A Point-Infiltration Model for Estimating Runoff from Rainfall on Small Basins in Semiarid Areas of Wyoming

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Prepared in cooperation with the U.S. Bureau of Land Management

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A Point-Infiltration Model for Estimating Runoff from Rainfall on Small Basins in Semiarid Areas of Wyoming

By J.G. RANKL

Prepared in cooperation with the
U.S. Bureau of Land Management

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SYMBOLS

a	Constant for a soil type, in inches
CL	Confidence limits
d	Surface-retention storage, in inches
$EVAR$	Estimated error of variance
f_c	Minimum infiltration rate, in inches per hour
H	Depth of ponded water, in inches
i	Accumulated infiltration in the soil column, in inches per hour
i_p	Water uptake at incipient ponding, in inches per hour
I_p	Rate of infiltration, in inches per hour
IRC	Incipient-runoff curve
K_h	Hydraulic conductivity at moisture content m, in inches per hour
m	Moisture content of the soil near saturation
m_o	Initial moisture content of the soil
n	Exponent parameter in empirical infiltration equation; a counter elsewhere
P	Capillary potential at the wetting front
$P(m-m_o)$	Effective product of capillary potential and moisture deficit
R	Supply rate or storm intensity, in inches per hour
s	Standard deviation
SEE	Standard error of estimate
t	Time, in hours
t_d	Time to satisfy retention storage, in hours
t_d^*	Time of equivalent duration to satisfy retention storage, in hours
t_p	Time to incipient ponding for a given intensity, in hours
t_p^*	Time required to yield an equivalent infiltration for the ponded Green-Ampt equation, in hours
t_r	Duration of rainfall, in hours
t_r^*	Time of equivalent duration of infiltration for the ponded Green-Ampt equation, in hours
y	Measured runoff value
$\bar{y}$	Mean of measured runoff values
$\hat{y}$	Simulated runoff value
Δi	Incremental infiltration during period, $(t_d^* - t_p^*)$

A Point-Infiltration Model for Estimating Runoff from Rainfall on Small Basins in Semiarid Areas of Wyoming

By J.G. Rankl

Abstract

A physically based point-infiltration model was developed for computing infiltration of rainfall into soils and the resulting runoff from small basins in Wyoming. The user describes a "design storm" in terms of average rainfall intensity and storm duration. Information required to compute runoff for the design storm by using the model include (1) soil type and description, and (2) two infiltration parameters and a surface-retention storage parameter. Parameter values are tabulated in the report.

Rainfall and runoff data for three ephemeral-stream basins that contain only one type of soil were used to develop the model. Two assumptions were necessary: antecedent soil moisture is some long-term average, and storm rainfall is uniform in both time and space. The infiltration and surface-retention storage parameters were determined for the soil of each basin. Observed rainstorm and runoff data were used to develop a separation curve, or incipient-runoff curve, which distinguishes between runoff and nonrunoff rainfall data. The position of this curve defines the infiltration and surface-retention storage parameters.

A procedure for applying the model to basins that contain more than one type of soil was developed using data from 7 of the 10 study basins. For these multiple-soil basins, the incipient-runoff curve defines the infiltration and retention-storage parameters for the soil having the highest runoff potential. Parameters were defined by ranking the soils according to their relative permeabilities and optimizing the position of the incipient-runoff curve by using measured runoff as a control for the fit.

Analyses of runoff from multiple-soil basins indicate that the effective contributing area of runoff is less than the drainage area of the basin. In this study, the effective drainage area ranged from 41.6 to 71.1 percent of the total drainage area. Information on effective drainage area is useful in evaluating drainage area as an independent variable in statistical analyses of hydrologic data, such as annual peak frequency distributions and sediment yield.

A comparison was made of the sum of the simulated runoff and the sum of the measured runoff for all available records of runoff-producing storms in the 10 study basins. The sums of the simulated runoff ranged from 12.0 percent less than to 23.4 percent more than the sums of the measured runoff. A measure of the standard error of estimate was computed for each data set. These values ranged from 20 to 70 percent of the mean value of the measured runoff.

Rainfall-simulator infiltrometer tests were made in two small basins. The amount of water uptake measured by the test in Dugout Creek tributary basin averaged about three times greater than the amount of water uptake computed from rainfall and runoff data. Therefore, infiltrometer data were not used to determine infiltration rates for this study.

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INTRODUCTION

The usual method of estimating runoff in ungaged streams is to apply regression equations previously developed from data from gaged streams. The equations relate runoff characteristics for a specified frequency (or probability) of occurrence to physical characteristics of the drainage basins. For small, ephemeral-stream basins in Wyoming, the equations for estimating the volume of runoff for a specified frequency were developed by Craig and Rankl (1978). The regression method, however, is independent of the magnitude, intensity, duration, and frequency of the precipitation that produces the runoff.

Rules and regulations of the Surface Mining Control and Reclamation Act of 1977 require that drainage and water-impoundment structures at surface mines be designed for runoff estimated on the basis of precipitation-frequency criteria. Because extensive surface mining of coal is taking place in Wyoming, there is need for a method of making such estimates. The question to be answered is, How much runoff from a given basin will occur as the result of a specified storm, such as a 100-year, 6-hour rainfall? If sufficient information is available, runoff can be computed by subtracting rainfall losses due to interception, retention storage, and infiltration from total rainfall. Although rainfall-frequency data are available from the National Weather Service, data on interception, retention storage, and infiltration rates are almost nonexistent. Soil-index data are available, but the soil-index method of estimating runoff does not take rainfall intensity into account.

During 1980–82 the U.S. Geological Survey (USGS), in cooperation with the U.S. Bureau of Land Management, conducted a study to develop a method of estimating runoff volumes from specified precipitation on small drainage basins. The study was an extension of work by Rankl (1982) to develop an empirical method of making such estimates. The empirical method was based on a power decay type of equation, called a separation curve, which differentiates between runoff-producing rainstorms and nonrunoff rainstorms. For this study, it was reasoned that the infiltration parameters, which control water uptake, also define the separation curve; therefore, the separation curve defines the infiltration parameters.

The objectives of the study were to

1. Investigate the use of a separation curve that is based on a physically based infiltration equation.
2. Develop a method for estimating runoff that is based on precipitation.
3. Define infiltration parameters for as many soils and basins as possible.
4. Evaluate the use of data from infiltrometer tests to define infiltration parameters for soils.

Purpose and Scope

The purpose of this report is to describe the point-infiltration model for estimating runoff—the principles and theory applied, the development and testing of the model, the applications of the model and the data required, and the limitations of the model. Also described and evaluated are the results of field tests with an infiltrometer.

Rainfall and runoff data used in this study were collected by the USGS (Craig and Rankl, 1978) from 1965 to 1973 at streamflow stations on small, ephemeral streams having drainage areas of less than 11.0 square miles (mi^2). Average storm intensity and storm length were computed for each storm selected, and the storm was identified as one that produced runoff or one that did not. The volume of runoff for each event was used to verify the method proposed in this report and to determine infiltration parameters in basins having multiple soils.

Soil maps for each basin were used to determine the area of each soil type. In addition, a description of the soils was used to rank the soils on the basis of relative permeability. Because it is important that the mapping units be consistent, soil maps and descriptions used in this study were obtained from the U.S. Department of Agriculture, Soil Conservation Service.

Acknowledgments

The data used were collected during a previous study by personnel of the the USGS in cooperation with the Wyoming State Highway Department and the Federal Highway Administration (Craig and Rankl, 1978).

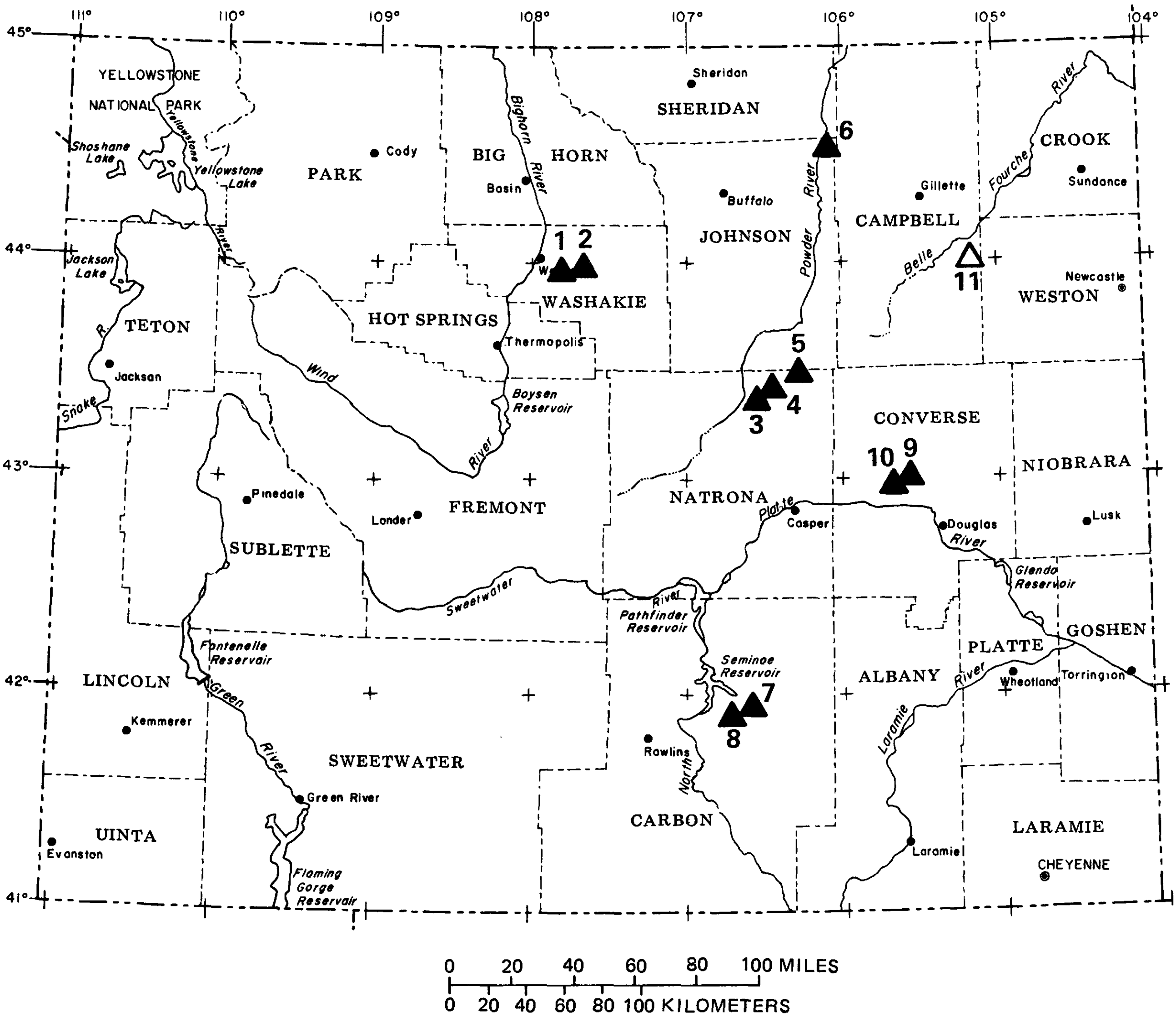
The author is indebted to many individuals for assistance throughout the course of this project. A special acknowledgment is made to Robert W. Lichty, USGS, for his time and effort spent on discussion and assistance in developing the equations used in this study.

Study Basins

Rainfall and runoff data from 10 small basins drained by ephemeral streams were analyzed for this study. Basin sizes ranged from 0.81 to 3.77 mi^2. Although hydrologic data were available for 12 additional stations, soil maps and descriptions were not. Three of the 10 study basins are underlain by the Cody Shale of Cretaceous age and are assumed to have spatially uniform soil types and infiltration characteristics. The other seven basins have multiple soils and are underlain by the Wasatch Formation and Willwood Formation of Eocene age, or by the Hanna Formation of Paleocene age. The rolling upland areas and areas along the main channels generally are covered with native grasses and sagebrush. The sparsely vegetated middle parts of the basins are dissected by head-cutting streams, resulting in exposed bedrock and deep gullies.

Basin numbers and station names are listed in the following table, and locations are shown in figure 1. Stations mentioned in this report have been assigned permanent USGS numbers. Each eight-digit number consists

Basin number	Basin name	Station number
1	North Prong East Fork Nowater Creek near Worland	06267260
2	North Prong East Fork Nowater Creek tributary near Worland	06267270
3	Dead Horse Creek tributary near Midwest	06312910
4	Dead Horse Creek tributary No. 2 near Midwest	06312920
5	Dugout Creek tributary near Midwest	06313180
6	Headgate Draw at upper station near Buffalo	06316480
7	Medicine Bow River tributary near Hanna	06634910
8	Hanna Draw tributary near Hanna	06634950
9	Frank Draw tributary near Orpha	06648720
10	Sage Creek tributary near Orpha	06648780
11	Demott Draw (example basin)	—



EXPLANATION

8▲ STREAMFLOW-GAGING STATION AND BASIN NUMBER

11△ EXAMPLE BASIN AND NUMBER

Figure 1. Location of streamflow-gaging stations and example basin in Wyoming.

of two parts: The first two digits, 06, indicate that the station is in the Missouri River drainage basin; the remaining six digits are the station number. The station numbers increase in a downstream direction.

