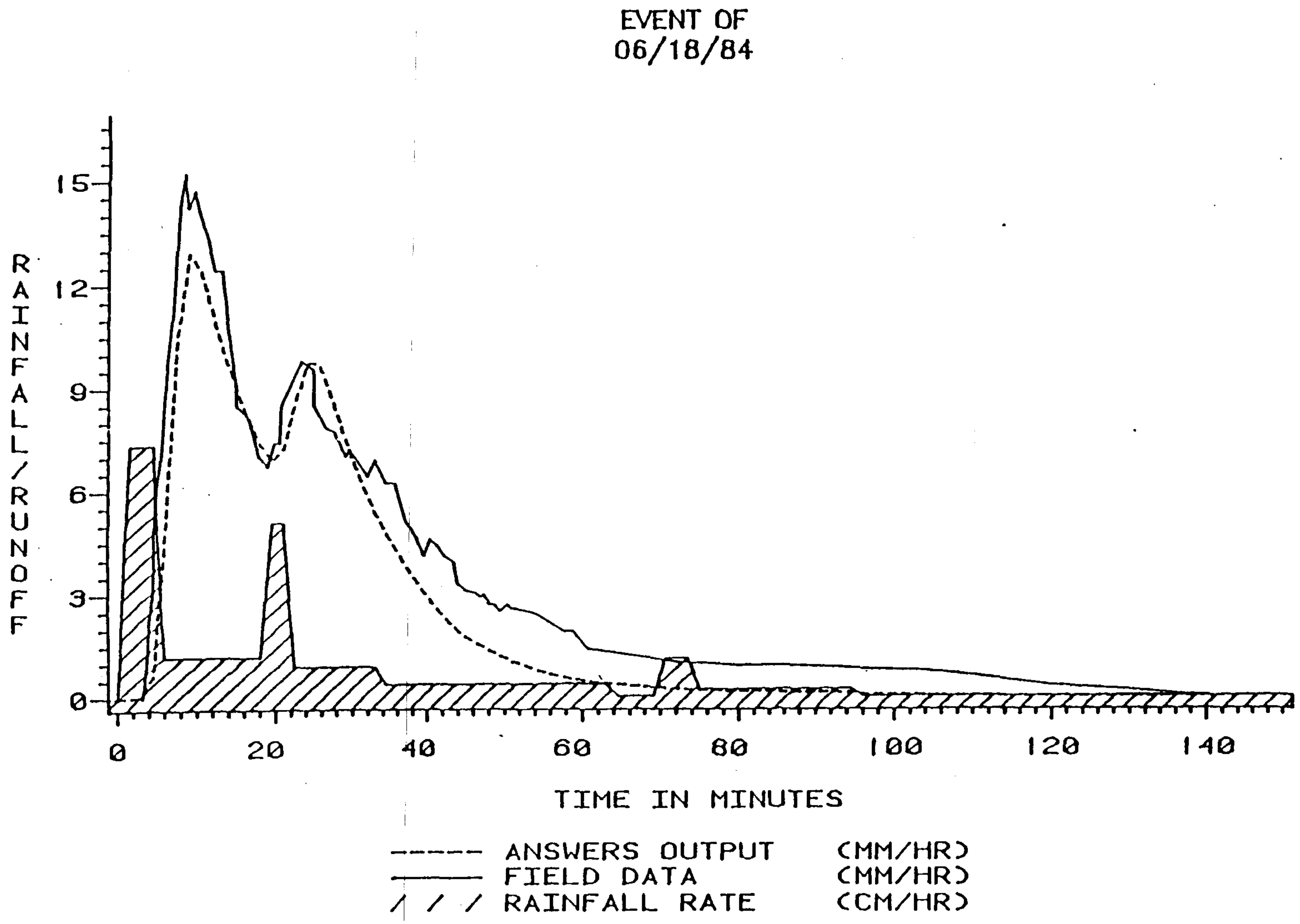


Figure 14. ANSWERS high intensity storm simulation of the Pine Glen watershed. Shows rainfall input and the observed and predicted runoff. From Jorgensen, 1985.

Table 10. Summary of Jorgensen's (1985) modeling results using the ANSWERS runoff model.

Event	06/18/84	07/01/84	10/19/84	10/26/84
Watershed	Pine Glen	Pine Glen	Moshannon	Moshannon
Average Rainfall Intensity, cm/hr	6	1.5	8	2
peak ratio[a]	116	47	212	53
timing ratio[b]	80	98	57	102
volume ratio[c]	80	30	131	52

[a]Ratio of predicted peak runoff to observed peak runoff.

[b]Ratio of predicted time to peak runoff to observed time to peak runoff.

[c]Ratio of predicted total runoff volume to observed runoff volume.

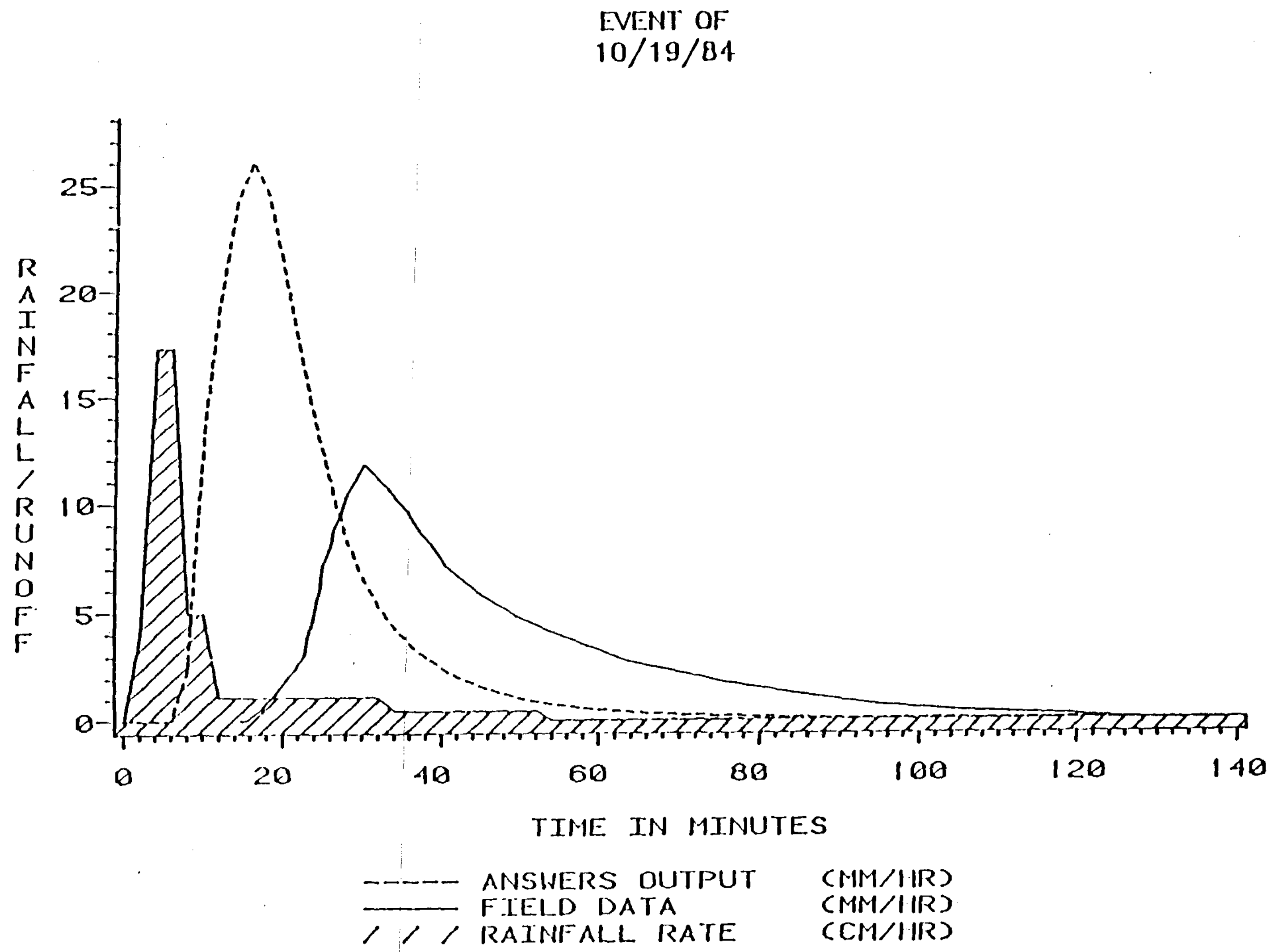


Figure 15. ANSWERS high intensity storm simulation of the Moshannon watershed. Shows rainfall input and the observed and predicted runoff. From Jorgensen, 1985.

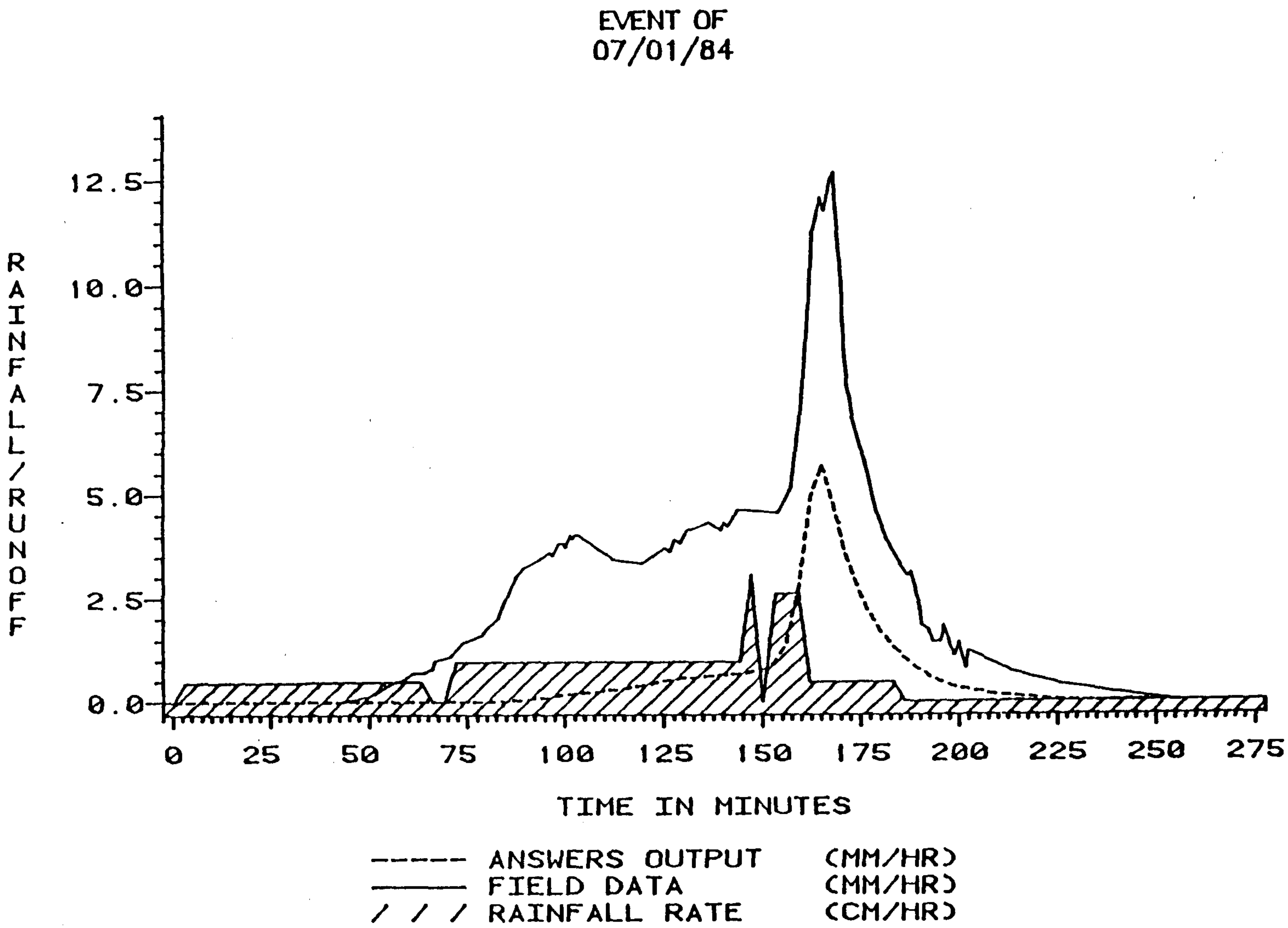


Figure 16. ANSWERS low intensity storm simulation of the Pine Glen watershed. Shows rainfall input and the observed and predicted runoff. From Jorgensen, 1985.