INCIPIENT-RUNOFF CURVES

Empirical Incipient-Runoff Curve

The empirical incipient-runoff curve was developed using a combination of graphical and mathematical procedures. Average intensities of rainstorms that produced runoff and those that did not produce runoff were plotted against storm duration on graph paper having logarithmic scales. A power decay type of equation with a constant (Rankl, 1982) was mathematically fitted between the two types of events by trial and error:

$$I_p = a\, t^{-n} + f_c, \qquad (1)$$

where

I_p = rate of infiltration when rainfall flux equals infiltration rate, in inches per hour;

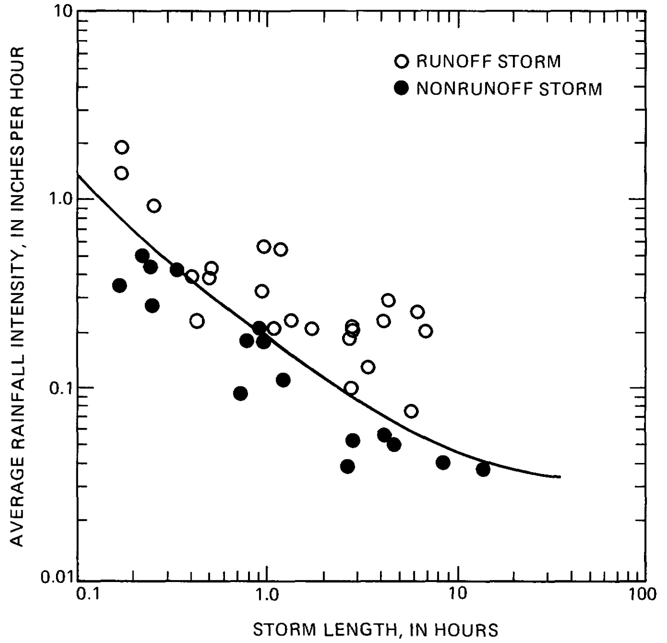


Figure 2. Relation of average rainfall intensity and storm length, and incipient-runoff curve for Dugout Creek tributary near Midwest (basin 5).

a = constant for a soil type, in inches;
t = time, in hours;
n = exponent parameter; and
f_c = minimum infiltration rate, in inches per hour.

Different combinations of values for the parameters were used. The best fit was determined visually. The data points and the empirical incipient-runoff curve for Dugout Creek tributary are shown in figure 2.

The incipient-runoff curve (IRC) reflects losses due to infiltration, interception, surface retention, and channel storage. R.W. Lichty (USGS, written commun., 1980) suggested that the empirical incipient-runoff curve can be represented by a physically based incipient-runoff curve that is a composite of an incipient-ponding curve and a surface-retention storage curve.

Physically Based Incipient-Runoff Curve

Incipient-Ponding Curve

Given a constant rainfall rate, incipient ponding can be defined as the state at which the rainfall rate is equal to the infiltration rate and free water begins to form at the soil surface. The following infiltration equation, developed by Green and Ampt (1911) and modified by Philip (1954) and Dawdy and others (1972), was used to compute the incipient-ponding component of the incipient-runoff curve:

$$\frac{di}{dt}=K_h\left[1+\frac{(P+H)\ (m-m_o)}{i}\right], \qquad (2)$$

where

di/dt = infiltration rate;
K_h = hydraulic conductivity at moisture content m;
$(P+H)(m-m_o)$ = effective product of the capillary potential, head, and moisture deficit;
P = capillary potential at the wetting front;
H = depth of ponded water;
m = relative moisture content of the soil near saturation;
m_o = initial relative moisture content of the soil; and
i = accumulated infiltration in the soil column.

This formulation, known as the Green-Ampt equation, was derived to describe the relation between infiltration rate and cumulative infiltration when the rate of water uptake is not limited by the supply of water. However, in this study it was assumed that the equation will describe soil water dynamics for both flux-controlled and ponded infiltration processes. In addition, it was assumed that an average antecedent-moisture condition exists (initially dry), and also that for a given soil the effective product of the capillary potential, the head, and the moisture deficit, $(P+H)(m-m_o)$, is a constant value. At the time of incipient ponding, t_p, the infiltration rate, di/dt, equals the supply rate, R, and the depth of water, H, is 0.00. Accumulated infiltration in the soil column, i, at the time of incipient ponding equals t_pR. Equation 2 is redefined using the above assumptions. Thus, equation 2 becomes

$$\frac{di}{dt}=R=K_h\left[1+\frac{P(m-m_o)}{t_pR}\right], \qquad (3)$$

time to incipient ponding is computed by solving for t_p in equation 3,

$$t_p=K_h\left[\frac{P(m-m_o)}{R(R-K_h)}\right], \qquad (4)$$

and water uptake at incipient ponding is defined as

$$i_p=Rt_p=K_h\left[\frac{P(m-m_o)}{R-K_h}\right]. \qquad (5)$$

A graphical representation of the incipient-ponding component of the incipient-runoff, or separation curve is shown in figure 3.

Surface-Retention Storage Curve

Surface-retention storage, d, is the amount of water that is intercepted and temporarily stored in depressions and

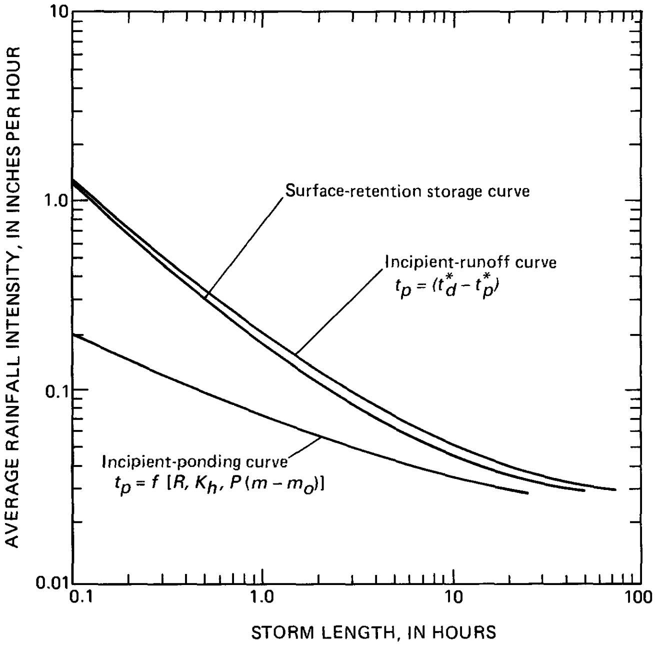


Figure 3. Incipient-ponding curve, surface-retention storage curve, and the composite incipient-runoff curve.

channels and on vegetation. This water remains in storage until it can infiltrate or evaporate.

Values for depression storage have been found to range from 0.10 inch (in) for clay soils to 0.20 in for sandy soils (Overton and Meadows, 1976, p. 21). As slope decreases, values for depression storage increase. Larger values for depression storage can be expected on flat, sandy, upland areas of natural basins. Values for channel storage were not available, but some stored water can be expected. In a semiarid climate, such as that of the study area, interception of water by vegetation is minimal.

The time required to satisfy surface retention, t_d, can be determined in two steps using the integrated form of equation 2, when the head is 0.0. The relation between time and accumulated infiltration is given as

$$t=\frac{1}{K_h}\left[i-P(m-m_o)\ln\left(1+\frac{i}{P(m-m_o)}\right)\right]. \qquad (6)$$

First, the water uptake at incipient ponding, i_p, is used to solve for the time period, t_p^*, which is the time required to yield an equivalent infiltration under ponded conditions—that is, infiltration not limited by supply rate:

$$t_p^*=\frac{1}{K_h}\left[i_p-P(m-m_o)\ln\left(1+\frac{i_p}{P(m-m_o)}\right)\right]. \qquad (7)$$

The relation between t_p^* and t_p is shown graphically in figure 4; both the flux-controlled and ponded forms of the Green-Ampt equation are depicted.

Next, an equation relating the pertinent variables is formulated to express surface-retention storage as a function of rainfall intensity:

$$d=R\,(t_d^*-t_p^*)-\Delta i, \qquad (8)$$

where

$(t_d^*-t_p^*)$ = time period required to generate a rainfall excess equivalent to surface-retention storage; and

Δi = incremental infiltration during the period $(t_d^*-t_p^*)$, where t_d^*=time of equivalent duration to satisfy retention storage.

Surface-retention storage, d, is shown as the cross-hatched area in figure 4, and water uptake by soil infiltration, i, is shown as the patterned area. Equation 2 is solved iteratively with short time steps to determine the infiltration, Δi, between incipient ponding and the beginning of runoff. The ratio between m and m_o for initially dry soil was, for this study, assumed to be 1.0. The change in $(P+H)(m-m_o)$ from head equal to 0.00 to head equal to retention storage was determined by fitting equations 2 and 8 to the runoff and nonrunoff data shown in figure 2. The difference between the values for the effective product of capillary potential, head, and moisture deficit at incipient ponding and at the point of runoff was the retention-storage value, d. In the final fit of the incipient-runoff curve, the value was varied linearly between the value determined at incipient ponding and the value determined at incipient runoff.

To determine the infiltration and retention-storage parameters for each basin, the procedure described above was repeated. Different combinations of parameter values were used to locate the incipient-runoff curve between the runoff and nonrunoff rainstorms. The best fit curve was determined visually for each basin.

POINT-INFILTRATION MODEL

Infiltration Equation

Water uptake by the soil for a rainfall event is computed as follows. First, the time to incipient ponding for a given rainfall intensity is computed using equation 4,

$$t_p=K_h\frac{[P(m-m_o)]}{R(R-K_h)},$$

and the uptake at incipient ponding, i_p, is given as Rt_p. Then from equation 7, the time required to yield an equivalent infiltration under ponded conditions is computed as

$$t_p^*=\frac{1}{K_h}\left[i_p-P(m-m_o)\ln\left(1+\frac{i_p}{P(m-m_o)}\right)\right].$$

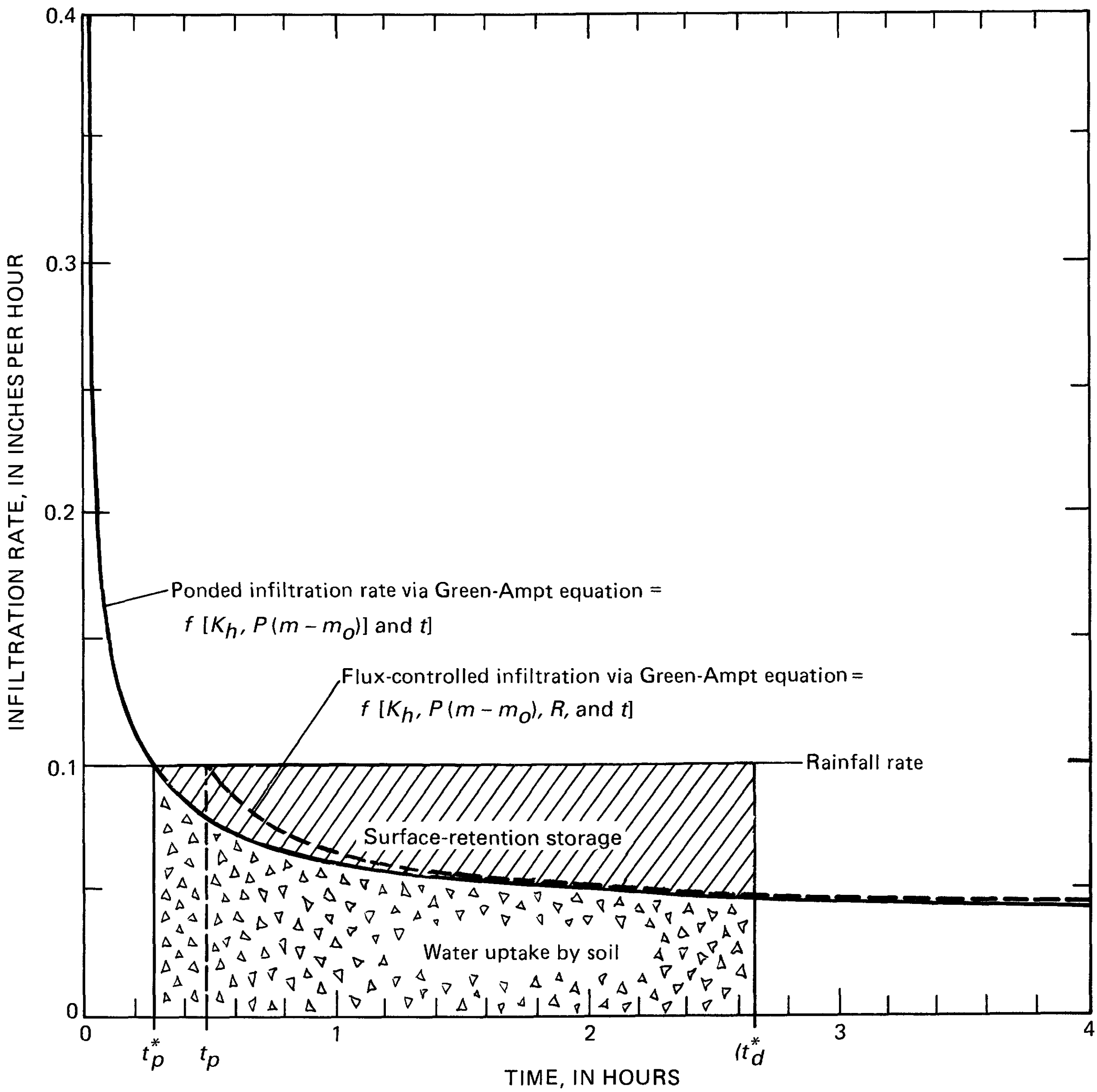


Figure 4. Relation between time and infiltration rate for both the ponded and flux-controlled forms of the Green-Ampt equation.

The duration of rainfall, t_r, and the variables t_p and t_p^* are related to give an equivalent duration of infiltration, t_r^*, for the ponded Green-Ampt equation:

$$t_r^*=t_r-t_p+t_p^*. \tag{9}$$

Next, infiltration is computed for the period $(t_d^*-t_p^*)$ to satisfy surface-retention storage, d. Then equation 2 is used to compute infiltration for the period t_d^* to t_r^*:

$$\frac{di}{dt}=K_h\left[1+\frac{(P+H)(m-m_o)}{i}\right].$$

The starting value for i for the initial time step is $(i_p+\Delta i)$. Finally, runoff is computed by a water-balance equation:

$$\text{Runoff}=\text{Rainfall}-\text{Infiltration}-\text{Surface retention}. \tag{10}$$

An estimate of the error variance, $EVAR$, is computed by dividing the sum of the squares of the deviations by the number of events, minus 2 degrees of freedom,

$$EVAR=\sum_{i=1}^{n}(y_i-\hat{y}_i)^2/(n-2)\ , \tag{11}$$

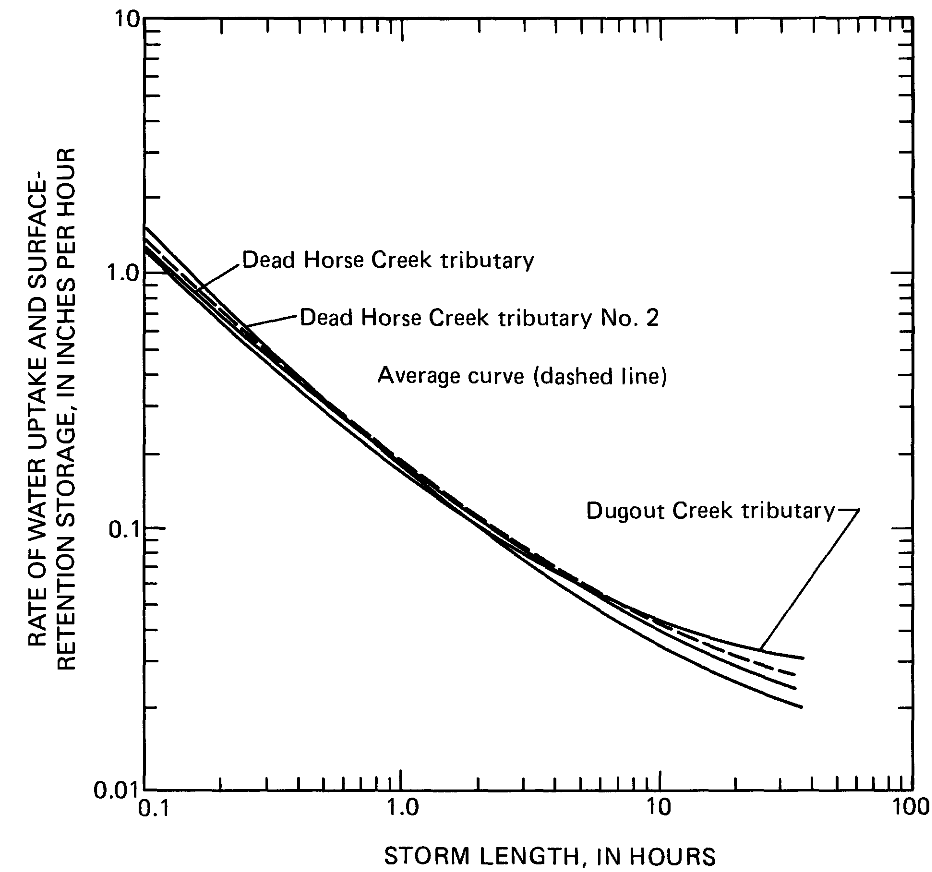


Figure 5. Comparison of incipient-runoff curves for three small basins containing soils derived from the Cody Shale near Midwest.

where

n = number of events;

y_i = measured runoff value; and

$\hat{y}_i$ = simulated runoff value.

A measure of the standard error of estimate, *SEE*, was calculated by computing the square root of the estimated error of variance and expressing this as a percentage of the mean of measured runoff:

$$SEE = 100 \times \sqrt{EVAR} / \bar{y}, \qquad (12)$$

where $\bar{y}$ is the mean of the measured runoff values.

Computation of Runoff from Single-Soil Basins

Three small basins, Dugout Creek tributary, Dead Horse Creek tributary, and Dead Horse Creek tributary No. 2, were used to evaluate the point-infiltration model. These basins are located in northern Natrona County, Wyo., in an area underlain by the Cody Shale. The basins have not been mapped for soil types, but soil maps and descriptions (Stephens, 1975) were available for soils derived from the Cody Shale a few miles to the north, in southern Johnson County, Wyo. Soils mapped in areas underlain by the Cody Shale or mapped as badlands consist of tight silty clays and clay loams. It was assumed that soils derived from the Cody Shale have one common low retention-storage value and infiltration rate for each basin. Retention-storage and infiltration parameters determined by the position of the incipient-runoff curve were used to compute runoff. Rainfall data, measured runoff, and simulated runoff for the three basins are listed in table 1. Average parameter values for the three basins, and statistics computed from equation 12 comparing measured and simulated runoff, are presented in table 2. Figure 5 is a graphical presentation of the three incipient-runoff curves and the average curve.

The relatively large values of the standard error of estimate for the three small basins can be explained in part by the difference in antecedent-moisture conditions for various runoff events. Because evaporation and evapotranspiration rates are large and drying is rapid, an average antecedent-moisture condition (initially dry) was assumed in order to permit computation of runoff for a design storm when the antecedent conditions are unknown.

Table 1. Rainfall data, measured runoff data, and simulated runoff data for single-soil basins

Date	Rainfall (inches)	Length of storm (hours)	Intensity (inches per hour)	Measured runoff (inches)	Simulated runoff (inches)
Dugout Creek tributary near Midwest, Wyoming (basin 5)					
05/23/65	0.49	0.92	0.533	0.140	0.305
06/24/65	.91	4.08	.233	.440	.578
07/01/65	.30	.17	1.760	.140	.173
09/01/66	.50	2.75	.182	.148	.228
06/09/67	.30	1.33	.266	.088	.097
06/13/67	.26	2.67	.094	.076	.000
06/14/67	.29	.92	.315	.130	.108
06/15/67	1.36	6.75	.201	.815	.925
09/18/67	.46	2.76	.172	.206	.191
09/26/67	.09	.42	.214	.022	.000
06/05/68	.22	1.08	.204	.027	.033
06/06/68	.37	5.58	.073	.106	.034
09/03/68	.41	3.33	.123	.202	.117
06/19/69	.22	.25	.880	.037	.086
05/22/70	1.25	4.25	.294	.661	.909
05/24/70	.59	1.17	.504	.213	.390
05/30/70	.20	.50	.400	.035	.047
06/17/72	.22	.17	1.290	.025	.094
06/18/72	.29	.92	.315	.085	.108
06/19/72	.57	2.75	.207	.330	.295
06/30/72	.18	.50	.360	.050	.028
08/02/72	.34	1.67	.204	.120	.119
08/24/72	1.54	6.08	.252	.820	1.123
09/11/72	.14	.42	.333	.041	.000
Dead Horse Creek tributary near Midwest, Wyoming (basin 3)					
06/16/65	.45	.83	.542	.292	.268
09/13/66	.23	.67	.343	.057	.060
09/14/66	.10	1.00	.210	.026	.027
06/15/67	1.31	7.00	.187	.939	.926
06/22/67	1.13	13.00	.087	.716	.608
07/12/67	.41	.33	1.242	.019	.256
07/15/67	.33	.17	1.941	.018	.190
07/18/67	.29	1.66	.175	.018	.079
09/18/67	.33	3.92	.084	.066	.049
05/22/68	.25	4.58	.054	.047	.000
05/23/68	.77	8.50	.091	.289	.360
05/25/68	.34	2.66	.128	.209	.094
06/06/68	.55	11.66	.047	.413	.076
06/06/68	.11	1.00	.130	.089	.000
06/07/68	.22	1.50	.147	.179	.019
05/22/70	.44	.50	.880	.091	.275
08/08/71	.10	.17	1.235	.006	.000
06/03/72	1.23	1.00	1.230	1.114	1.036
06/03/72	.40	1.08	.370	.389	.207
08/02/72	.79	4.58	.172	.337	.474
08/24/72	1.07	10.25	.104	.531	.606
Dead Horse Creek tributary No.2 near Midwest, Wyoming (basin 4)					
05/23/65	.22	1.58	.139	.043	.007
07/05/65	.34	2.58	.132	.099	.093
07/25/65	.19	.75	.253	.046	.006
06/22/66	.52	.75	.693	.136	.328
09/01/66	.44	1.58	.278	.130	.217
09/01/66	.41	2.25	.182	.146	.168
06/07/67	.12	.08	1.500	.059	.000
06/14/67	.21	1.00	.210	.072	.016
06/14/67	1.31	11.83	.099	.488	.707
06/20/67	.12	.42	.286	.106	.000

Table 1. Rainfall data, measured runoff data, and simulated runoff data for single-soil basins—Continued

Date	Rainfall (inches)	Length of storm (hours)	Intensity (inches per hour)	Measured runoff (inches)	Simulated runoff (inches)
Dead Horse Creek tributary No.2 near Midwest, Wyoming (basin 4)—Continued					
06/20/67	.35	.42	.833	.230	.176
06/22/67	.39	2.83	.138	.120	.134
06/22/67	.65	8.17	.080	.201	.271
07/15/67	.46	.58	.793	.262	.277
06/07/68	.24	.50	.480	.093	.065
07/20/69	.09	.17	.529	.015	.000
08/09/71	.31	.17	1.824	.119	.154
06/19/72	.46	3.33	.138	.116	.188
08/02/72	.43	2.50	.164	.030	.161
08/02/72	.35	1.42	.246	.057	.135
08/24/72	.97	9.75	.079	.233	.353

Test of Parameter Sensitivity

Information on model response to changes in parameter values is useful in understanding the model. A mathematical fit of the data, using some fitting criteria, is necessary to determine sensitivity of the parameters. Unfortunately, a mathematical fitting scheme for the incipient-runoff curve was not available, so the best fit had to be determined visually. Therefore, a graphical approach to the sensitivity test was used. Values 10, 20, and 30 percent greater than, and 10, 20, and 30 percent less than, the optimum parameter values were used for each of the three parameters and plotted on a graph with the data points. The best fit curve and the curves of +30 percent and −30 percent for the parameters for Dugout Creek tributary are shown in figures 6 through 8. The largest change in runoff is the result of the most sensitive parameter, retention storage (d). A change in the retention-storage parameter affects simulated runoff from short-duration high-intensity storms (fig. 8). A change in the saturated hydraulic conductivity parameter (K_h) affects simulated runoff from long-duration storms (fig. 6).

Rainfall-intensity and storm-length data from Dugout Creek tributary were used to evaluate the effects of parameter changes on simulated runoff. The results are tabulated below:

Parameter	Parameter change (percent)	Runoff change (percent)
K_h	+30	−8.6
K_h	−30	+10.2
$P(m-m_o)$	+30	−2.6
$P(m-m_o)$	−30	+2.9
d	+30	−11.4
d	−30	+12.8

Table 2. Soil parameters, fitting statistics, and average values for three small basins having single-soil cover

Basin number	Basin name	Soil parameters: K_h (inches per hour)	$P(m-m_o)$ (inches)	d (inches)	Data-fitting errors: Difference (percent)[1]	Standard error (percent)[2]
3	Dead Horse Creek tributary	0.017	0.049	0.110	−2.9	50
4	Dead Horse Creek tributary No. 2	.013	.053	.129	23.4	70
5	Dugout Creek tributary	.025	.060	.090	20.8	55
	Average	.018	.054	.118	—	—

[1] Difference between the sum of the measured and simulated events.
[2] Percent standard error of the mean value of the data set.