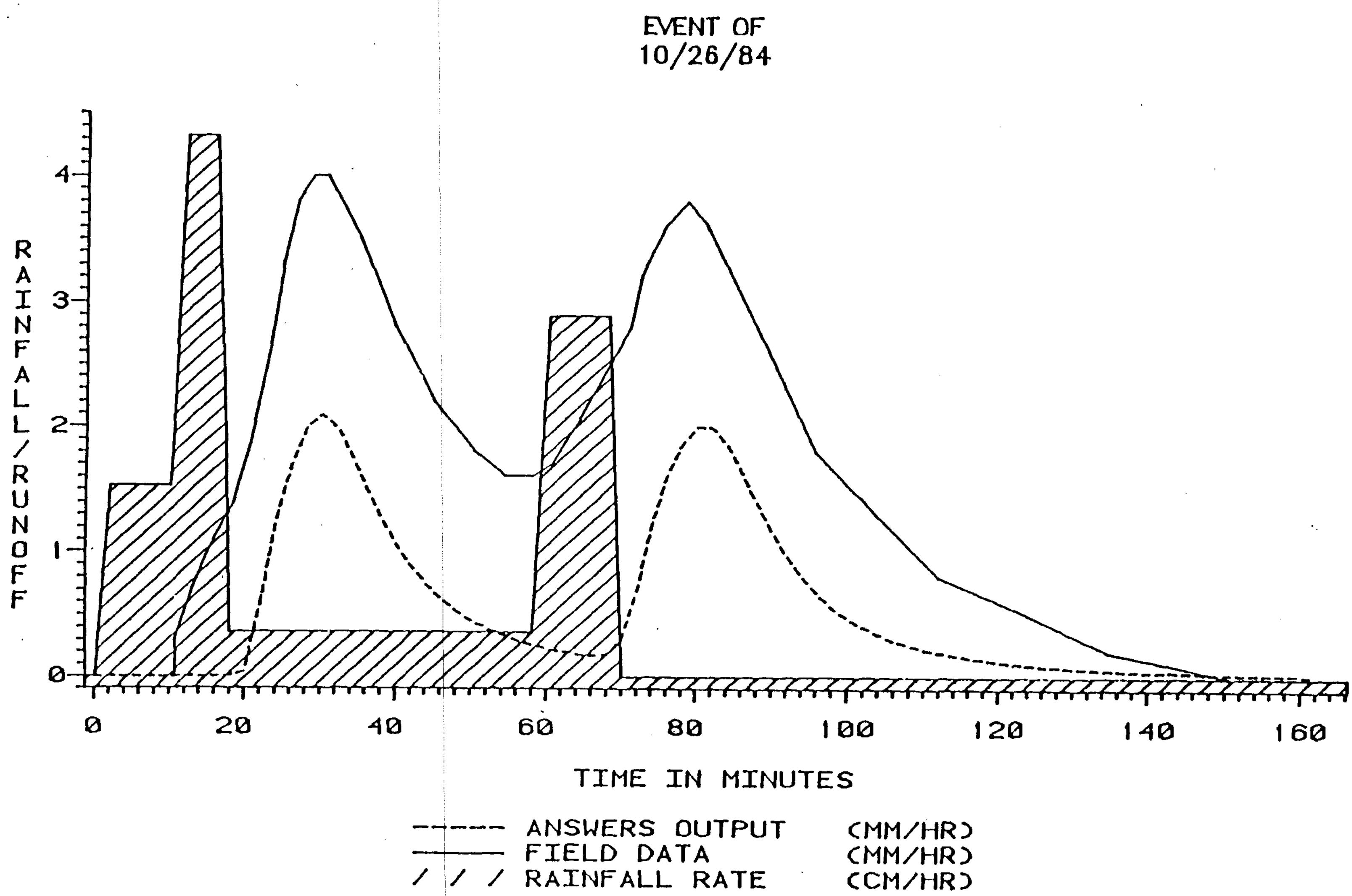


Figure 17. ANSWERS low intensity storm simulation of the Moshannon watershed. Shows rainfall input and the observed and predicted runoff. From Jorgensen, 1985.

cm) and no diversion channels. Surface roughness features store water on the surface and can increase flow path lengths substantially. The effect of surface roughness on flow path length can also change with water depth on the surface: When water depth is shallow, roughness elements force water into more circuitous routes, increasing flow path lengths. As the water depth increases and roughness elements are submerged, flow path lengths shorten. ANSWERS seems better able to simulate the response of the less rough surface.

A second factor that may have contributed to ANSWERS poorer performance in simulating the Moshannon watershed is the level of detail used to simulate watershed topography. Runoff models are sensitive to the topography and watershed geometry used for the simulation (Lane and Woolhiser, 1977). The Moshannon topographic model used by Jorgensen (1985) was constructed from a transit survey consisting of 3 transects across the watershed (SW - NE) and one around the perimeter of the basin. Pine Glen topography was constructed from a much more detailed plane-table survey. Thus, the more detailed Pine Glen survey may have resulted in a more accurate simulation.

ANSWERS also performed better on high intensity simulations than on low intensity simulations. Jorgensen calculated the infiltration parameters (Fc, So and P) for ANSWERS from high intensity infiltration tests and applied these parameters to simulations of both high and low intensity rainfall events. The control zone depth (DF) used for the simulations was also estimated from observations made during the high intensity infiltrometer tests. It has been shown (Chapter II) that the infiltration parameters vary with rainfall intensity. Thus, infiltration parameters calculated from the high intensity tests are too high for simulations of low intensity rainfall events, resulting in an underprediction of runoff.

Topography, infiltration parameters, and roughness parameters will be evaluated in an attempt to improve the simulation results for Moshannon. (Appendix B contains the input data for each element, and a summary of each modeled storm.) The topography of the Moshannon watershed was initially surveyed using a transit (Figure 18a, Jorgensen, 1985). The transit survey consisted of 73 surveyed points distributed over the 11.6 ha area along three transects and around the perimeter of the basin (point density = 6 pts/ha). Average slope for the transit survey is 11.6°, and the grid cell size used for the ANSWERS simulation was 20 m on a side (Figure 19a). To improve the topographic model of the Moshannon watershed, a plane-table and alidade survey was conducted (Figure 18b). The plane-table survey consisted of 234 surveyed points distributed evenly over the watershed area (point density = 20 pts/ha). The plane table survey produced lower average slopes (10.6°) than the transit survey, more precisely defined the main channel

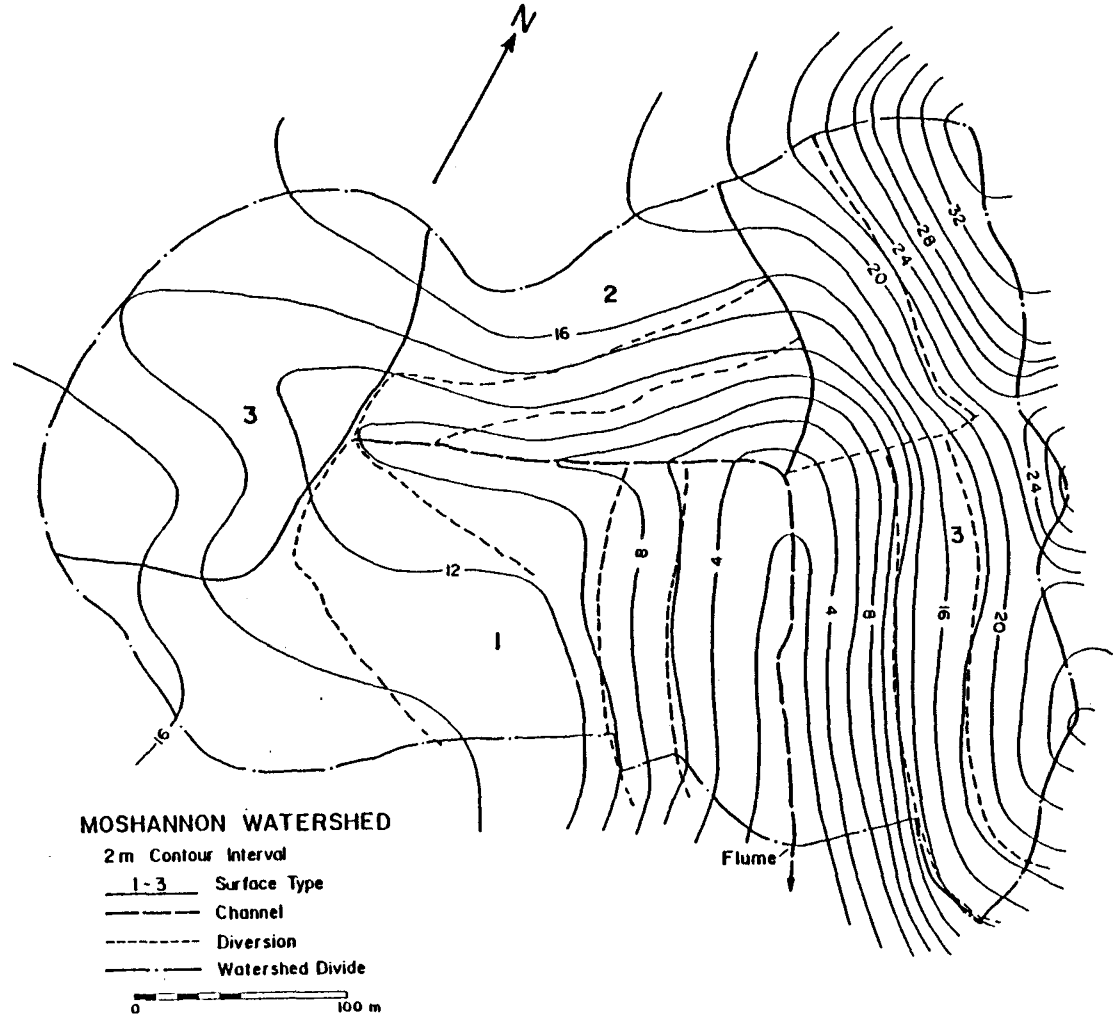
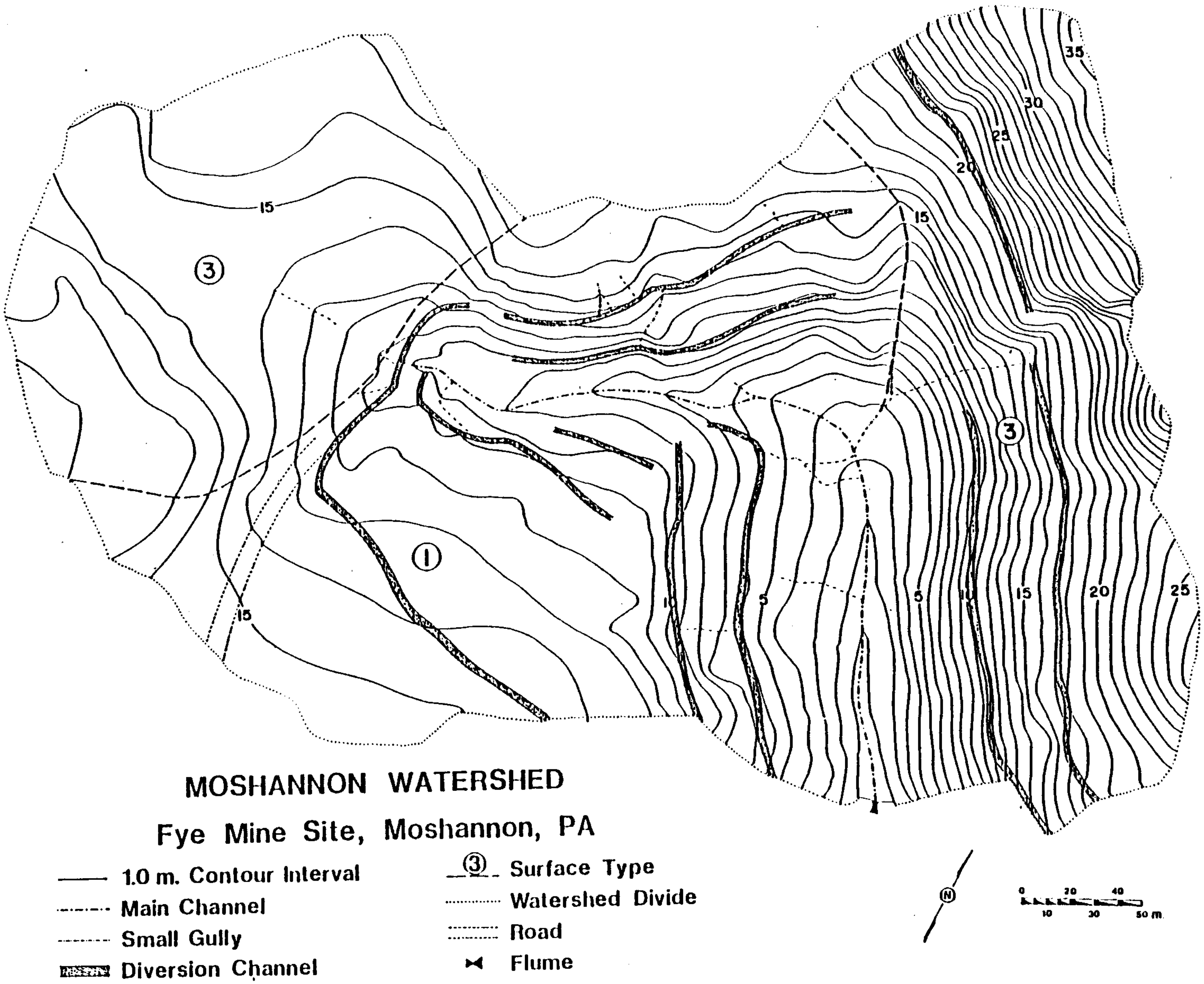


Figure 18A. Topographic map of the Moshannon watershed, surveyed by transit. The designated surface types differ in age and/or vegetation characteristics. Surfaces 1 and 2 were reclaimed in 1984, surface 3 in 1983. From Jorgensen, 1985.

Figure 18B. Topographic map of the Moshannon watershed, surveyed by plane table and alidade. Jorgensen's surfaces 1 and 2 were combined because differences between the two are no longer discernable.



MOSHANNON WATERSHED

Fye Mine Site, Moshannon, PA

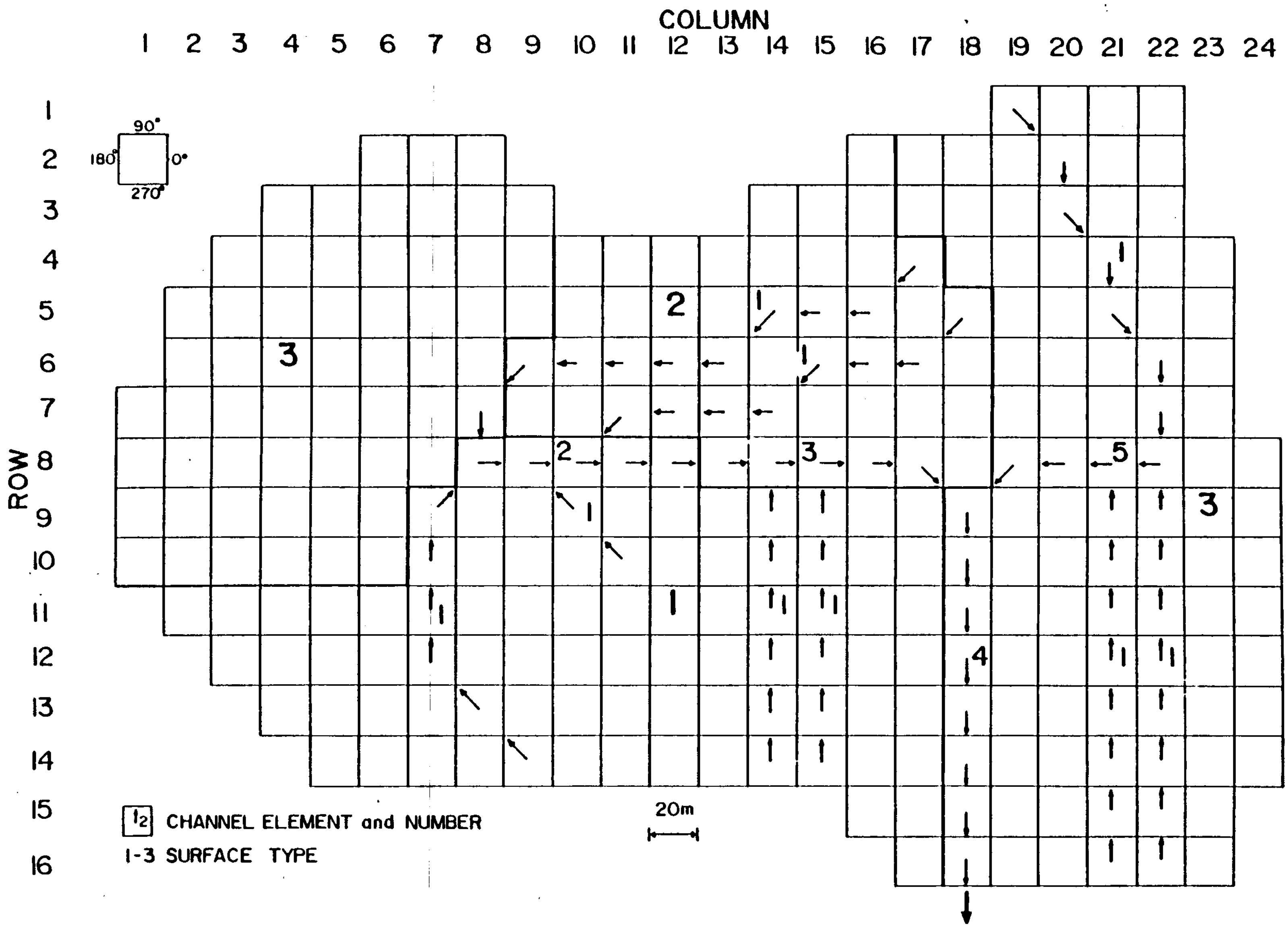
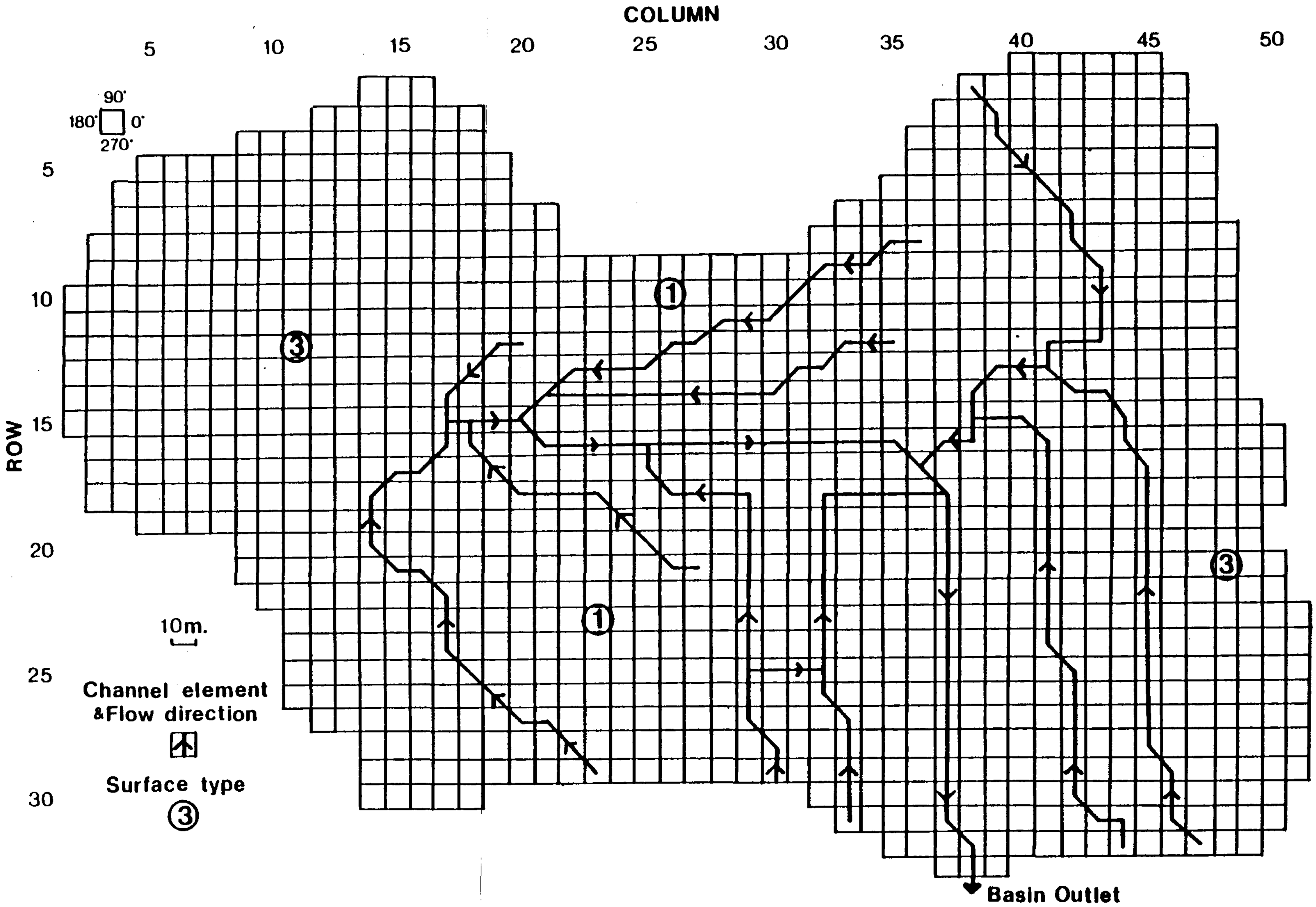


Figure 19A. ANSWERS element grid for the Moshannon watershed, 20 m elements. Arrows indicate direction of channel flow. From Jorgensen, 1985.

Figure 19B. ANSWERS element grid for the Moshannon watershed, 10 m elements (this study). Arrows indicate direction of channel flow. (See Appendix B for input data.)


COLUMN
5
10
15
20
25
30
35
40
45
50
ROW
5
10
15
20
25
30
90°
180°
0°
270°
①
③
①
③
10m.
Channel element &Flow direction
Surface type
③
Basin Outlet

(for example, row 15, columns 17-19 in Figure 19b), and diversion channels (for example, row 17-18, columns 25-27, Figure 19b), and delineated several small gullies (row 25, column 29-32, Figure 19b). The more detailed survey also increased overall channel length. The grid cell size for the ANSWERS simulation was reduced from 20 m (Figure 19a), to 10 m on a side (Figure 19b). The change in grid cell size allowed simulation of the more detailed topography and channel network provided by the plane-table survey.

To examine the effects of changing the topography on predicted runoff, a storm modeled by Jorgensen (1985, event 10/19/84) was re-run (Figure 20) using his original input parameters, with the new, more detailed topography (storm 1a and 1b, Table 11). The runoff peak height decreased significantly, from 212% to 123% of the observed runoff peak (Table 11). However, the time to peak discharge shifted slightly to the left (from 57% to 43% of observed), away from the observed time to peak discharge. The decrease in runoff can be attributed to lower slopes obtained during the plane-table survey, particularly in the southwestern portion of the watershed (figures 18A and B). The effects of decreasing the watershed slopes in the model are threefold: the amount of water retained on the surface by roughness elements increases, the area over which infiltration can occur increases, and surface runoff velocity decreases. These effects contribute to higher infiltration rates and lower runoff volumes. Increased

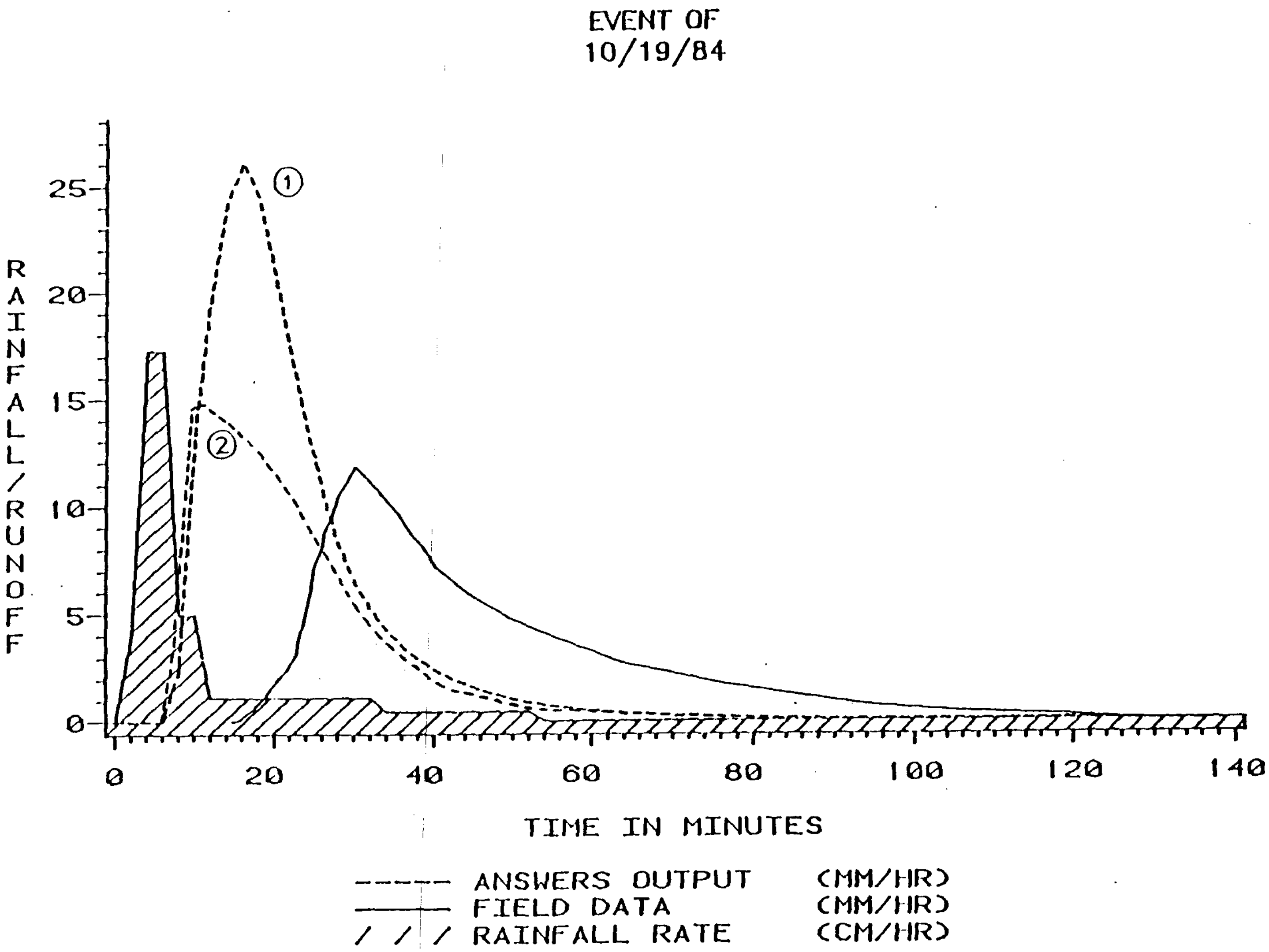


Figure 20. ANSWERS simulation of the Moshannon watershed, showing the effect of increased topographic detail on predicted runoff. Curve 1 is simulated using transit data. Curve 2 is simulated using plane table and alidade data. (See table 11 for input.)

Table 11. Surface and crop input parameters for ANSWERS runs and simulation results.

Parameter/ surface		Runs 1a	1b	2a	2b	2d	2e	2f	2g	2h	3	4	5	6
TP	84	44	*	39	*	*	*	*	*	*	33	34	33	33
	83	40	*	33	*	*	*	*	*	*	39	33	39	39
FP	84	62	*	60	*	*	*	*	*	*	60	60	60	60
	83	60	*	60	*	*	*	*	*	*	60	60	60	60
ASM	84	0.18	*	0.23	*	0.06	0.23	*	*	*	0.28	0.22	0.14	0.28
	83	0.20	*	0.17	*	0.06	0.17	*	*	*	0.34	0.28	0.14	0.34
FC	84	13.4	*	33.0	*	*	*	*	26.4	*	21.2	13.6	12.1	8.9
	83	25.5	*	23.2	*	*	*	*	16.6	*	30.9	13.7	21.9	18.7
SO	84	82.0	*	9.81	*	*	*	*	3.86	*	0.73	3.85	0.73	0.73
	83	77.0	*	0.73	*	*	*	*	0.73	*	7.30	0.73	2.03	1.29
P	84	9.0	*	11.3	*	*	*	*	7.97	*	3.16	22.3	2.10	1.84
	83	2.2	*	3.46	*	*	*	*	2.58	*	13.7	2.27	8.50	15.5
DF	84	50.0	*	69.5	*	*	*	*	53.7	*	63.0	4.74	45.8	40.9
	83	50.0	*	67.9	*	*	*	*	67.9	*	69.5	48.4	69.5	69.5
PIT	84	0.50	*	0.80	*	*	*	*	*	*	0.80	0.80	0.80	0.80
	83	0.70	*	0.80	*	*	*	*	*	*	0.80	0.70	0.80	0.80
PER	84	0.15	*	0.40	*	*	*	*	*	*	0.40	0.40	0.40	0.40
	83	0.60	*	0.40	*	*	*	*	*	*	0.40	0.30	0.40	0.40
RC	84	0.45	*	0.45	*	*	0.55	0.45	*	0.25	0.25	0.25	0.25	0.25
	83	0.45	*	0.45	*	*	0.55	0.45	*	0.25	0.25	0.26	0.25	0.26
HU	84	10.0	*	20.0	*	*	*	45.0	20.0	60.0	48.0	54.0	48.0	48.0
	83	35.0	*	16.0	*	*	*	40.0	16.0	48.0	60.0	48.0	60.0	60.0
n	84	0.06	*	0.09	0.40	0.09	*	*	*	0.55	0.55	0.55	0.65	0.65
	83	0.08	*	0.09	0.40	0.09	*	*	*	0.55	0.55	0.56	0.55	0.55
Topo[e]		t	pa	*	*	*	*	*	*	*	pa	pa	pa	pa
RF[a]		6.0	*	6.5	*	*	*	*	4.0	4.0	5.2	2.9	2.3	1.0
peak[b]		212	123	148	89	146	146	150	181	101	106	73	54	35
timing[c]		57	43	67	76	67	67	67	65	82	49	81	77	93
volume[d]		131	86	86	60	86	86	91	111	82	49	62	48	34

[a]Rainfall intensity used to calculate infiltration parameters.
[b]Ratio of predicted peak runoff to observed peak runoff.
[c]Ratio of predicted time to peak runoff to observed time to peak runoff.
[d]Ratio of predicted total runoff volume to observed total runoff volume.
[e]Topography used: t = transit survey topography
pa = plane-table and alidade survey topography
*Value is same as in preceding column.

channel length decreased the time to concentration for the watershed, causing the shift in time to peak discharge.