Test of Nonuniform Rainfall Intensities

Tests were made to evaluate the assumption of "an average" storm intensity. Two assumed storms, each having an average intensity of 0.30 inch per hour (in/h) and a storm duration of 1.60 hours, were used in the analyses. The storm for the first test was designed so that one-third of the total precipitation fell during the first half of the storm (from beginning of rainfall to beginning of runoff) and two-thirds fell during the second half. The second test storm had the same duration as the first, but with two-thirds of the total precipitation falling during the first half and one-third during the second half. Runoff was computed for the two assumed storms and for the mean of the two tests. The same incipient-runoff curve was used for all computations. A second set of assumed storms, each having an average intensity of 0.08 in/h and a storm duration of 10.00 hours, was used to check lower intensity storms. The same methods were used for this set of storms as were used for the first set.

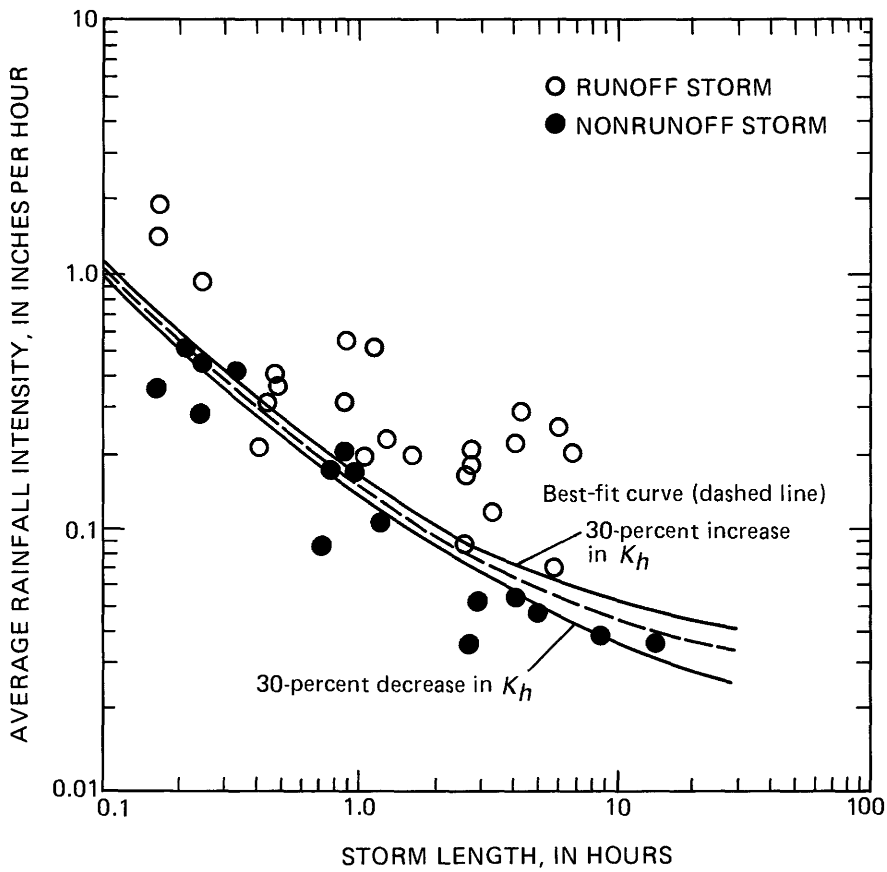


Figure 6. Incipient-runoff curves for changes in hydraulic conductivity (K_h) for Dugout Creek tributary near Midwest (basin 5).

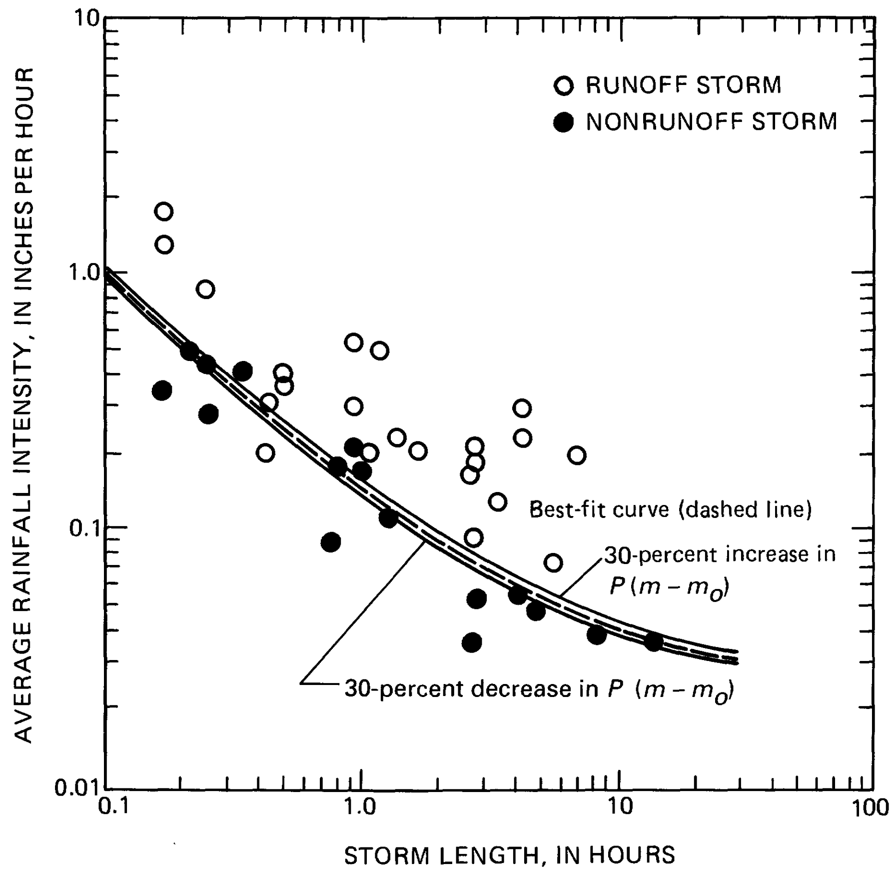


Figure 7. Incipient-runoff curves for changes in the effective product of capillary potential ($P(m\text{-}m_o)$) for Dugout Creek tributary near Midwest (basin 5).

Results of the analyses of both storm sets show that when the low-intensity part of the storm occurred during the first half of the event, the computed runoff was about 2.3 percent higher than the runoff computed for the mean; when the high-intensity part of the storm occurred first, the computed runoff was 1.8 percent lower than the runoff computed for the mean. A small error was introduced by assuming a constant rainfall rate.

COMPUTATION OF RUNOFF FROM MULTIPLE-SOIL BASINS

Very few natural basins contain only one type of soil or several types of soils that have a common or single infiltration rate. The incipient-runoff-curve method of distinguishing between runoff and nonrunoff rainstorms is applicable to multiple-soil basins. However, the incipient-runoff curve defines the infiltration and surface-retention storage parameters for only the soil having the highest runoff potential, rather than for the entire basin (Rankl, 1982). When the method is used for multiple-soil basins, each soil type must be ranked in relation to its relative permeability and the area of each soil type must be determined.

Ranking of Soil Permeability

Infiltration rates of soils can be ranked by first determining the relative permeability using methods described in a report by the U.S. Department of Agriculture (1962, p. 168), which states, "In the absence of precise measurements, soils may be placed into relative permeability classes through studies of structure, texture, porosity, cracking, and other characteristics of the horizons in the soil profile in relation to local use experience." For convenience in this study, the classes of relative soil permeability used by the U.S. Soil Conservation Service (Stephens, 1975) were equated to single values rather than class ranges of values. The Soil Conservation Service class ranges, as well as the single values, are listed in table 3. The midpoint (or single value) for each class was computed by determining the logarithmic values of the endpoints and taking the

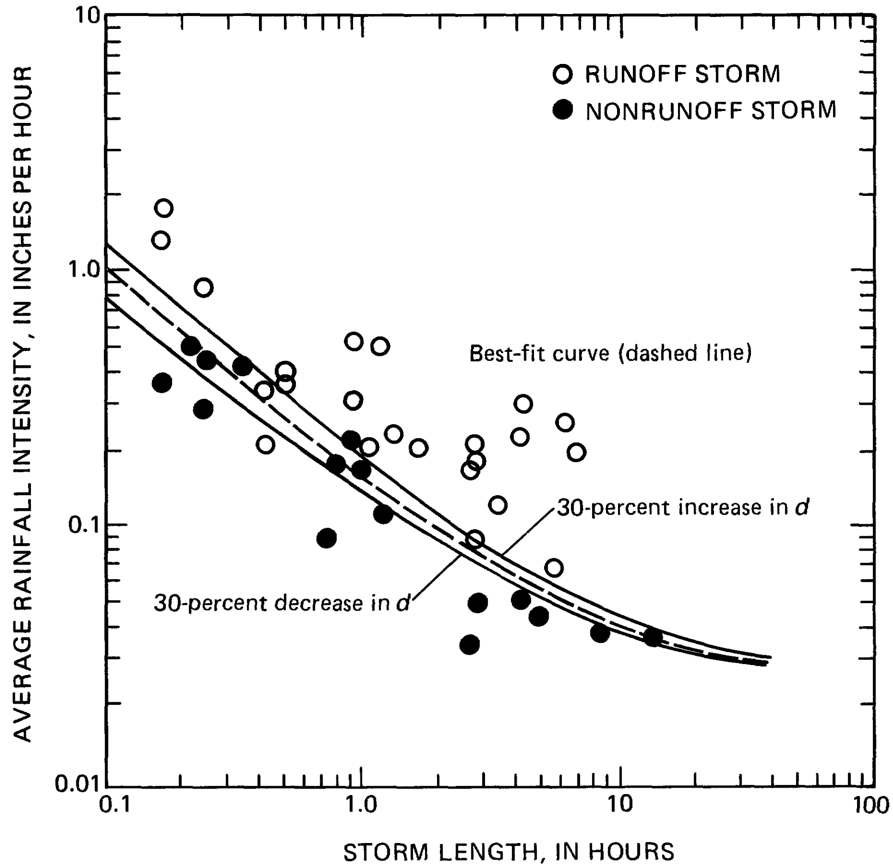


Figure 8. Incipient-runoff curves for changes in surface-retention storage (*d*) for Dugout Creek tributary near Midwest (basin 5).

antilog of their mean. This single value of relative soil permeability is used as a soil-group identifier in this report.

The next steps in computing runoff from multiple-soil basins are to determine the percentage of each basin covered by each soil group and to arrange the soil groups in the order of their relative infiltration rates.

In the empirical analysis of infiltration, Rankl (1982) computed values of relative permeability for soil complexes or associations. That approach made it difficult to estimate infiltration-rate curves for soil complexes other than those tested. In this study, an alternative approach using only soil texture—clay, silty clay loams, clay loams, loams, and sandy loams—as a criterion for grouping soils was investigated. It was found that soil texture generally was related to relative permeability, but numerous anomalies made the method impractical.

Soil complexes and associations mapped and described by the Soil Conservation Service were divided into individual soil units and were assigned a value of relative soil permeability based on the class description. The soils were regrouped using the relative permeability value as a criterion. These soil groups were then used with the procedure outlined in the next section to determine infiltration rates.

Table 3. Class values of relative soil permeability

Class description	Numerical class range (inches per hour)	Relative soil permeability (inches per hour)
1 Very slow	less than 0.06	[1]0.06
2 Slow	.06 to .2	.11
3 Moderately slow	.2 to .6	.35
4 Moderate	.6 to 2.0	1.10
5 Moderately rapid	2.0 to 6.0	3.46
6 Rapid	6.0 to 20.0	11.0

[1] Upper endpoint was used.

Optimization of Incipient-Runoff Curves

A storm whose average intensity and duration is greater than the average intensity and duration needed to define the IRC (incipient-runoff curve) for the soil having the highest runoff potential, but whose average intensity and duration is less than that needed to define the IRC for the remainder of the soils, will produce runoff from only the soil having the highest runoff potential. The IRC of all the

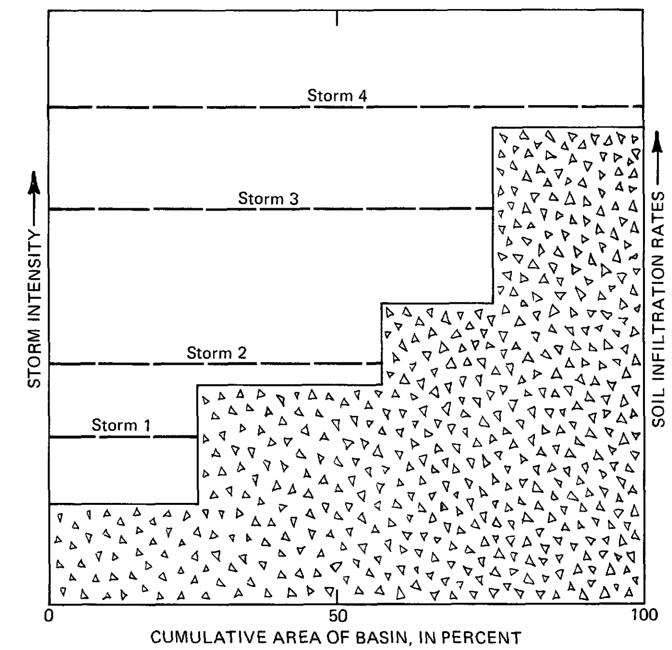


Figure 9. Schematic model of subbasin infiltration rates.