Although model predictions improved considerably by increasing the accuracy of the surface topography, further improvement can be made to the model. When Jorgensen modeled this site, the surfaces were age 1 and 2. Because data on an age 1 surface could not be obtained for this study (the youngest minesoil on the site was age 2), nothing more could be done with this particular storm event to try to improve the simulation. Therefore, a new storm (Storm 2), one that occurred during a year for which data were available for the surface ages, was chosen.

Calibration and Sensitivity Analysis

Storm 2 (Table 11) occurred on June 7, 1986. The surfaces on the Moshannon watershed for this storm were ages 3 and 4. This storm was chosen to calibrate the ANSWERS model for several reasons: it is approximately 30 minutes in duration (the same as the infiltration plot tests), antecedent moisture is relatively low (Table 11), the rainfall intensity is fairly constant throughout the storm, and the observed hydrograph is simple and smooth (Figure 21).

The input data for the initial simulation are listed in Table 11 (Storm 2a). Values for total porosity (TP), percent vegetation (PER) and height of roughness elements

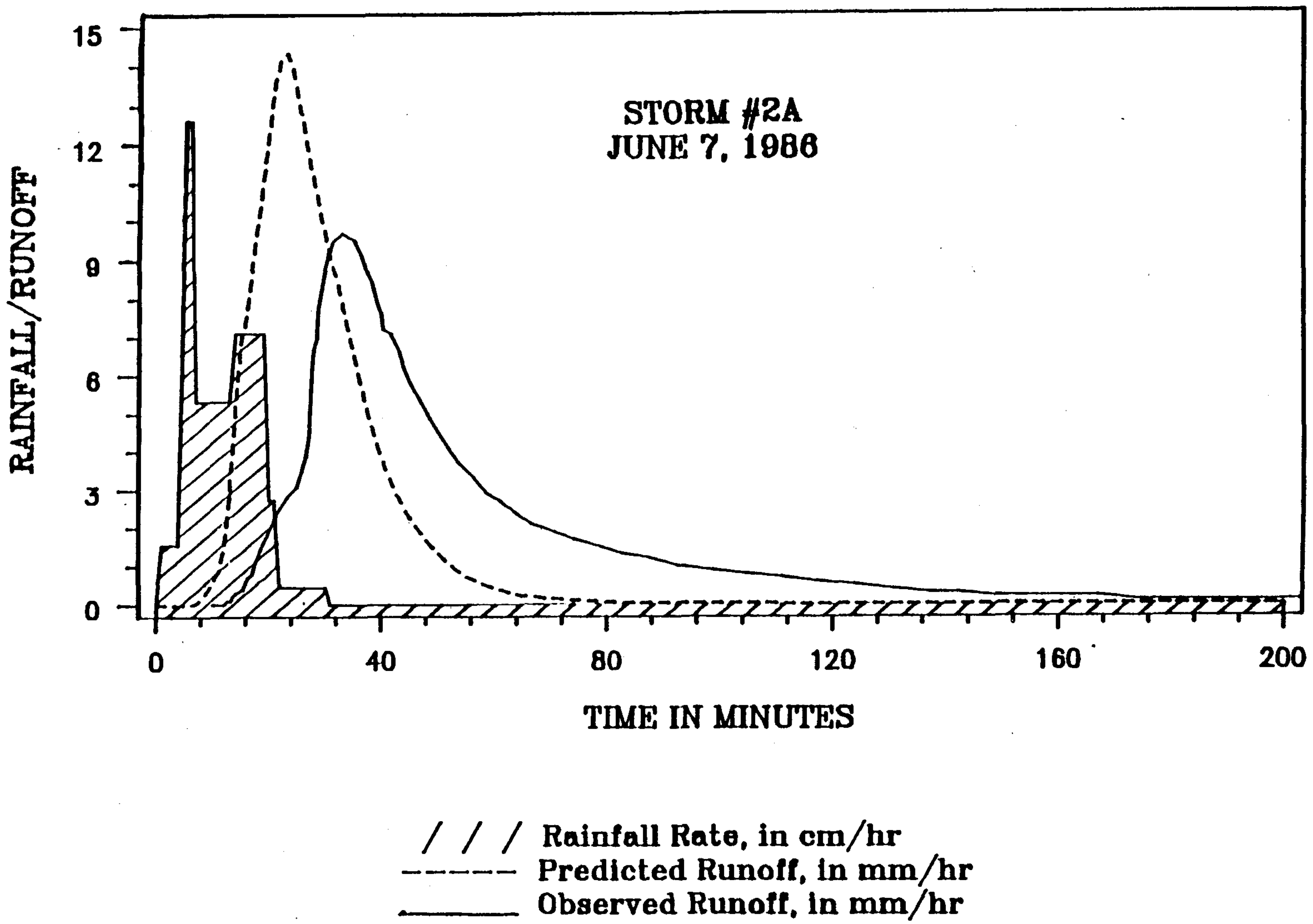


Figure 21. Initial ANSWERS simulation of Storm 2, showing rainfall input and observed and predicted runoff. (See table 11 for input data.)

(HU) are mean values for each surface age (Table 5). Field capacity (FP), potential interception (PIT), roughness factor (RC), and Manning's n were estimated from values given in Beasley and Huggins (1980). Antecedent moisture (AM) for each surface age was estimated from the AM value of a comparable infiltration test. (A comparable infiltration test has the same surface age and approximately the same elapsed time since a prior rainfall event as the event being modeled.) The infiltration parameters (steady-state infiltration rate (FC), Holtan's So and P (eqn. 16), and the control zone depth (DF)) were calculated from regression equations developed in Chapter II (Table 8): FC is calculated directly from the regression equation for FC (Table 8). Holtan's So (eqn. 16) is calculated directly from the regression equation for Horton's So (Table 8). Holtan's P is related to Horton's Ex parameter by:

$$P = 0.29\ Ex \qquad (19)$$

(Jorgensen, 1985). Thus, Ex was calculated for each surface age in the watershed from the regression equation (Table 8) and converted to P by the above equation (19). Multiple regression equations for the saturated wetting depth (WD) (Table 8) were used to approximate the control zone depth (DF) for each surface age. Values for variables used in the regression equations (for example, BD or SL, Table 6) are the mean values for the specified surface age (Table 5).

Calibration of the ANSWERS model began with a sensitivity analysis. In this analysis, model parameters are varied individually to evaluate the magnitude and direction (i.e., increase or decrease in runoff volume or timing) of change in predicted runoff caused by varying each parameter. The parameters evaluated include the infiltration parameters FC, So, P and DF (functions of rainfall intensity); antecedent moisture (AM); field capacity (FP); potential interception volume (PIT); and roughness parameters RC, HU, and n. Mean values determined from the infiltration tests for each surface age were used for total porosity (TP) and percent vegetation cover (PER). TP and PER were not varied during the sensitivity analysis because mean values are considered to be the best estimate for simulation of these two parameters.

Field data were not collected for field capacity (FP) and potential interception volume (PIT). The values used for FP and PIT were therefore varied over the range recommended by Beasley and Huggins (1980) - from 50 to 70% for FP and from 0.3 to 1.4 mm for PIT. The variation in FP and PIT resulted in insignificant changes in the predicted runoff volume and peak height, and did not affect timing. Consequently, mean values from the recommended range were used for these parameters (Table 11).

Model sensitivity to infiltration parameters FC, So, P, and DF was explored first. These parameters were calculated from multiple regression equations (Table 8) as a function of rainfall intensity. The rainfall intensity used in the calculations was somewhat arbitrary, because during any given natural rainfall event, rainfall intensity varies through the event. Therefore, two methods were used to calculate rainfall intensity for use in the infiltration regression equations: An "average" rainfall intensity was calculated by dividing total rainfall by the rainfall duration. A "maximum" rainfall intensity was calculated using a series of overlapping time intervals generated over the storm hydrograph, such that each interval received one half of the total rainfall volume. The mean rainfall rate was calculated for each time interval, and the largest mean rate was selected for the "maximum" rainfall rate (Jorgensen, 1985). The "maximum" and "average" rainfall intensities were calculated for Storm 2, yielding intensities of 6.5 cm/hr, and 4.0 cm/hr, respectively. Infiltration parameters (FC, So, P, and DF) were then calculated from the multiple regression equations using the maximum intensity (6.54 cm/hr, Storm 2a, Table 11) and average intensity (4.0 cm/hr Storm 2g, Table 11), and simulations were conducted with both sets of infiltration parameters (Figure 22). FC, So, Ex, and DF all increase with the intensity used to calculate the parameters. As infiltration increased, the predicted peak runoff correspondingly decreased from 181% to 148% of the observed peak runoff (Table 11). Time to peak runoff also decreased slightly from 67 to 65% of the observed time to peak.

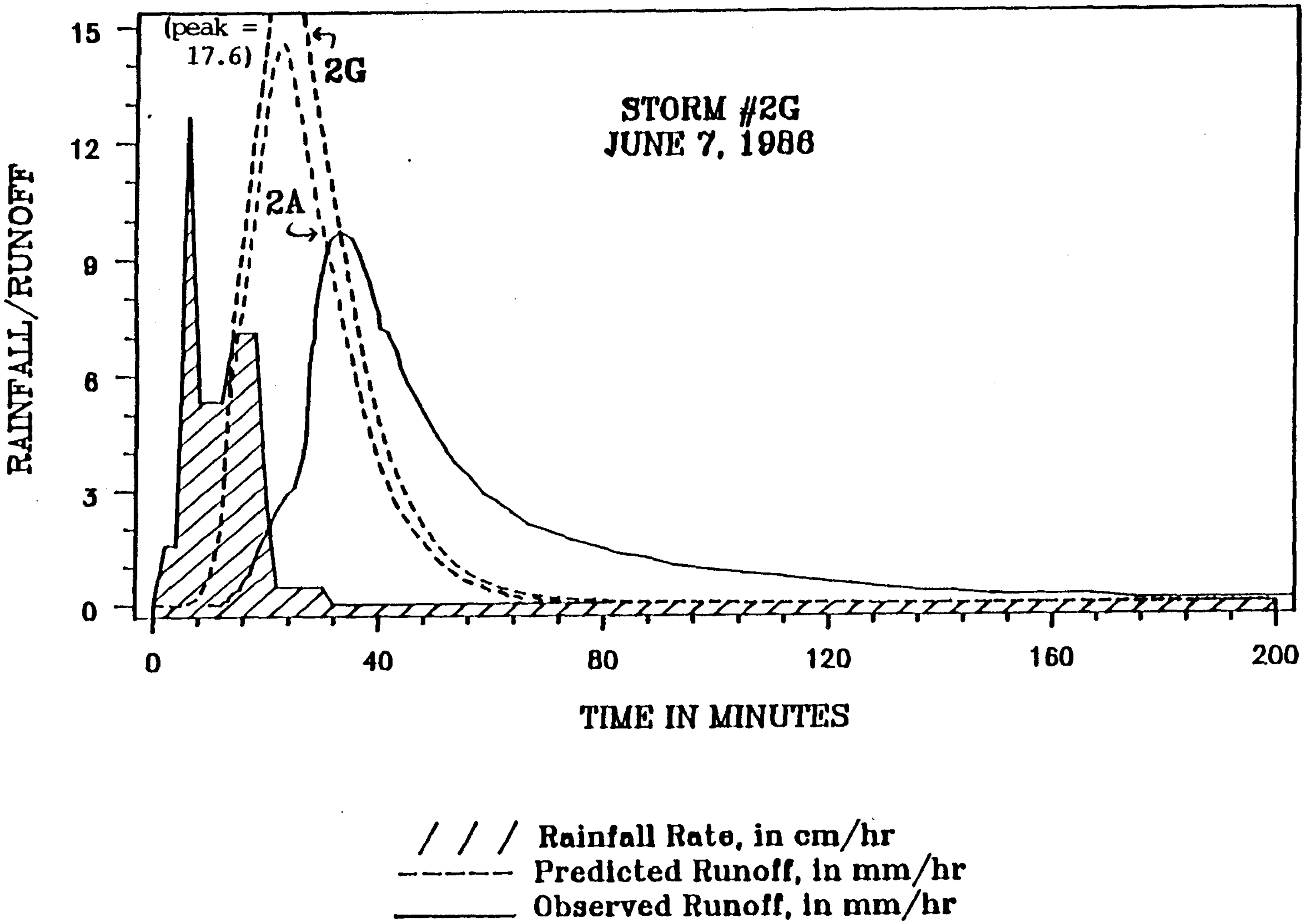


Figure 22. ANSWERS simulation of the Mosahnnon watershed, showing the effect of decreasing the intensity used to calculate the infiltration parameters on predicted runoff. Run 2A: intensity = 6.5 cm/hr; Run 2G: intensity = 4.0 cm/hr. (See table 11 for input data.)