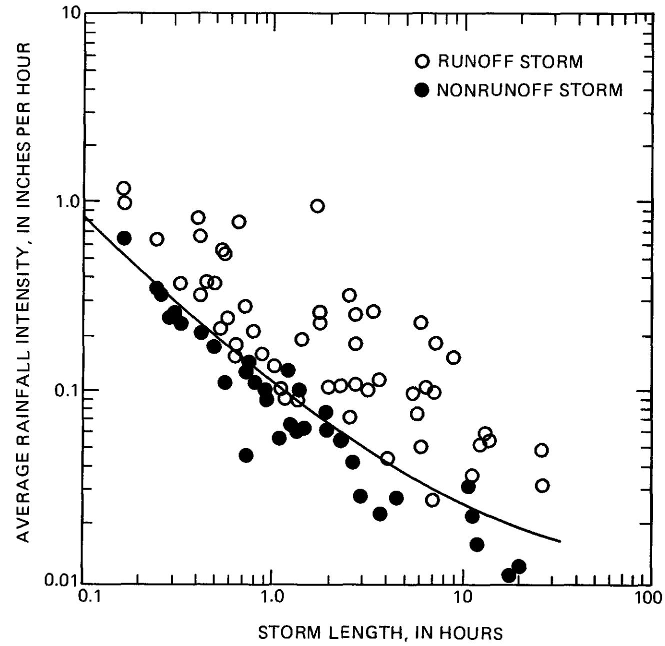


Figure 10. Common incipient-runoff curve for North Prong East Fork Nowater Creek near Worland (basin 1) and North Prong East Fork Nowater Creek tributary near Worland (basin 2).

soil types in a basin can be evaluated by using data for a number of storms, with a range in average intensities and durations from just greater than the lowest IRC to intensities and durations greater than the highest IRC. A schematic model of subbasin infiltration rates is shown in figure 9.

A solution is possible by assuming a series of incipient-runoff curves parallel to the lowest curve and using them to compute runoff for the subbasin areas. The runoffs from the subbasin areas are summed to obtain the total runoff for the storm. Each simulated value of runoff is compared with the measured value of runoff. This process is repeated until the difference between simulated runoff and measured runoff is some acceptable sum of the least squares fit of all the events for the basin. Infiltration and retention-storage parameters are determined for each subbasin by the fitting process, while the original order, based on permeability of soils, is maintained. The assumption that the IRC's are parallel to the lowest, or base, IRC is made in order to use a single multiplier for the three parameters needed to define the IRC for each soil.

The large number of trials required to obtain an acceptable fit is nearly impossible without the aid of a computer and an optimization technique. A modified Rosenbrock-optimization technique used by Dawdy and others (1972) for rainfall-runoff studies was adapted to aid in the data fit. Upper and lower constraints were set on the multiplier of infiltration and retention parameters to keep the ranking of permeabilities of soil types in the correct order.

Rainfall data and measured runoff data for North Prong East Fork Nowater Creek tributary were used to develop the procedure for determining values for IRC parameters for small basins containing more than one soil type. This basin was selected because of the range of rainfall data available, the limited number of soil types, and available infiltrometer data. Rainfall and runoff data for North Prong East Fork Nowater Creek, a small basin in the same area, were available to test transferability of fitted parameters. The IRC was defined using runoff and nonrunoff rainstorm data for both North Prong East Fork Nowater Creek tributary and North Prong East Fork Nowater Creek. Both basins contain areas of shale outcrop and gullies having low permeability, and this similarity resulted in a common incipient-runoff curve (fig. 10). Soil types, soil groups, textures, relative permeabilities, and percentages of basin area are listed in tables 4 and 5.

Data for 15 rainfall-runoff events in North Prong East Fork Nowater Creek tributary were used to determine the position of the IRC for each soil. The base IRC (fig. 10) defines the parameters for the soil and soil material having the highest runoff potential. The lower constraints for the parameters were set to be equal to the base curve values, and the upper constraints were set to be equal to the values for the storm of greatest intensity and duration. The results of the optimization of IRC parameter values from data collected for the drainage basin during an 8-year period show that only two soil types had a retention-storage loss and an infiltration rate small enough to produce runoff from the rainstorms; that is, runoff occurred from only 37.2

Table 4. Soil types and groupings for North Prong East Fork Nowater Creek tributary near Worland (basin 2)

Soil name	Soil texture	Percentage of basin area
Soils with a relative permeability of 0.06 inch per hour		
Rock outcrop	Shale	18.6
Total		18.6
Soils with a relative permeability of 0.11 inch per hour		
Muff	Fine sandy loam	18.6
Total		18.6
Soils with a relative permeability of 0.35 inch per hour		
Persayo	Clay loam	21.2
Youngston	Silty clay loam	1.8
Uffens	Fine sandy loam	1.8
Greybull	Clay loam	1.7
Total		26.5
Soils with a relative permeability of 1.10 inches per hour		
Neiber	Fine sandy loam	20.6
Fruita	Fine sandy loam	7.8
Lostwell	Sandy clay loam	4.8
Total		33.2
Soils with a relative permeability of 3.46 inches per hour		
Wallson	Loam fine sand	3.1
Total		3.1

percent of the basin. The optimized parameters for the soil groups listed in table 4 are tabulated in table 6.

Rainstorm dates, amounts, lengths, intensities, and measured and simulated runoff values for North Prong East Fork Nowater Creek tributary are presented in table 7. Standard deviation as computed by equation 12 is 0.015 in, or about 20 percent of the mean runoff value. The sum of simulated runoff for all available runoff events is 1.3 percent greater than the sum of measured runoff. Figure 11 is a graphical comparison of measured and simulated runoff.

Table 5. Soil types and groupings for North Prong East Fork Nowater Creek near Worland (basin 1)

Soil name	Soil texture	Percentage of basin area
Soils with a relative permeability of 0.06 inch per hour		
Rock outcrop	Shale	29.3
Total		29.3
Soils with a relative permeability of 0.11 inch per hour		
Muff	Fine sandy loam	9.6
Total		9.6
Soils with a relative permeability of 0.35 inch per hour		
Persayo	Clay loam	20.0
Youngston	Silty clay loam	11.6
Uffens	Fine sandy loam	7.3
Greybull	Clay loam	3.3
Total		42.2
Soils with a relative permeability of 1.10 inches per hour		
Neiber	Fine sandy loam	7.7
Fruita	Fine sandy loam	0.6
Lostwell	Sandy clay loam	8.8
Total		17.1
Soils with a relative permeability of 3.46 inches per hour		
Wallson	Loam fine sand	0.2
Sandy alluvium	Sandy	1.6
Total		1.8

Table 6. Soil groups, infiltration parameters, and percent area of soil groups for North Prong East Fork Nowater Creek tributary near Worland (basin 2)

Soil-group identifier	Soil-infiltration parameters: K_h (inches per hour)	$P(m\text{-}m_o)$ (inches)	$\dot{d}$ (inches)	Percentage of basin area
0.06	0.011	0.050	0.073	18.6
.11	.037	.168	.245	18.6
[1].35	.074	.340	.496	26.5
[2]1.10	.074	.340	.496	33.2
[2]3.46	.074	.340	.496	3.1

[1] Infiltration rates maybe greater than the parameter values indicate.
[2] Infiltration rates are undefined.

Split-Sample Test

To test the prediction capabilities of the point-infiltration model, the data set for North Prong East Fork Nowater Creek tributary (table 7) was divided into two sets of eight and seven rainstorms. A random numbers table (Dixon and Massey, 1957, p. 366–370) was used to select the eight storms for control sample 1. The remaining seven storms were used for test sample 2 (and later for control sample 2).

The control samples were optimized using the same soil grouping and parameter constraints as the full set. Optimized parameters from control sample 1 were used to simulate runoff by using rainfall data from test sample 2.

Table 7. Rainfall data, measured runoff data, and simulated runoff data for North Prong East Fork Nowater Creek tributary near Worland (basin 2)

Date	Rainfall (inches)	Length of storm (hours)	Intensity (inches per hour)	Measured runoff (inches)	Simulated runoff (inches)
05/23/65	0.12	0.33	0.364	0.006	0.003
06/06/67	.51	.67	.761	.094	.095
06/23/67	.70	6.75	.104	.083	.083
09/18/67	1.40	9.08	.154	.304	.284
06/05/68	.46	1.83	.251	.055	.057
06/07/68	.14	1.08	.130	.004	.002
07/27/68	.14	.92	.152	.008	.003
08/23/68	1.40	6.25	.224	.301	.322
05/21/70	.24	3.42	.070	.009	.010
05/28/71	.41	1.83	.224	.025	.048
05/29/71	.32	3.25	.098	.022	.025
05/30/71	.79	13.42	.059	.116	.080
08/23/72	.30	2.83	.106	.016	.023
09/08/73	.31	6.71	.050	.018	.016
09/08/73	.27	.42	.643	.034	.030

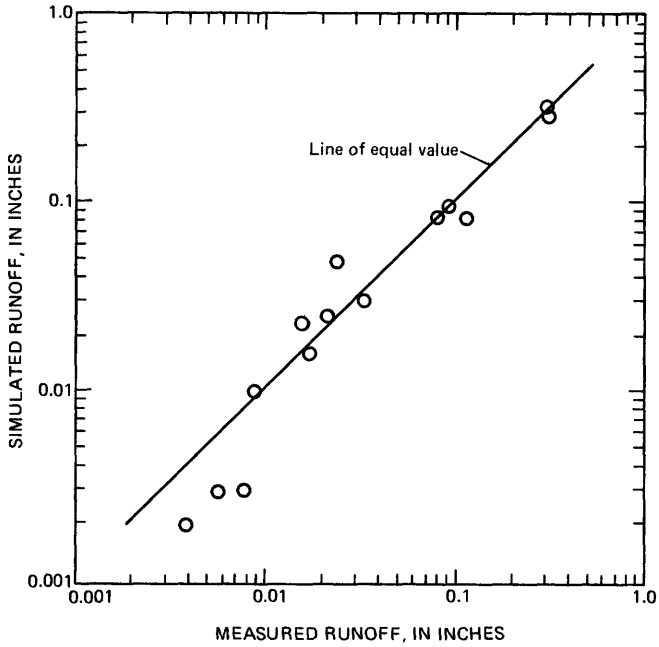


Figure 11. Comparison of simulated runoff and measured runoff for North Prong East Fork Nowater Creek tributary near Worland (basin 2).

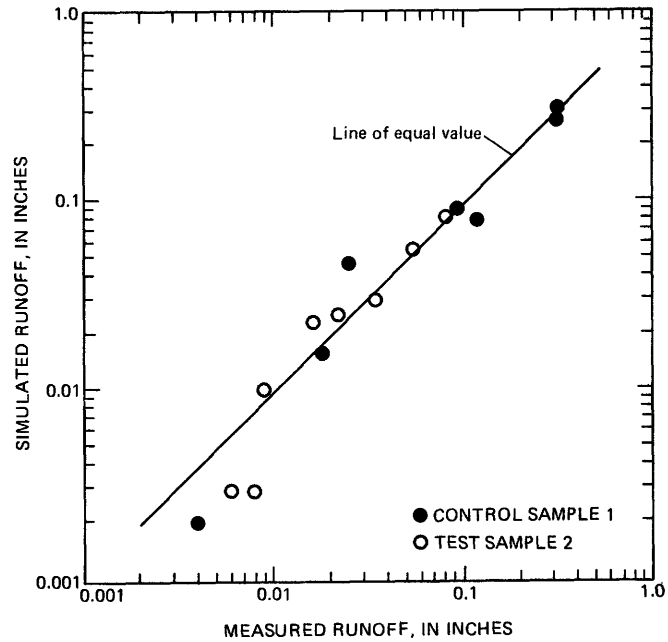


Figure 12. Split-sample test for North Prong East Fork Nowater Creek tributary near Worland (basin 2), control sample 1.

The process was reversed by using test sample 2 as control sample 2. The results of the split-sample tests are shown graphically in figures 12 and 13.

The fitting errors for the test using equations 11 and 12 are as follows:

Control sample	Standard deviation (inches)	Percentage of mean
1	0.004	15
2	0.023	19
All	0.015	20

Results of the tests show that the model was capable of predicting runoff from the uncalibrated half of the data set within 19 percent.

Interbasin Transfer of Soil Parameters

Tests were conducted to determine if infiltration parameters could be transferred from one basin to another. Rainfall data and areal extent of soils for North Prong East Fork Nowater Creek and the optimized infiltration parameters for North Prong East Fork Nowater Creek tributary were used to simulate runoff for each storm. The standard deviation of the simulated runoff when compared with the measured runoff was 0.031 in, about 46 percent of the mean measured runoff. The sum of the simulated runoff events was 10.2 percent less than the sum of the measured runoff events. The distribution appears uniform about the line of equal value, as shown in figure 14.

Data Analysis

Seven basins having multiple soils, rainfall data, and runoff data were available for this study. Soil names, textures, relative permeabilities, and percentages of basin

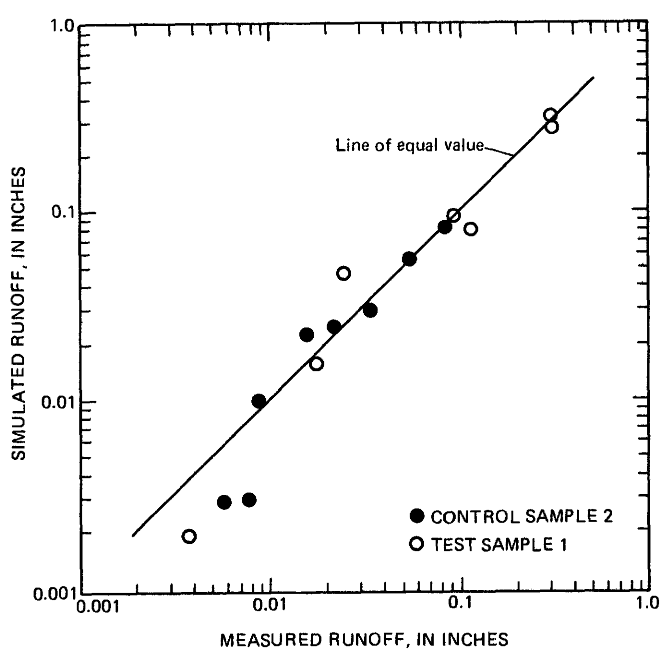


Figure 13. Split-sample test for North Prong East Fork Nowater Creek tributary near Worland (basin 2), control sample 2.

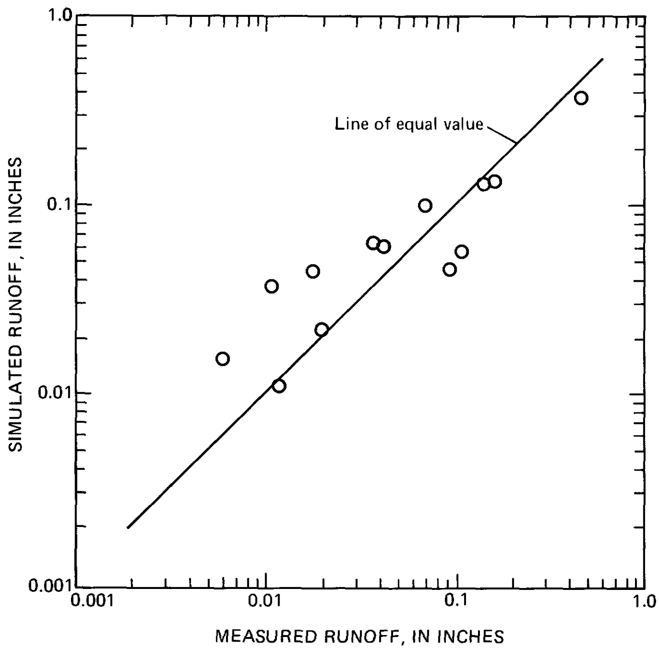


Figure 14. Comparison of simulated runoff and measured runoff for North Prong East Fork Nowater Creek near Worland (basin 1), using fitted infiltration parameters from North Prong East Fork Nowater Creek tributary near Worland (basin 2).

area for five of the basins are listed in table 8. Soil data for the other two basins, North Prong East Fork Nowater Creek tributary and North Prong East Fork Nowater Creek, are listed in tables 4 and 5.

Incipient-runoff curves for the soil groups were optimized to determine the best values of infiltration parameters for computing runoff from rainfall data. Rainfall data, measured runoff data, and simulated runoff data for the multiple-soil basins are listed in tables 7 and 9.

Optimized infiltration and retention-storage parameters for the incipient-runoff curve for each soil group in each of the seven basins are listed in table 10. Also listed are fitting errors for each data set. The difference between the sum of the measured runoff events and the sum of the simulated runoff events is a measure of the fit of the data. A measure of dispersion is computed by dividing the standard deviation by the mean value of the data set. For a given basin, soil groups having an infiltration rate greater than that of the highest intensity rainstorm have a set of soil-parameter values that are defined by the intensity of the rainstorm. The loss rate equals the supply rate. These soil groups are flagged in table 10. Soil groups having infiltration and retention-storage values greater than those that are set equal to the values defined by the largest storm are flagged in table 10 as undefined.

When the combination of infiltration rate and retention storage equals or exceeds the supply rate for a soil group, runoff does not occur. The data for each multiple-

Table 8. Soil types, texture, relative permeability, and percent area for multiple-soil basins

Soil name	Soil texture	Percentage of basin area
Headgate Draw at upper station, near Buffalo, Wyoming (basin 6)		
Soils with a relative permeability of 0.06 inch per hour		
Rockland	Shale	15.3
Total		15.3
Soils with a relative permeability of 0.11 inch per hour		
Gaynor	Silty clay loam	7.0
Razor	Silty clay loam	3.4
Renohill	Clay loam	9.2
Samsil	Silty clay loam	19.9
Total		39.5
Soils with a relative permeability of 0.35 inch per hour		
Briggsdale	Fine sandy loam	6.2
Total		6.2
Soils with a relative permeability of 1.10 inches per hour		
Ascolon	Fine sandy loam	1.4
Cushman	Fine sandy loam	4.5
Kim	Loam	3.0
Olney	Fine sandy loam	2.3
Shingle	Silty clay loam	17.2
Stoneham	Sand loam	1.6
Thedalund	Loam	6.1
Undefined loams	Sandy clay loam	1.0
Worf	Loam	1.1
Zigwield	Loam	.8
Total		39.0
Medicine Bow River tributary near Hanna, Wyoming (basin 7)		
Soils with a relative permeability of 0.06 inch per hour		
Rockland	Shale and sandstone	10.0
Total		10.0
Soils with a relative permeability of 0.11 inch per hour		
Abston	Sandy loam	17.1
Playa	Silt	0.1
Tisworth	Sandy clay loam	2.4
Total		19.6
Soils with a relative permeability of 0.35 inch per hour		
Blazon	Clay loam	36.9
Seaverson	Clay loam	1.3
Total		38.2
Soils with a relative permeability of 1.10 inches per hour		
Blackhall	Sandy loam	0.5
Delphill	Loam	1.3
Shinbara	Loam	9.0
Yamac	Loam	3.7
Total		14.5
Soils with a relative permeability of 3.46 inches per hour		
Absher	Fine sandy loam	2.1
Forelle	Loamy	1.8
Rentsac	Channery sandy loam	5.3
Rock River	Sandy loam	0.4
Stanka	Sandy loam	7.5
Spool	Loamy sand	0.6
Total		17.7
Hanna Draw tributary near Hanna, Wyoming (basin 8)		
Soils with a relative permeability of 0.06 inch per hour		
Rockland	Shale and sandstone	17.6
Total		17.6

Table 8. Soil types, texture, relative permeability, and percent area for multiple-soil basins—Continued

Soil name	Soil texture	Percentage of basin area
Hanna Draw tributary near Hanna, Wyoming—Continued		
Soils with a relative permeability of 0.11 inch per hour		
Abston	Sandy loam	0.8
Playa	Silt	0.4
Tisworth	Sandy clay loam	0.6
Total		1.8
Soils with a relative permeability of 0.35 inch per hour		
Blazon	Clay loam	20.6
Seaverson	Clay loam	1.6
Total		22.2
Soils with a relative permeability of 1.10 inches per hour		
Blackhall	Sandy loam	0.6
Delphill	Loam	2.8
Shinbara	Loam	12.4
Yamac	Loam	0.1
Total		15.9
Soils with a relative permeability of 3.46 inches per hour		
Rentsac	Channery sandy loam	13.8
Rock River	Sandy loam	5.2
Stanka	Sandy loam	21.7
Spool	Loamy sand	1.8
Total		42.5
Frank Draw tributary near Orpha, Wyoming (basin 9)		
Soils with a relative permeability of 0.11 inch per hour		
Limon	Silty clay loam	2.8
Razor	Silty clay loam	0.7
Renohill	Clay loam	9.0
Samsil	Silty clay loam	0.7
Ulm	Loam	7.9
Worfka	Clay loam	3.8
Total		24.9
Soils with a relative permeability of 0.35 inch per hour		
Bidman	Loam	3.5
Briggsdale	Fine sandy loam	4.6
Total		8.1
Soils with a relative permeability of 1.10 inches per hour		
Bowbac	Sandy loam	11.6
Cushman	Fine sandy loam	0.5
Fort Collins	Sandy loam	1.4
Kim	Clay loam	5.2
Olney	Fine sandy loam	13.3
Shingle	Silty clay loam	4.3
Stoneham	Sand loam	0.5
Thedalund	Loam	0.6
Worf	Loam	0.7
Total		38.1
Soils with a relative permeability of 3.46 inches per hour		
Tassel	Fine sandy loam	6.4
Terry	Fine sandy loam	3.2
Total		9.6
Soils with a relative permeability of 11.0 inches per hour		
Dwyer	Fine sand	0.9
Lesset	Fine sandy loam	1.6
Rugsley	Sandy loam	0.3
Rockland	Sandstone	1.0
Sandy loams (misc.)	—	8.3
Tulluck	Loamy sand	3.6
Valent	Loamy sand	1.3
Vona	Sandy loam	2.3
Total		19.3

Table 8. Soil types, texture, relative permeability, and percent area for multiple-soil basins—Continued

Soil name	Soil texture	Percentage of basin area
Sage Creek tributary near Orpha, Wyoming (basin 10)		
Soils with a relative permeability of 0.11 inch per hour		
Renohill	Clay loam	1.1
Samsil	Silty clay loam	0.5
Worfka	Clay loam	0.1
Total		1.7
Soils with a relative permeability of 1.10 inches per hour		
Bowbac	Sandy loam	13.0
Cushman	Fine sandy loam	3.3
Fort Collin	Sandy loam	1.3
Kim	Clay loam	0.9
Olney	Fine sandy loam	20.5
Shingle	Silty clay loam	1.2
Thedalund	Loam	1.4
Worf	Loam	1.2
Total		42.8
Soils with a relative permeability of 3.46 inches per hour		
Tassel	Fine sandy loam	11.9
Terry	Fine sandy loam	6.9
Total		18.8
Soils with a relative permeability of 11.0 inches per hour		
Dwyer	Fine sand	1.8
Lesset	Fine sandy loam	2.1
Rockland	Sandstone	0.1
Sandy loams (misc.)	—	7.8
Tulluck	Loamy sand	9.8
Valent	Loamy sand	3.5
Vona	Sandy loam	11.6
Total		36.7

soil basin were examined to determine the area of soil groups that did and did not contribute to runoff during the 8 years of data collection. The soil areas that contributed to runoff from the multiple-soil basins ranged from 41.6 percent of the total drainage area (Hanna Draw tributary) to 71.1 percent (Frank Draw tributary). Information concerning contributing areas is useful when applying statistical analysis in hydrologic studies.

The area contributing to runoff in a small basin is the effective drainage area. In most studies, the total drainage area of a basin is used as an independent variable in regression equations for estimating runoff; the procedure commonly results in large standard errors of estimate. That may be due, in part, to the lack of information about the contributing areas for the runoff-producing storms recorded at the station. In addition, the effective area, as determined in this study, must be the only source area for fluvial-sediment yield from small, ephemeral-stream basins.