To examine the sensitivity of ANSWERS to antecedent moisture (AM) values, the estimated value was decreased by a factor of three essentially decreasing AM to zero (Storms 2a and 2d, Table 11). ANSWERS is not very sensitive to AM values, because the threefold decrease in AM caused only a slight decrease in peak runoff (from 148% of observed peak runoff to 146%, Table 11, Figure 23).

Three surface roughness parameters, Manning's n, the roughness factor (RC), and height of the roughness elements (HU), were also varied during the sensitivity analysis. Manning's n was initially set to a value of 0.09, the lower end of the range recommended by Beasley and Huggins (1980) for chisel plowed, row cropped surfaces. An increase in n to 0.40 (an extremely rough surface) (Storm 2b, Table 11) resulted in a corresponding decrease in peak height (from 148% to 89% of observed) and increase in the time to peak height (from 67% to 76% of observed) (Figure 24). An increase in n decreases flow velocity, and consequently increases the amount of infiltration that can take place, decreases runoff volume, and increases time to peak runoff.

RC, the roughness factor, is a parameter which accounts for the spacing of the roughness elements; because it is a frequency, a high RC indicates close spacing. Increasing RC slightly from an initial estimate of 0.45 (Beasley and Huggins, 1980) to 0.55 (Storm 2e, Table 11) results in a corresponding slight decrease in peak runoff from 148 to 146% of the observed (Figure 25), because a rougher surface can store more water.

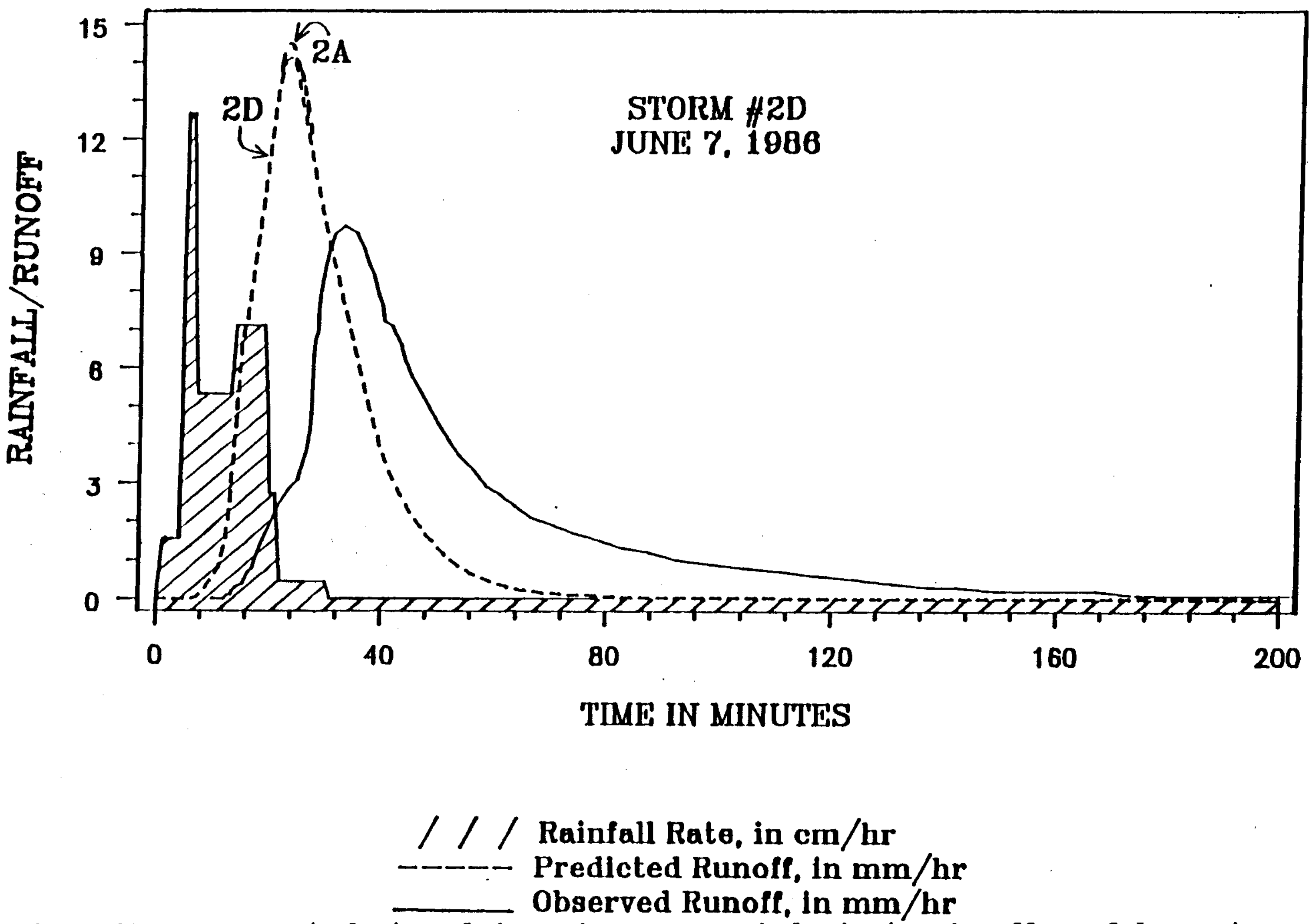


Figure 23. ANSWERS simulation of the Moshannon watershed, showing the effect of decreasing antecedent moisture on predicted runoff. Run 2A: Moisture = 0.065 ('84 surface) and 0.060 ('83 surface); Run 2D: Moisture = 0.23 ('84) and 0.17 ('83). (See table 11 for input data.)

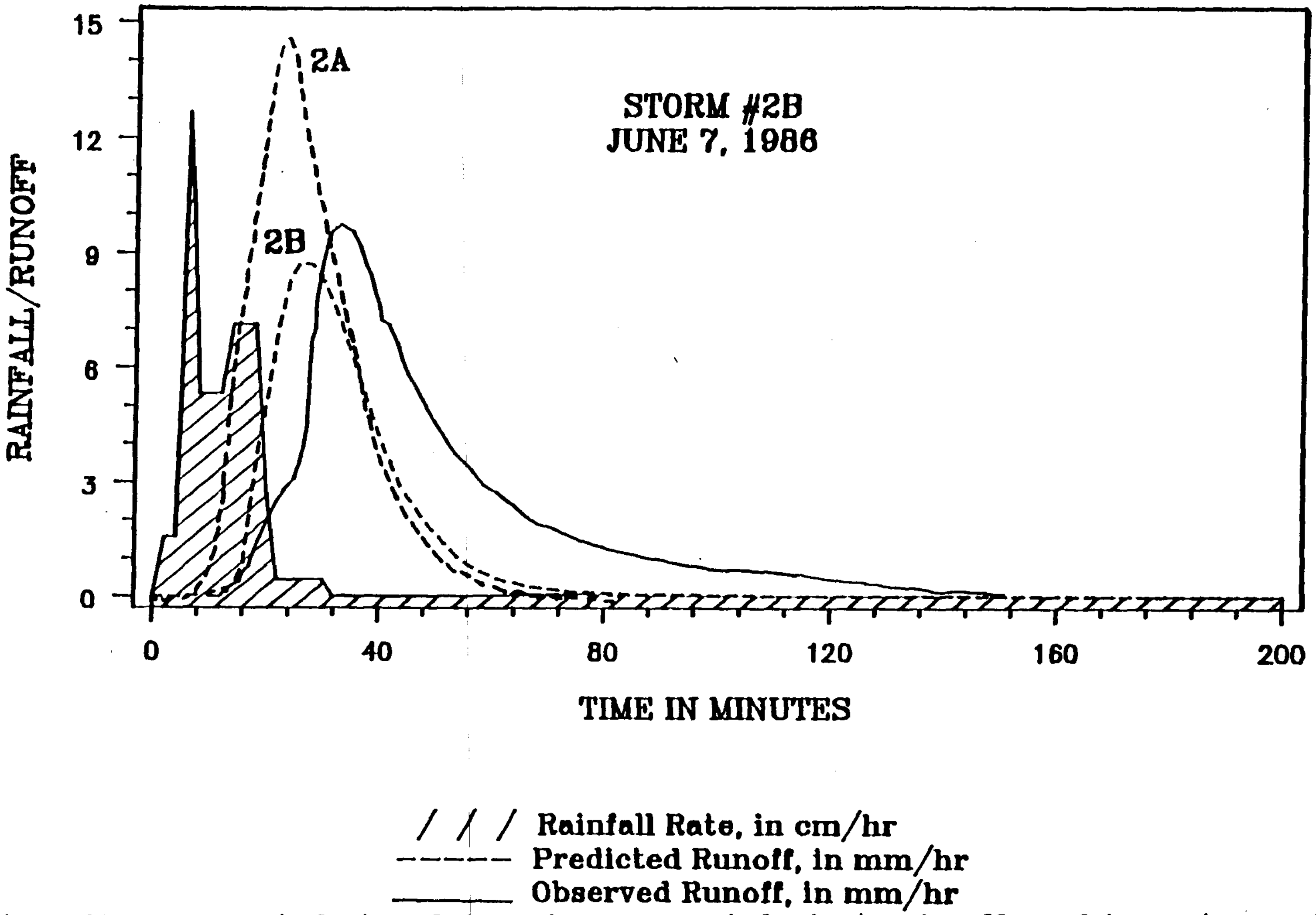


Figure 24. ANSWERS simulation of the Moshannon watershed, showing the effect of increasing Manning's n on predicted runoff. Run 2A: n = 0.09. Run 2B: n = 0.40. (See table 11 for input data.)

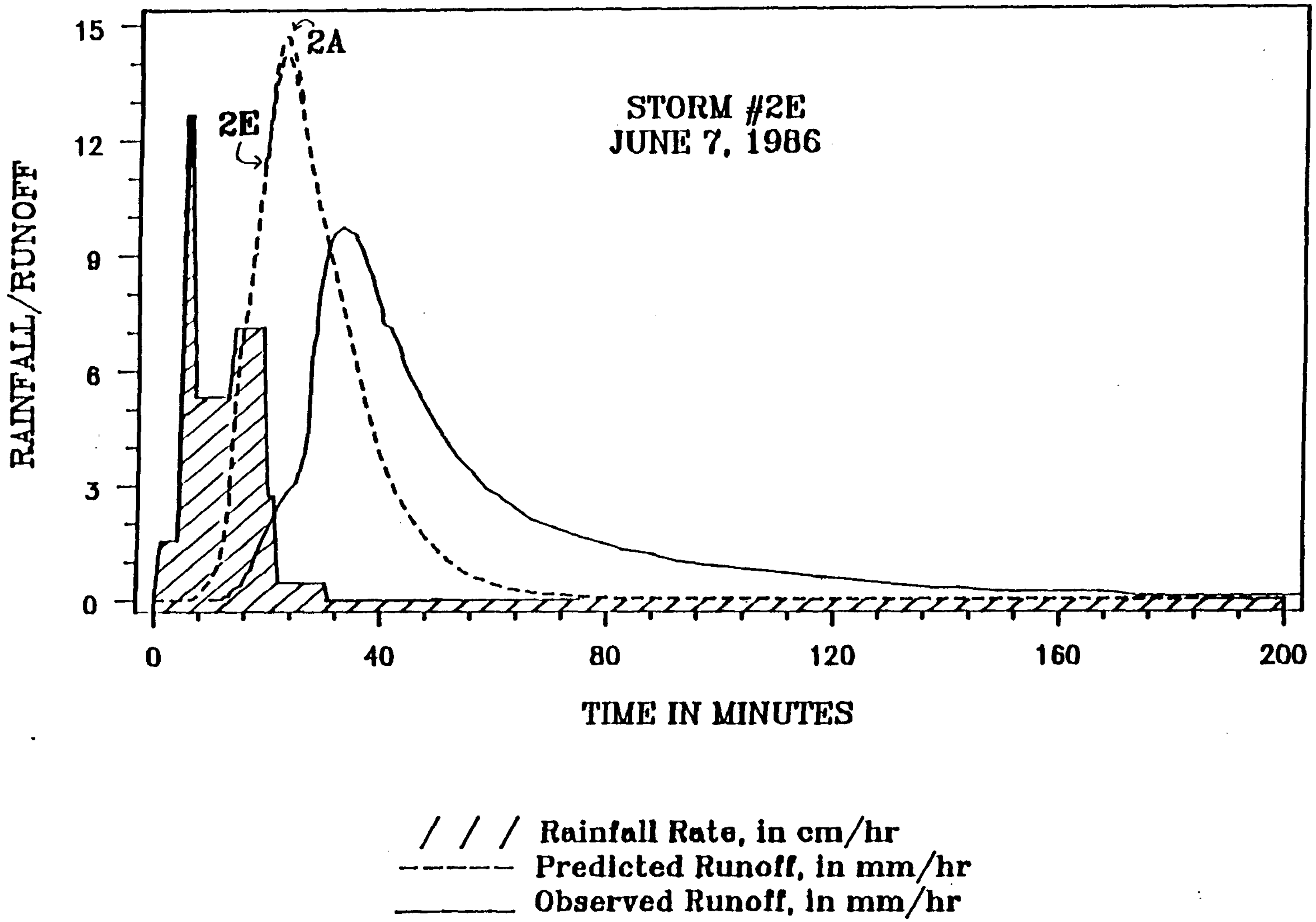


Figure 25. ANSWERS simulation of the Moshannon watershed, showing the effect of increasing RC on predicted runoff. Run 2A: RC = 0.45. Run 2E: RC = 0.55. (See table 11 for input data.)

The HU parameter is defined as a measure of the maximum surface roughness height (Beasley and Huggins, 1980). The values used in Storm 2a were average values from the field data, 20 mm for the age 3 surface and 16 mm for the age 4 surface (Table 5). When HU parameter values were increased to 45 mm for the age 3 surface and 50 mm for the age 4 surface (values approximating the maximum surface roughness height observed in the field) (Storm 2f, Table 11), the result was an unexpected increase in runoff volume (Figure 26). An increase in the height of the roughness elements would be expected to pond more water, causing greater infiltration and decreased runoff. This apparent discrepancy results because, in addition to influencing surface water storage potential, this parameter also affects the surface area over which infiltration can take place: ANSWERS simulates infiltration only for ponded surfaces. As water depth in depressions increases, the area over which infiltration can take place expands. Thus the increase in infiltration area as the rainfall volume increases is greater for low roughness elements than for higher ones (provided RC remains constant). Hence, higher roughness elements have less infiltration potential.

The effect of roughness element height on infiltration potential can be demonstrated by quantitatively examining the relationship between infiltration area and rainfall volume. The infiltrating area for a roughness element similar to the one in Figure 27A is equal to (l)(w), the

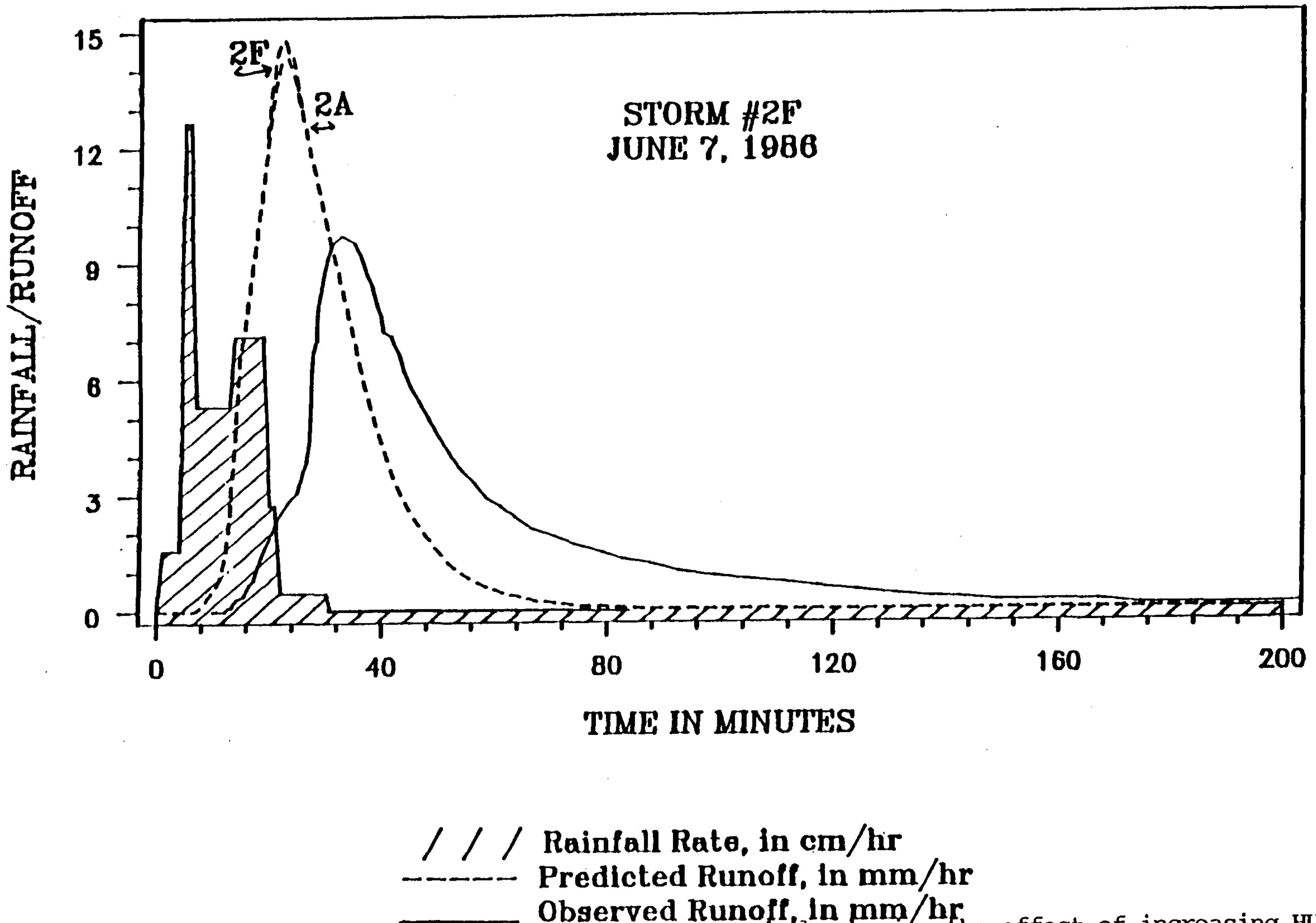


Figure 26. ANSWERS simulation of the Moshannon watershed, showing the effect of increasing HU on predicted runoff. Run 2A: HU = 20.0 ('84 surface) and 16.0 ('83 surface). Run 2F: HU = 45.0 ('84) and 40.0 ('83). (See table 11 for input data.)

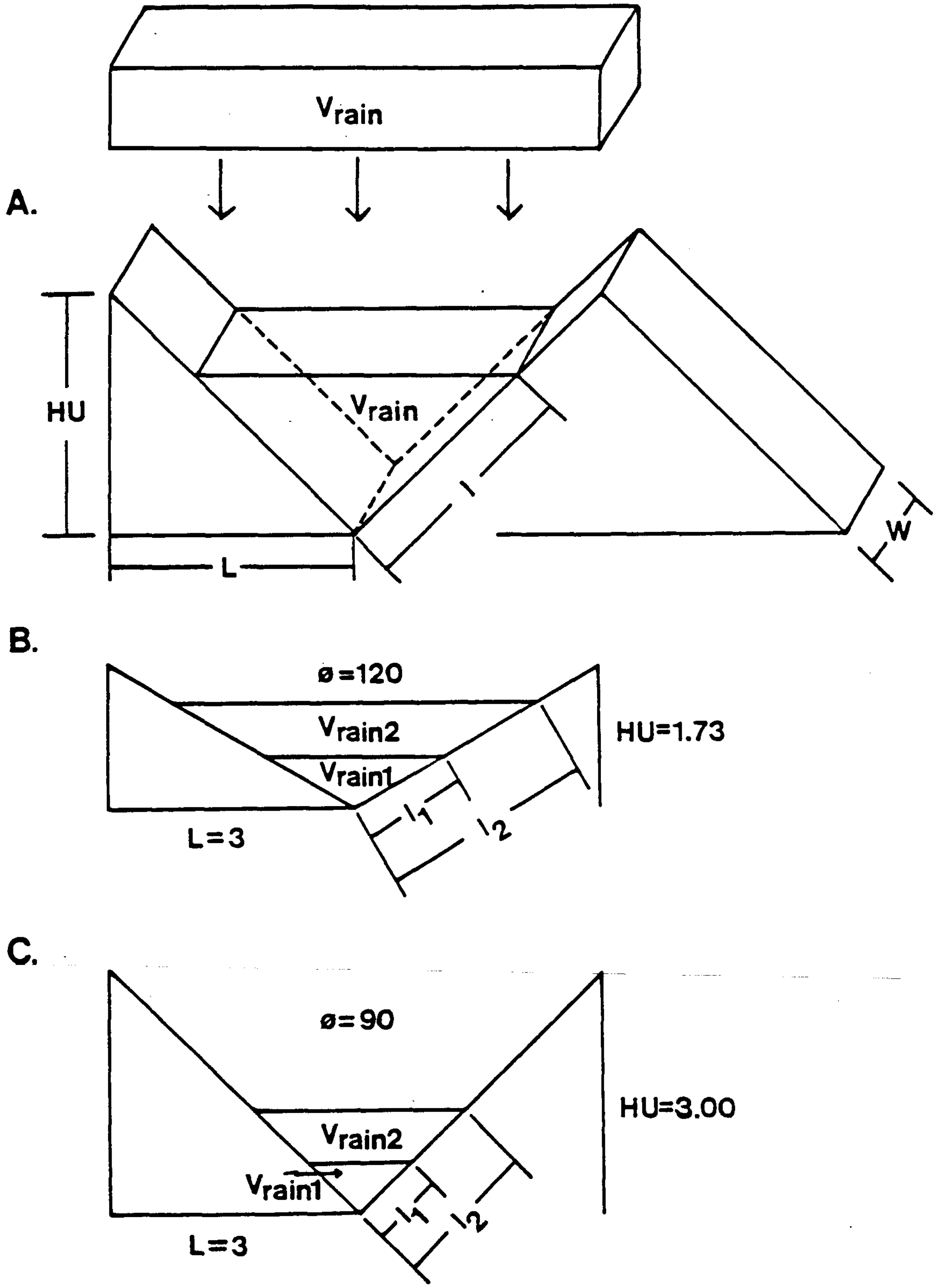


Figure 27. (A) Schematic block diagram of a roughness element.
(B) Schematic diagram of low roughness element, showing change in l for Vrain values of 2 and 4.
(C) Schematic diagram of high roughness element, showing change in l for Vrain values of 2 and 4.

length of the saturated area times the width. Infiltration area can be described as

$$Ainf = lw = Vrain/L\cos(\varphi/2) \qquad (20)$$

where Ainf = infiltration area (cm^2)

l = length of infiltration area (cm)

w = width of infiltration area (cm)

Vrain = rainfall volume applied over roughness element (cm^3)

L = half the horizontal spacing of roughness element (cm)

φ = angle formed between opposing sides of roughness element.

The relationship defining change in infiltration area with change in rainfall volume is then given by

$$dAinf/dVrain = 1/L\cos(\varphi/2) \qquad (21)$$

A unit change in Vrain changes Ainf on the low roughness element by 0.67 (Figure 27B), but changes Ainf on the high roughness element by only 0.47 (Figure 27C).

Although calculating infiltration area with roughness elements may work well for plowed agricultural soils with long, regularly spaced furrows, it is not generally applicable to reclaimed surface mines. On reclaimed mines, surface roughness consists of boulders and cobbles which can be important obstructions to water flow, but do not add to the infiltrating area. The change in area over which ponded infiltration takes place may not change as radically with depth of ponding for surface minesoils as it does for agricultural soils. The use of the HU parameter in ANSWERS does not seem to represent the true nature of its counterpart on reclaimed surface mined watersheds. Thus, it cannot be measured in the field and directly applied to the model. This is one disadvantage to using ANSWERS to model reclaimed watersheds.

During the sensitivity analysis, the magnitude and direction of change in the predicted hydrograph with variation in each input parameter were determined. ANSWERS was found to be most sensitive to variation in Manning's n, and the rainfall intensity used to calculate the infiltration parameters, FC, So, P, and DF, and topographic accuracy. In summary, a decrease in n increases runoff and time to peak runoff; and a decrease in the rainfall intensity used to calculate the infiltration parameters results in a decrease in infiltration and a consequent increase in runoff.

ANSWERS was calibrated against observed runoff for Storm 2 by applying the sensitivity analysis results to the original estimated input data (2a, Table 11). The rainfall intensity used to calculate infiltration parametics were adjusted over the range of recommended values (Beasley and Huggins, 1980) until the best fit between the predicted and observed runoff was obtained. The average rainfall intensity (4.0 cm/hr) was used to calculate FC, So, P and DF from the regression equations (Table 8); HU was three times the value measured in the field (60 mm for age 3 surface, and 48 mm for age 4 surface); a value of 0.55 was used for n; and a value of 0.25 was used for RC. The final calibrated simulation (Storm 2g, Table 11) resulted in 82% of the observed volume, 101% of the observed peak runoff, and 82% of the observed time to peak runoff (Figure 28).

Application to Other Storm Events

To test the accuracy of parameter values determined for Storm 2, four other storm events were modeled (Storms 3, 4, 5 and 6, Table 11). Because Storms 3, 5, and 6 occurred in 1986, the watershed surfaces (reclaimed in 1983 and 1984) were ages 4 and 3, respectively. Because Storm 4 occurred in 1985, the watershed surfaces were ages 3 and 2, respectively. The four storms were chosen to obtain a range of rainfall intensities, from an average intensity of 5.7 cm/hr for Storm 3 to 1.0 cm/hr for Storm 6 (Table 11). These storms also had very simple hydrographs.