Values of surface-retention storage and infiltration parameters for each soil classified by relative permeability, except one, were averaged to determine the set of soil-parameter values that best represents each soil group (table 11). Because of the limited number of data sets, a statistical analysis was not useful; therefore, a graphical approach was

Table 9. Rainfall data, measured runoff data, and simulated runoff data for multiple-soil basins

Date	Rainfall (inches)	Length of storm (hours)	Intensity (inches per hour)	Measured runoff (inches)	Simulated runoff (inches)
North Prong East Fork Nowater Creek near Worland, Wyoming (basin 1)					
05/08/65	0.35	3.92	0.089	0.018	0.044
06/15/65	.08	.33	.242	.002	.000
06/04/67	.14	1.33	.105	.006	.002
06/05/67	.16	.83	.193	.012	.011
06/06/67	.32	.67	.478	.041	.059
06/11/67	.15	2.58	.058	.006	.000
06/23/67	.69	7.00	.099	.139	.127
09/18/67	1.40	9.08	.154	.441	.437
05/23/68	.33	.67	.493	.037	.063
05/21/70	.27	.58	.465	.092	.045
05/28/71	.56	5.17	.108	.068	.097
05/29/71	.20	2.67	.075	.036	.009
05/30/71	.66	5.00	.132	.157	.133
08/23/72	.30	2.83	.106	.011	.036
07/29/73	.25	4.00	.062	.006	.015
09/08/73	.31	6.25	.050	.020	.021
09/08/73	.30	.42	.714	.106	.057
Headgate Draw at upper station, near Buffalo, Wyoming (basin 6)					
08/15/68	.18	.25	.720	.004	.000
08/23/68	.50	2.67	.187	.006	.010
07/16/69	1.39	.58	2.397	.400	.438
05/23/70	.46	.50	.920	.005	.030
06/19/70	1.06	.92	1.152	.241	.222
06/29/70	.17	.17	1.000	.002	.000
07/08/70	.29	.25	1.160	.005	.009
07/10/70	.37	.42	.881	.028	.018
06/09/72	.95	1.83	.519	.070	.086
07/23/72	.34	.75	.453	.006	.008
09/11/72	.30	.50	.600	.008	.006
Medicine Bow River tributary near Hanna, Wyoming (basin 7)					
06/27/65	.35	2.08	.168	.042	.022
09/16/65	.28	1.58	.177	.015	.010
06/12/67	.33	.75	.440	.034	.040
06/13/67	.39	1.83	.213	.051	.037
06/15/67	.40	3.17	.126	.025	.014
09/18/67	.17	3.10	.055	.007	.000
09/26/67	.16	.58	.276	.009	.002
07/11/69	.28	.92	.304	.002	.022
08/05/70	.23	.58	.396	.012	.015
08/09/71	.30	.58	.517	.024	.036
08/29/71	.36	.67	.537	.027	.051
06/09/72	.26	.50	.520	.036	.026
07/22/72	.32	.42	.762	.015	.045
08/02/72	.56	.67	.836	.114	.109
06/28/73	1.02	.67	1.522	.347	.381
07/13/73	.73	4.00	.182	.031	.102
07/19/73	.67	7.67	.087	.057	.036
07/19/73	.24	2.25	.107	.002	.000
07/21/73	.33	1.00	.330	.108	.035
09/01/73	.59	4.92	.120	.044	.049
09/09/73	.97	1.75	.554	.246	.234
09/10/73	1.78	3.17	.561	.630	.643
09/11/73	1.94	13.92	.139	.569	.331
Hanna Draw tributary near Hanna, Wyoming (basin 8)					
07/23/65	.76	.92	.826	.085	.112
09/01/66	.48	5.25	.091	.028	.023

Table 9. Rainfall data, measured runoff data, and simulated runoff data for multiple-soil basins—Continued

Date	Rainfall (inches)	Length of storm (hours)	Intensity (inches per hour)	Measured runoff (inches)	Simulated runoff (inches)
Hanna Draw tributary near Hanna, Wyoming—Continued					
06/11/67	.25	.58	.431	.003	.019
06/20/67	.23	1.75	.131	.016	.005
06/23/67	.26	1.75	.149	.021	.010
06/23/67	.33	3.00	.110	.025	.013
06/28/67	.39	6.17	.063	.014	.002
07/15/67	.71	.92	.772	.181	.102
08/12/67	.12	.17	.706	.004	.002
08/05/70	.86	.75	1.147	.138	.138
08/09/71	.15	.58	.258	.004	.002
08/29/71	.20	.42	.476	.005	.012
07/20/72	.25	.33	.758	.031	.022
08/01/72	.27	.33	.818	.031	.026
08/23/72	.47	2.50	.188	.030	.040
09/01/72	.15	.92	.159	.005	.000
07/19/73	.32	3.00	.107	.011	.011
07/23/73	.16	1.08	.148	.006	.000
09/01/73	.68	6.92	.098	.029	.047
09/11/73	1.96	14.00	.140	.302	.242
Frank Draw tributary near Orpha, Wyoming (basin 9)					
05/23/65	1.06	2.75	.385	.194	.225
06/10/65	.50	2.58	.194	.094	.029
06/24/65	.88	.83	1.060	.287	.241
08/19/66	1.62	.50	3.240	.586	.795
06/15/67	1.30	9.50	.137	.225	.154
07/15/68	.84	.92	.967	.131	.239
06/11/69	.64	1.21	.529	.016	.081
05/30/71	1.19	.92	1.290	.473	.445
08/02/72	.40	1.67	.240	.006	.017
07/30/73	1.25	4.92	.254	.358	.234
08/11/73	.37	.50	.740	.037	.028
Sage Creek tributary near Orpha, Wyoming (basin 10)					
06/10/65	.51	1.17	.436	.015	.003
06/14/65	.37	.50	.740	.011	.002
06/16/65	.65	.58	1.121	.063	.070
07/25/65	1.19	.66	1.803	.303	.303
08/19/66	.57	.50	1.140	.033	.041
06/15/67	1.16	7.66	.151	.040	.031
06/22/67	1.09	7.00	.156	.057	.024
06/12/70	1.28	7.50	.171	.033	.086
05/30/71	.69	.92	.750	.052	.067
08/02/72	.82	1.58	.519	.053	.090
07/22/73	.65	1.05	.600	.073	.036
09/09/73	.68	2.92	.233	.026	.005

used to show the distribution and average curves for each soil group. Figures 15 through 18 illustrate incipient-runoff curves and the average curve for the four soil groups. Soil group 1.10 (that is, soils having a relative permeability of 1.10 in per hour) (fig. 18, table 10) is an average for two sets of parameter values based on maximum rainfall intensity and the two sets of optimized parameter values. The parameter values for this soil group become the upper limit of the study.

Optimized parameter values for Headgate Draw were not used in the computation of the average parameter

Table 10. Relative permeabilities, infiltration parameters, and fitting errors for multiple-soil basins

Basin number	Basin name	Relative permeability (inches per hour)	Parameter			Percentage area of soil group	Percentage difference in runoff	Standard error of estimate
			K_h	$P(m-m_o)$	d			
1	North Prong East Fork Nowater Creek	0.06	0.011	0.050	0.073	29.3		
		.11	.031	.141	.206	17.1		
		[1].35	.074	.340	.496	42.0		
		[2]1.10	.074	.340	.496	17.1		
		[2]3.46	.074	.340	.496	1.8	−8.5	42
2	North Prong East Fork Nowater Creek tributary	.06	.011	.050	.073	18.6		
		.11	.037	.168	.245	18.6		
		[1].35	.074	.340	.496	26.5		
		[2]1.10	.074	.340	.496	33.2		
		[2]3.46	.074	.340	.496	3.1	−1.3	20
6	Headgate Draw at upper station	.06	.040	.084	.161	15.3		
		.11	.104	.218	.417	39.5		
		[1].35	.211	.443	.849	6.2		
		[2]1.10	.211	.443	.849	39.0	7.5	24
7	Medicine Bow River tributary	.06	.026	.053	.075	10.0		
		.11	.036	.074	.105	19.6		
		.35	.117	.238	.337	38.2		
		[1]1.10	.185	.378	.535	14.5		
		[2]3.46	.185	.378	.535	17.7	−8.0	53
8	Hanna Draw tributary	.06	.026	.053	.075	17.6		
		.11	.054	.110	.156	1.8		
		.35	.147	.300	.426	22.2		
		[1]1.10	.151	.308	.436	15.9		
		[2]3.46	.151	.308	.436	42.5	−12.0	56
9	Frank Draw tributary	.11	.026	.070	.180	24.9		
		.35	.056	.150	.385	8.1		
		1.10	.063	.171	.439	38.1		
		[1]3.46	.166	.448	1.15	9.6		
		[2]11.0	.166	.448	1.15	19.3	3.4	45
10	Sage Creek tributary	.11	.026	.070	.180	1.7		
		1.10	.043	.116	.299	42.8		
		[1]3.46	.116	.313	.805	18.8		
		[2]11.0	.116	.313	.805	36.7	−1.3	44

[1] Infiltration rates may be greater than the value listed.
[2] Infiltration rates are undefined.

values. A visit to Headgate Draw revealed that the channel at the streamflow-gaging station is located in a wide, alluvial fan that will reduce runoff by bank storage. The point-infiltration model will not compute the loss of water to bank storage; therefore, the model will compute a false retention-storage and infiltration rate.

Table 11. Average infiltration parameter values for soils classified by relative permeability

Relative permeability (inches per hour)	Average parameter value			Number of basins used to compute the average value
	K_h (inches per hour)	$P(m-m_o)$ (inches)	d (inches)	
0.06	0.018	0.052	0.074	4
.11	.035	.106	.179	6
.35	.094	.274	.428	5
1.10	.112	.248	.438	4

APPLICATION OF MODEL

The results of this study can be applied to determine runoff from precipitation for small, ungaged ephemeral streams in the plains and intermontane areas of Wyoming. Large amounts of precipitation data are not needed to apply the methods. The following steps are needed to compute runoff:

1. Obtain soil maps and descriptions of the area of interest from the U.S. Soil Conservation Service. Several counties and most areas that have had environmental assessments have been mapped.
2. Arrange soil types into their appropriate groups, determine the percentage of the basin covered by each soil group, and select the parameter values for each soil group. Because parameter values for soil group 11 have not been defined, parameter values for soil group 1.10 should be used for soil group 11. Parameter values for each soil group are listed in table 11.

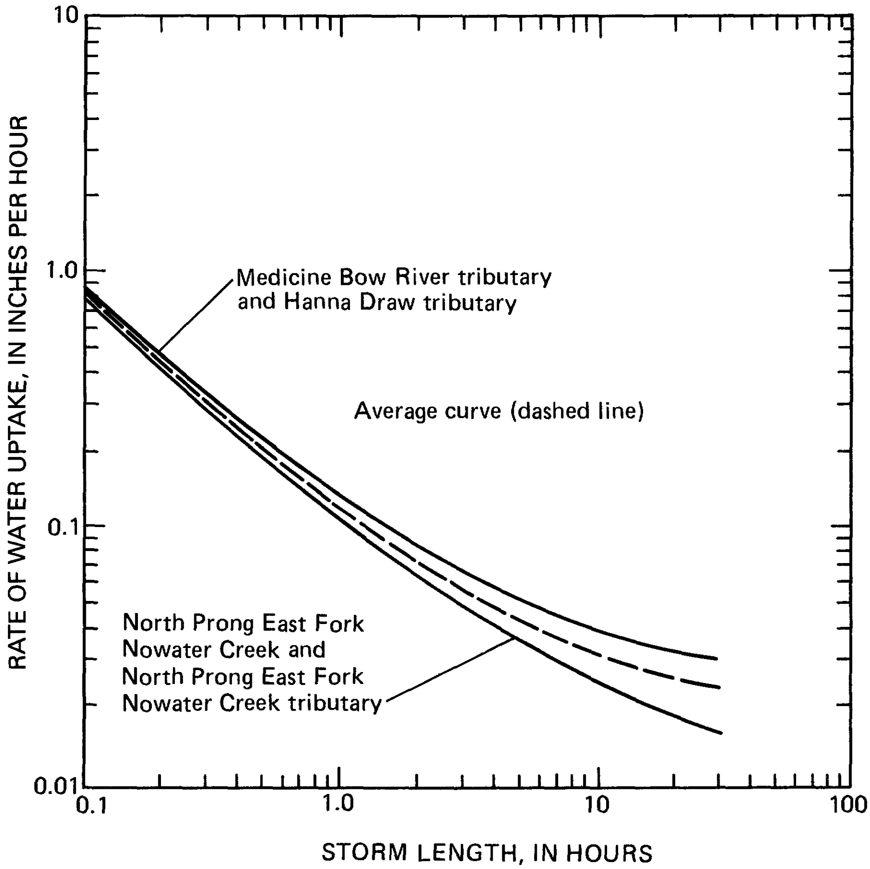


Figure 15. Incipient-runoff curves for North Prong East Fork Nowater Creek near Worland, North Prong East Fork Nowater Creek tributary near Worland, Medicine Bow River tributary near Hanna, and Hanna Draw tributary near Hanna, and average curve for soils having a relative permeability of 0.06.

3. Define the design storm: total precipitation (inches), storm length (hours), and average intensity (inches per hour). Design storm information can be obtained from a report entitled "Precipitation-Frequency Atlas of the Western United States" by Miller and others (1973). Average intensity is total precipitation divided by storm length.
4. Follow the procedures outlined in the flowchart in the next section to apply the point-infiltration model.