For each of the four storms, the antecedent moisture and infiltration parameters were re-calculated to reflect the conditions of the storm (Table 11). RC and n values were kept at the optimized values from the calibration run. The HU parameters used in Storm 2 were optimized to three times the average roughness values measured in the field; therefore, the same proportionality was used to determine the HU parameter for each additional storm. The

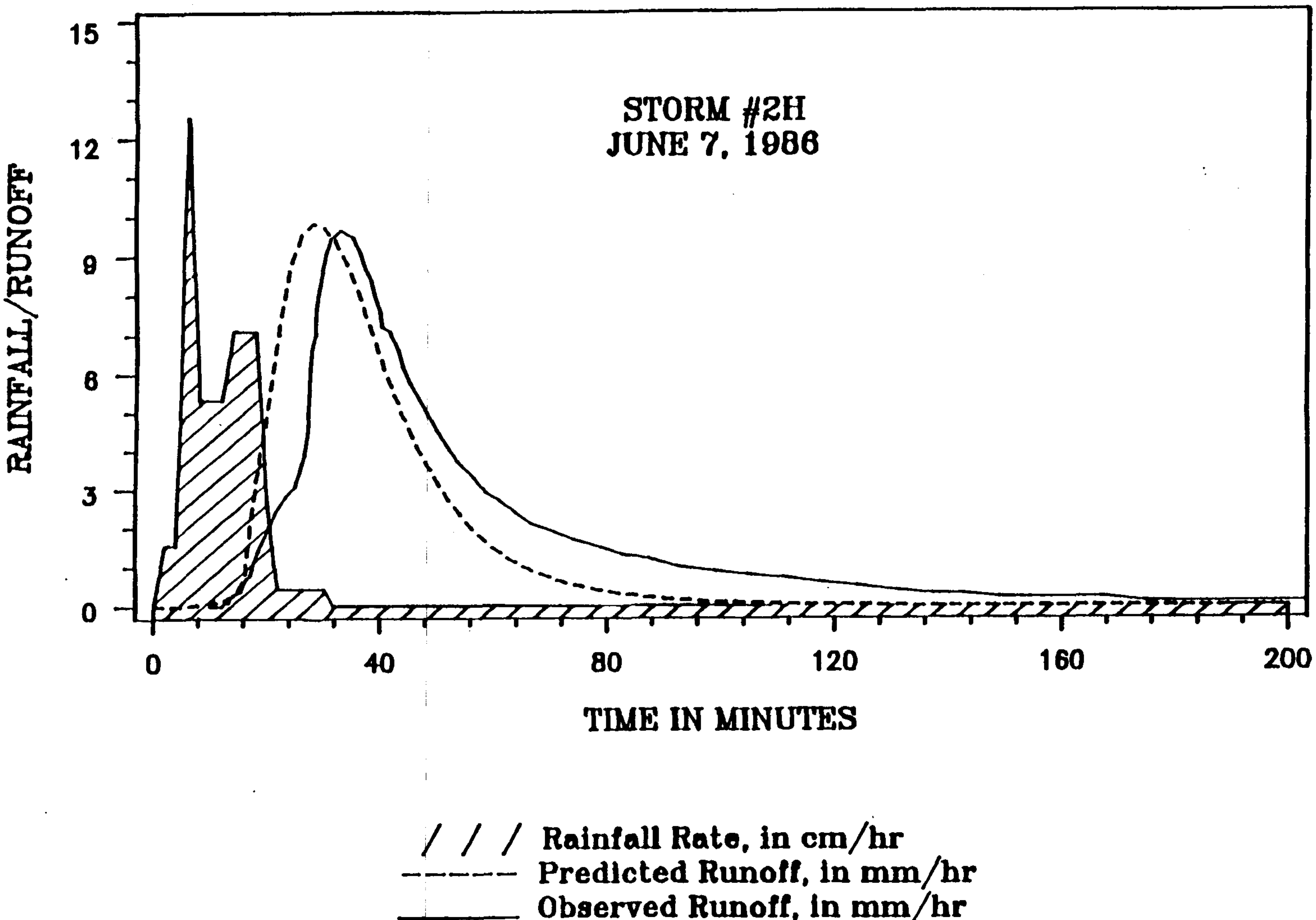


Figure 28. Final, calibrated ANSWERS simulation of Storm 2, showing rainfall input and observed and predicted runoff. Average rainfall intensity of 4.0 cm/hr. (See table 11 for input data.)

remaining input parameters (TP, FP, PIT, and PER) were calculated in the same manner as for Storm 2, according to the age of the surfaces at the time of the storm.

Simulation results for Storms 3, 4, 5, and 6 are shown in figures 29, 30, 31, and 32. Storm 3 has a higher average rainfall intensity (5.7 cm/hr) than Storm 2 (4.0 cm/hr). The predicted peak height is very close to the observed (106% of observed, Table 11), an encouraging observation because among the parameters peak runoff, time to peak, and total runoff volume, peak runoff is most critical for flood forecasting and erosion control. Storms 4, 5, and 6 have progressively lower average rainfall intensities (Table 11), and the accuracy of predicted peak runoff decreases with rainfall intensity, from 73% of observed peak height for Storm 4 to 35% for Storm 6.

In all four storms, the total volume of runoff is underpredicted. An overestimation of the infiltration parameters caused by erroneously including depression storage in with infiltrated volume (chapter II) may be part of the cause of the underprediction of runoff volumes: During high intensity infiltration tests, the depression storage volume is negligible (perhaps 5% of infiltrated volume - see Chapter II, p. 41) compared to the total infiltrated volume, and has little effect on the total predicted runoff. For lower intensity infiltration tests, the volume of depression storage becomes more significant compared to the infiltrated volume (15-20%) and

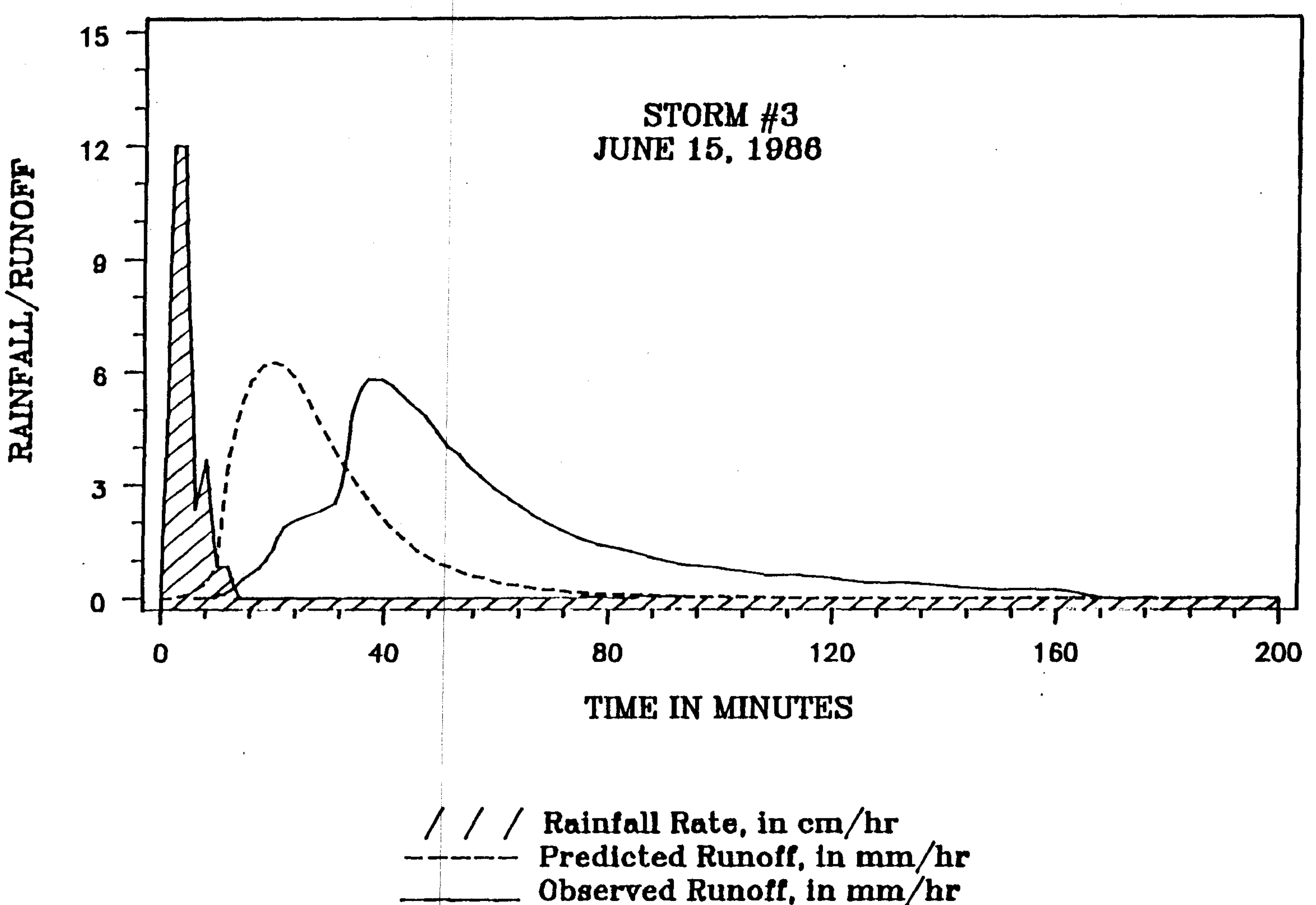


Figure 29. ANSWERS simulation of Storm 3, showing rainfall event and observed and predicted runoff. Average rainfall intensity of 5.2 cm/hr. (See table 11 for input data.)

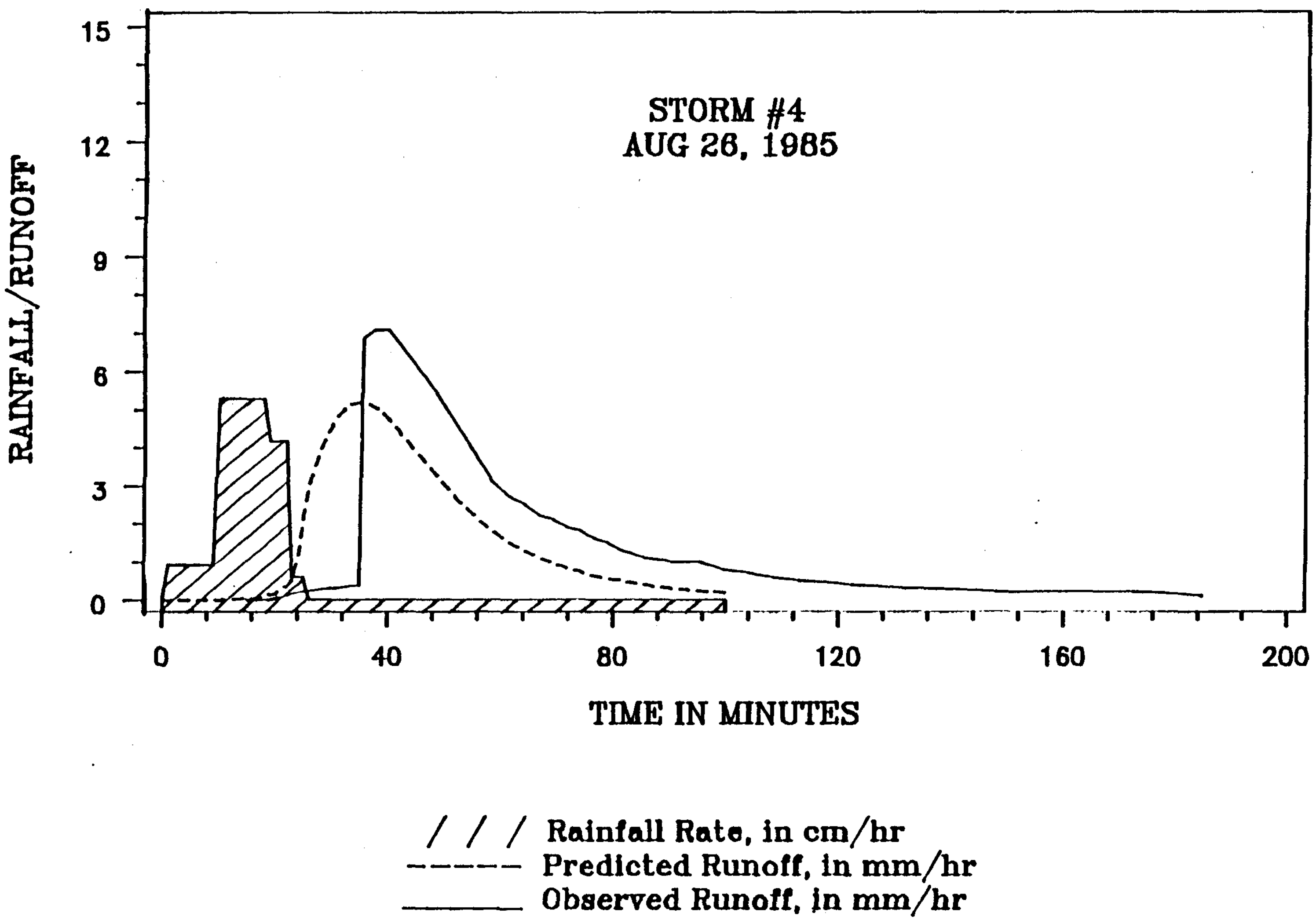


Figure 30. ANSWERS simulation of Storm 4, showing rainfall event and observed and predicted runoff. Average rainfall intensity of 2.9 cm/hr. (See table 11 for input data.)

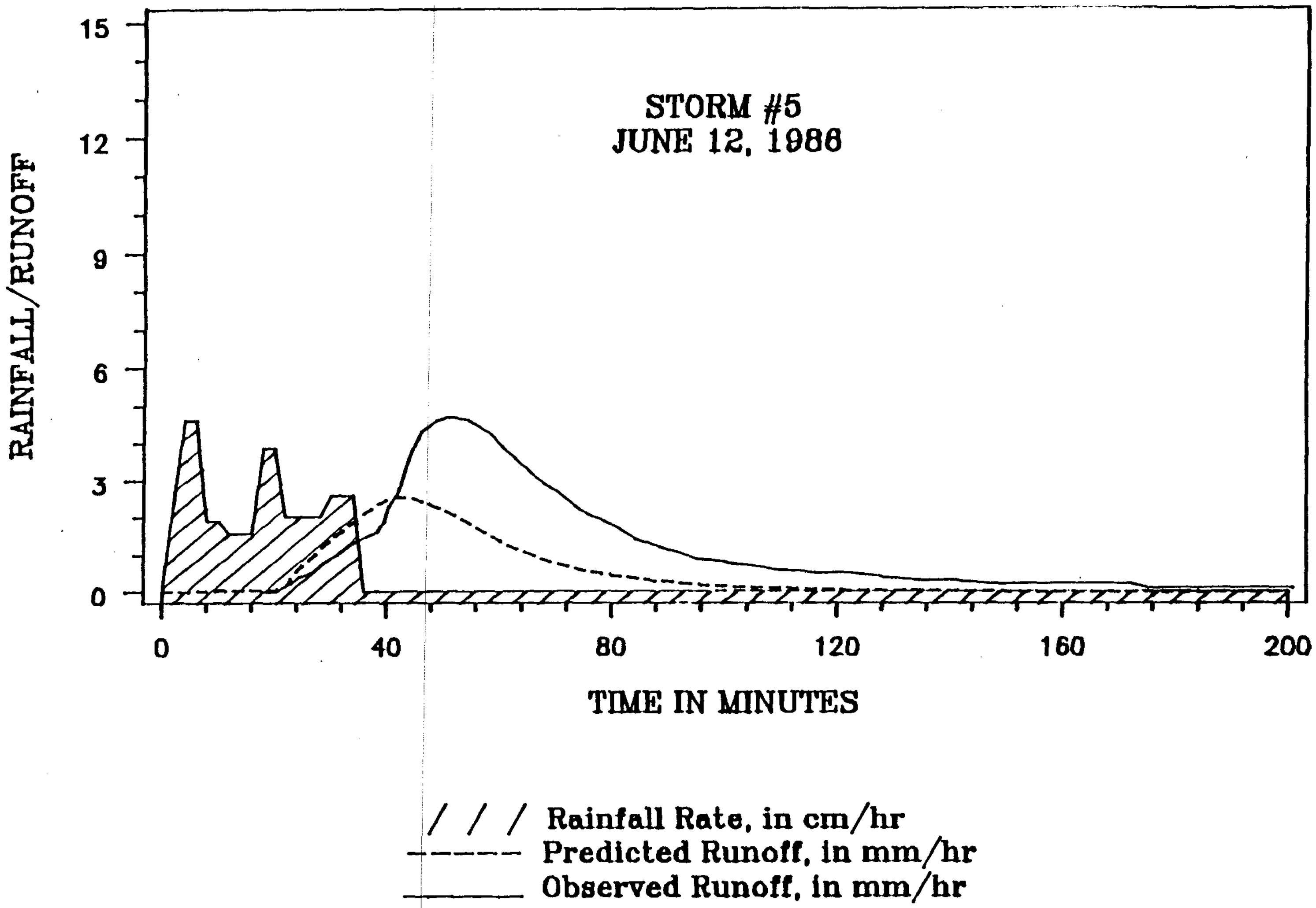


Figure 31. ANSWERS simulation of Storm 5, showing rainfall event and observed and predicted runoff. Average rainfall intensity of 2.3 cm/hr. (See table 11 for input data.)

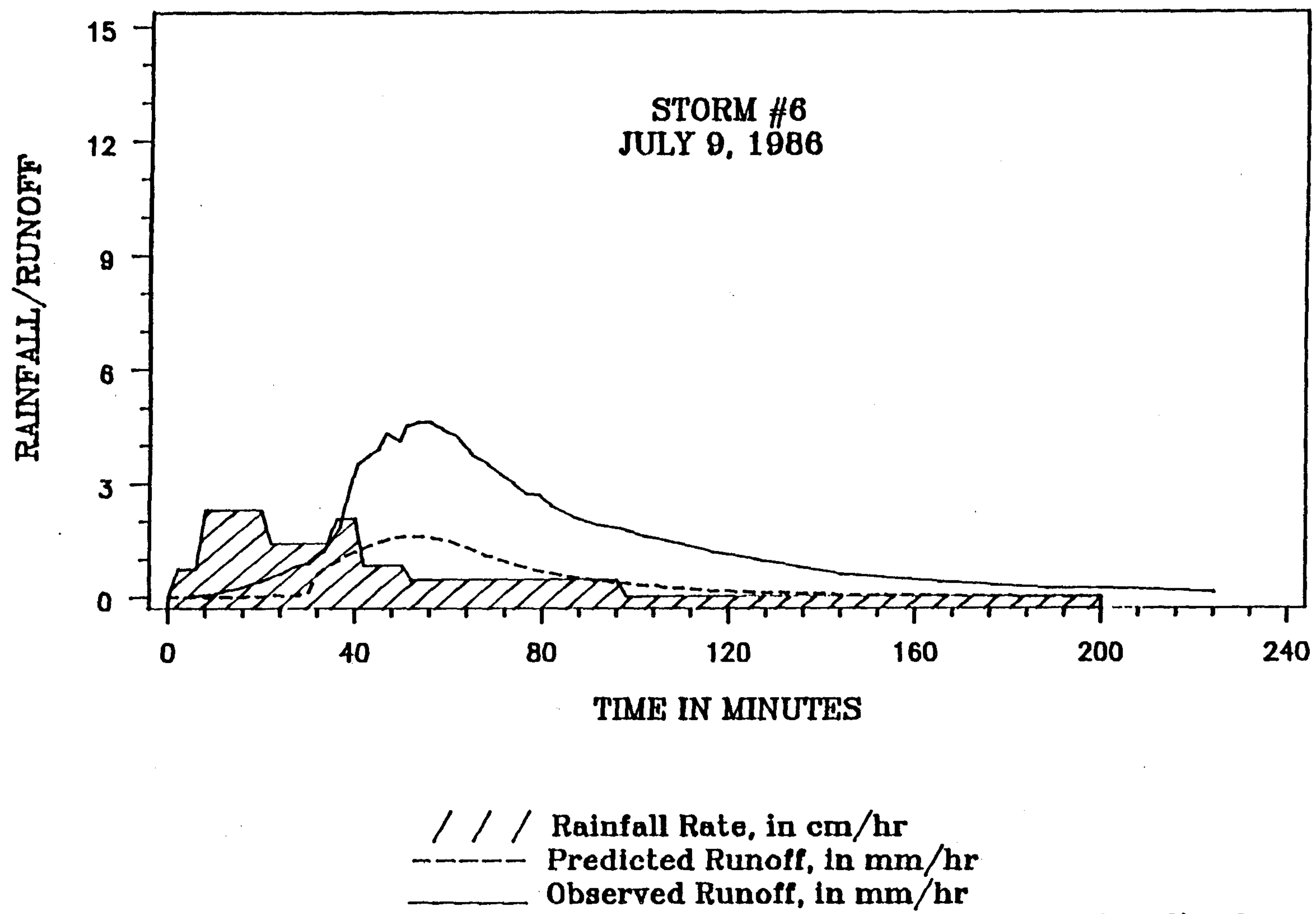


Figure 32. ANSWERS simulation of Storm 6, showing rainfall event and observed and predicted runoff. Average rainfall intensity of 1.0 cm/hr. (See table 11 for input data.)

overestimation of the infiltration rate has a much larger effect on the predicted volume. This does not, however, explain the underprediction of runoff volume for Storm 3 (a high intensity storm).

A second possibility for the underprediction of runoff volumes involves the lateral movement of water once it infiltrates into the soil. ANSWERS simulates only downward movement of infiltrating water. On a slope, water moves laterally downslope as well as vertically (Zaslavsky and Sinai, 1981). Lateral water movement can saturate areas lower on the slope, generating runoff in areas that would otherwise remain unsaturated and not contribute to runoff. Downslope water movement within the soil was observed on the Fye site during a number of infiltration tests. ANSWERS also simulates only saturated overland flow. In places, the reclaimed minesoils can be completely armored and unsaturated overland flow may be generated, producing runoff when the model predicts none.

Time to peak runoff is also underpredicted for each storm, an indication that ANSWERS is moving water off the watershed too quickly. Modeling of diversion channels on the Fye mine site may be the cause of this problem. Diversion channels are not present on the Pine Glen watershed modeled by Jorgensen (1985), and the predicted times to peak were all within 10% of the observed peak. The diversion channels on the Fye mine site are very irregular and do not maintain a constant gradient across the slope. The undulating floor of the ditches and small breaches in the berms pond water in some places and shunt it out of the diversion channels and downslope in others. In ANSWERS, these ditches are treated as channels with very high roughness values. The model's simulation of the diversion channels may be much more efficient than the actual diversion system. Thus, runoff reaches the main channel too quickly, and time to peak runoff is underpredicted.

Summary

The Moshannon watershed was modeled using the ANSWERS runoff model. The purpose of using a watershed model is to evaluate the effects of the physical soil characteristics and infiltration parameters on the watershed hydrograph. Input values for the model were taken from data collected in the field (topography, TP, AM and PER), multiple regression equations developed from infiltration tests (FC, A, P, and DF), and by calibration to observed runoff (RC, HU and n).

Manning's roughness coefficient was found to significantly affect both the timing and volume of predicted runoff. Some problems were encountered in the way ANSWERS defines and uses the HU parameter. HU is defined as the maximum height of roughness elements. It affects not only the amount of water ponded on the soil surface, but also the area over which infiltration occurs, resulting in an increase in runoff when HU is increased. This effect is contrary to what actually happens on the watershed and is viewed as a disadvantage to the use of the ANSWERS model on reclaimed watersheds.

ANSWERS was calibrated using a high intensity storm by optimizing the roughness parameters to bring the predicted and observed runoff into close agreement. The calibrated model was then applied to four other storms, one of slightly higher intensity and three with progressively lower intensities. In the high intensity simulation (Storm 3), predicted peak runoff was in close agreement with the observed (106% of observed). The accuracy of the peak runoff prediction decreased with decreasing rainfall intensity. Total runoff volume and time to peak runoff were also underpredicted for each storm.

CHAPTER IV

SUMMARY

Conclusions

A series of 97 infiltration tests was conducted on a single mine site under variable surface age, rainfall intensity, and antecedent moisture content conditions. The resulting infiltration curves were fit to both the Philip (eqn. 13) and Horton (eqn. 14) equations. Overall, the Horton equation provided a better fit to the data.

Statistical analyses were conducted on both the field and Horton curve-fit infiltration data. The test results emphasize the highly complex and variable nature of infiltration on reclaimed minesoils. Both the physical characteristics of the soil and the conditions of a particular storm event affect infiltration. Minesoil infiltration rates increase with rainfall intensity. The degree to which rainfall intensity affects infiltration is dependent upon minesoil age. Antecedent moisture content of the minesoil was not found to be an important control on infiltration rate. The most important physical soil characteristics that affect infiltration are grain size distribution (in the top 5 cm of soil), vegetation, and surface roughness. These physical characteristics change with age of the reclaimed surface; consequently, infiltration characteristics change with minesoil age as well. The change in infiltration with age cannot be accounted for by any single physical parameter; furthermore, the degree to which the individual physical parameters affect infiltration also changes with surface age. As surface age increases, more of the variation in infiltration rates can be explained by the soil's physical characteristics.

Multiple regression equations were developed to describe the influence of rainfall intensity and soil/surface properties on each infiltration parameter (final experimental infiltration rate, 30-minute infiltrated volume, sorptivity, Horton exponent, and saturated wetting depth) for each surface age. Coefficients of determination for the regression equations tend to be low, attesting to the highly variable nature of the infiltration process itself. Rainfall intensity, grain size parameters (percent gravel, sand, and silt plus clay), roughness parameters (surface and form roughness), percent vegetation, bulk density (at surface ages 4 and 9) and antecedent moisture content were the significant independent variables in the regression equations (Table 8). The significant independent variables and coefficients in the regression equations changed with age for each dependent infiltration variable.

The ANSWERS runoff model was used to simulate infiltration and runoff characteristics of the Moshannon watershed, a small watershed on the Fye mine site. Input parameters for the model were determined from data collected during infiltration tests and from regression equations developed for the infiltration parameters.

The runoff hydrograph predicted by ANSWERS is very sensitive to topography, infiltration parameters (FC, So, P, and DF, Table 7) and Manning's roughness coefficient, n. Re-surveying Moshannon topography in greater detail (changing the point density from 6 points/ha to 20 points/ha) decreased predicted peak runoff from 212% to 123% of observed runoff (Storms 1a and 1b, Table 11). An increase in the rainfall intensity in the regression equations used to calculate the infiltration parameters (Table 8) from 4.0 to 6.5 cm/hr increased FC, So, P, and DF, and consequently decreased peak runoff from 181% to 89% of observed peak runoff (Storms 2g and 2b, Table 11). Finally, an increase in n from 0.09 to 0.40 resulted in a decrease in peak runoff from 148% to 89% of observed peak runoff.

Values for the roughness parameters RC and HU are not measurable in the field and could only be determined by optimization procedures. HU is defined as the height of roughness elements, but its use in the model did not correspond to the way its field counterpart would be expected to function: An increase in HU would be expected to increase surface ponding and reduce runoff. However, an increase in HU decreases the area over which ponded infiltration can occur (Figure 27), resulting in increased runoff. The use of the HU parameter may be a significant source of error in model simulations of surface mined watersheds.

A high intensity storm (4.0 cm/hr, Storm 2g, Table 11) was calibrated against observed runoff, and then the calibrated parameters were applied to a higher intensity storm (5.7 cm/hr, Storm 3) and three lower intensity storms (2.9 cm/hr, Storm 4; 2.3 cm/hr, Storm 5; 1.0 cm/hr, Storm 6, Table 11). Predicted peak runoff was 106% of observed for Storm 3, but the accuracy of the predicted peak decreased with rainfall intensity (73% for Storm 4, 54% for Storm 5, and 35% for Storm 6, Table 11). In each case, however, total runoff volume and time to peak runoff were underpredicted (Table 11).

Recommendations for Further Study

This study explores the relationships between rainfall intensity and minesoil infiltration, and between soil/surface properties and minesoil infiltration. Understanding the infiltration process on reclaimed watersheds is critical to the prediction of mining effects within the basin and downstream (Figure 1). The following recommendations may improve ANSWERS simulations and the understanding of the infiltration process on surface minesoils:

(1) An investigation of minesoil pore size distribution and its changes with time should be

conducted. The size of pore spaces through which infiltrating water moves controls both sorptivity and final infiltration rates. In natural soils, the bulk density and grain size distribution are correlated and determine the pore size distribution (Brady, 1974). In minesoils, these parameters do not seem to be well correlated, most likely because of compaction during reclamation. Defining the pore space distribution may provide insight into changes in infiltration characteristics resulting from compaction and subsequent loosening of the soil by vegetation, freeze-thaw action, and weathering processes.

2) Surface depression storage should be quantified and abstracted from the rainfall volume before infiltration curves are calculated. This may be particularly important for low intensity storms where the volume of surface storage is significant compared to the infiltrated volume.

(3) A recent study of the Green-Ampt storage factor (Sf, eqn. 3) (Springer and Cundy, 1987) may enable the Green-Ampt equation to be applied to the data collected at the Fye mine site. The Green-Ampt equation has a strong theoretical basis and may describe the infiltration curves better than the empirical Horton equation. However, the assumptions inherent in the Green-Ampt equation may still restrict its usage on minesoils.

(4) A series of infiltration tests should be conducted at different rainfall rates on the same test plot, allowing soil moisture to return to intial conditions between

tests. This may demonstrate whether curve type is a function of rainfall intensity, or a property of a given test plot.

(5) Finally, the ANSWERS routines which use the surface roughness parameters RC and HU should be modified, or the two parameters should be redefined to correspond to the actual mine surface conditions.

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Infiltration Characteristics and Hydrologic Modeling of Disturbed Land, Moshannon, Pennsylvania

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Corinne Renée Lemieux

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