Flowchart

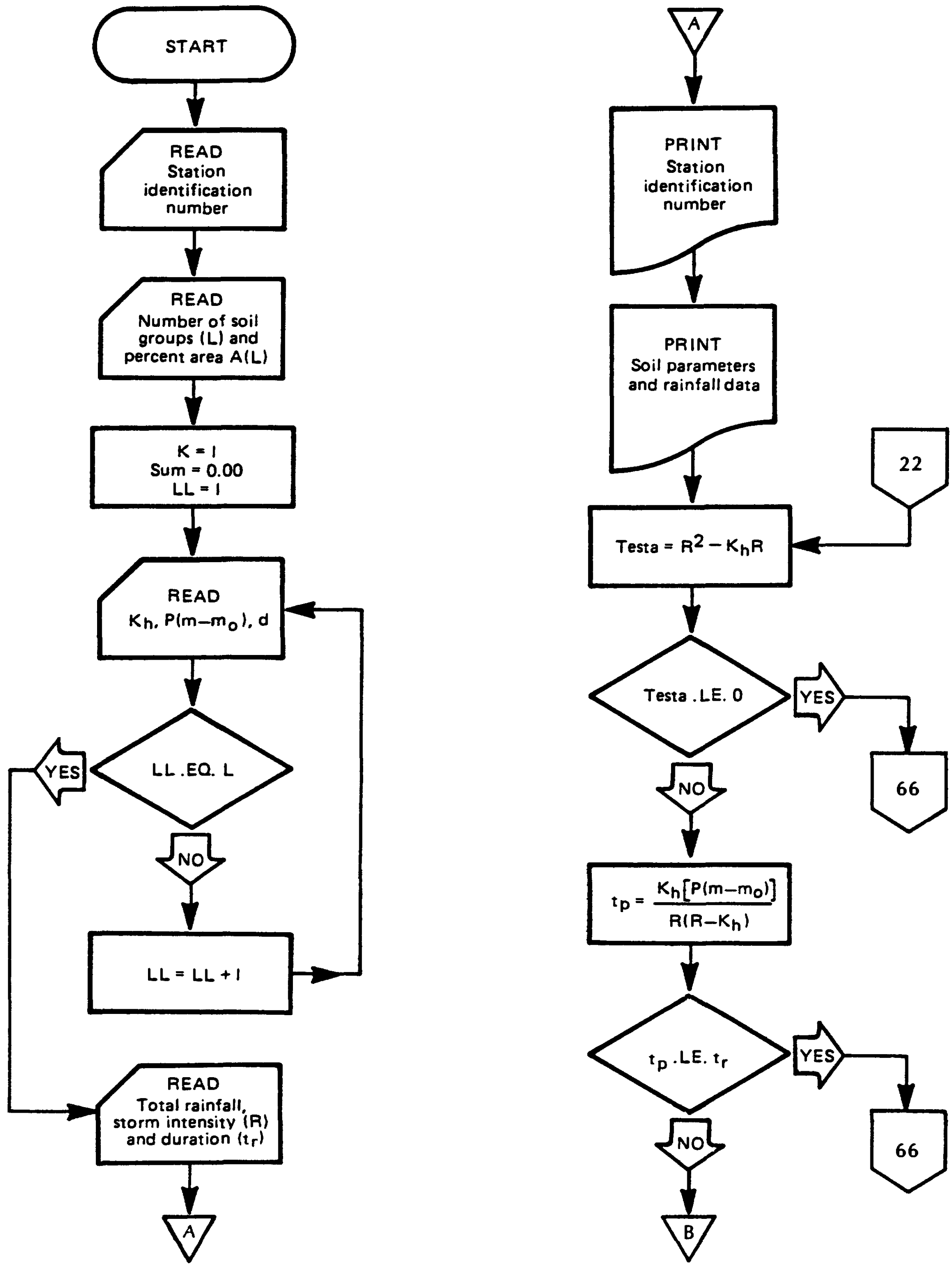
The computation of infiltration using equation 2 is iterative and requires a computer program. The program to compute water uptake and runoff can be written for a hand-held programmable calculator. The flowchart on pages 20 and 21 outlines the necessary steps.

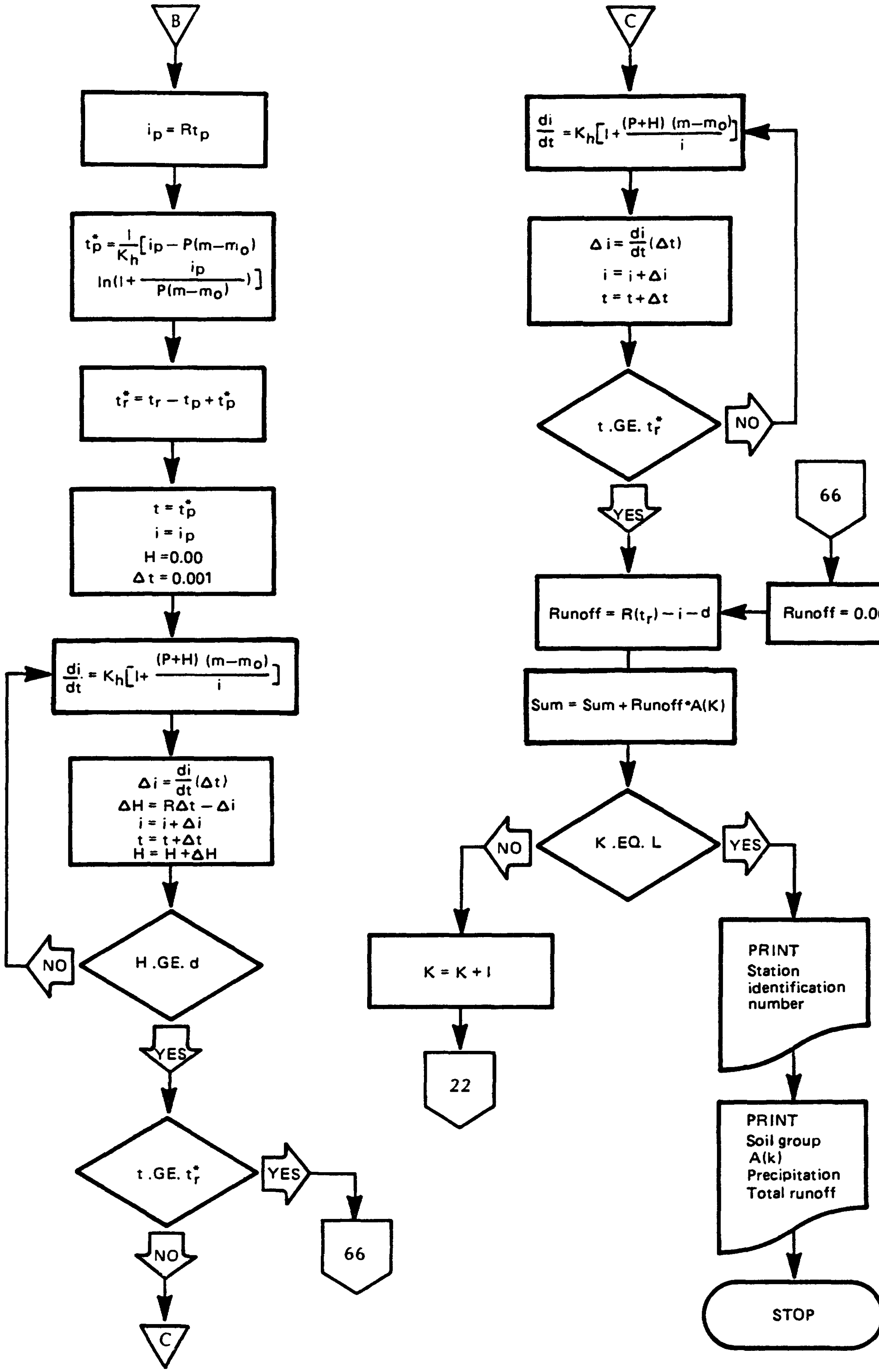
Example Basin

Demott Draw, a 0.91-mi^2 basin (basin 11, fig. 1) on Mobil Oil Corporation's Federal coal lease in Campbell County, is used as an example for computing runoff. Soils data and descriptions compiled by the U.S. Soil Conservation Service were published in an environmental impact report prepared for Mobil Oil Corporation (D'Appolonia Consulting Engineers, Inc., 1976). The following soil groups were identified for the basin:

Soil group	Percentage of basin area
0.06	5.5
.11	7.2
1.10	85.7
11.0	1.6

The design storm is a 100-year, 6-hour event (Miller and others, 1973, fig. 25). Total precipitation for the storm is 3.4 in. Runoff can be computed by applying average storm intensity, storm length, and the soil parameters for the identified soil groups. The procedures for doing so are listed in the flowchart in the preceding section. The computed runoff for the design storm is 1.83 in, or 89 acre-feet (acre-ft).


START
READ
Station
identification
number
READ
Number of soil
groups (L) and
percent area A(L)
K = I
Sum = 0.00
LL = I
READ
Kh, P(m—mo), d
LL .EQ. L
YES
NO
LL = LL + I
READ
Total rainfall,
storm intensity (R)
and duration (tr)
A
A
PRINT
Station
identification
number
PRINT
Soil parameters
and rainfall data
22
Testa = R2 — KhR
Testa .LE. 0
YES
66
NO
tp = Kh[P(m—mo)] / R(R—Kh)
tp .LE. tr
YES
66
NO
B



B
$i_p = Rt_p$
$t_p^* = \frac{1}{K_h}[i_p - P(m-m_o) \ln(1 + \frac{i_p}{P(m-m_o)})]$
$t_r^* = t_r - t_p + t_p^*$
$t = t_p^*$
$i = i_p$
H = 0.00
$\Delta t = 0.001$
$\frac{di}{dt} = K_h[1 + \frac{(P+H)(m-m_o)}{i}]$
$\Delta i = \frac{di}{dt}(\Delta t)$
$\Delta H = R\Delta t - \Delta i$
$i = i + \Delta i$
$t = t + \Delta t$
$H = H + \Delta H$
H .GE. d
NO
YES
t .GE. t_r^*
YES
66
NO
C
C
$\frac{di}{dt} = K_h[1 + \frac{(P+H)(m-m_o)}{i}]$
$\Delta i = \frac{di}{dt}(\Delta t)$
$i = i + \Delta i$
$t = t + \Delta t$
t .GE. t_r^*
NO
YES
66
Runoff = $R(t_r) - i - d$
Runoff = 0.00
Sum = Sum + Runoff*A(K)
K .EQ. L
NO
YES
K = K + 1
22
PRINT
Station
identification
number
PRINT
Soil group
A(k)
Precipitation
Total runoff
STOP

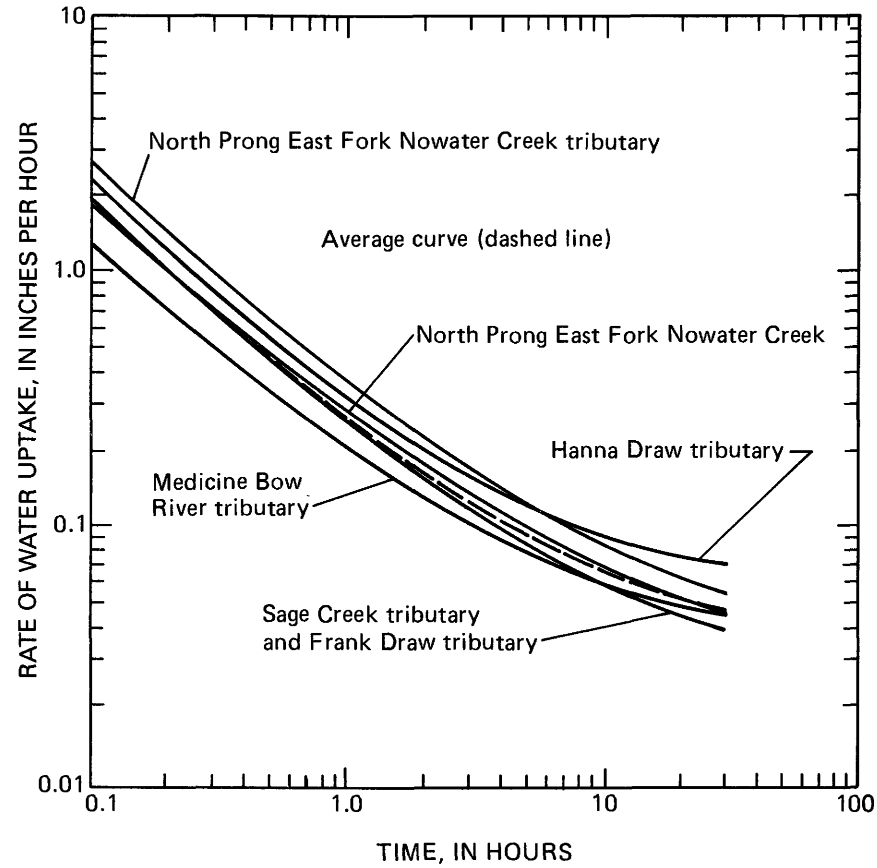


Figure 16. Incipient-runoff curves for North Prong East Fork Nowater Creek near Worland, North Prong East Fork Nowater Creek tributary near Worland, Medicine Bow River tributary near Hanna, Hanna Draw tributary near Hanna, Frank Draw tributary near Orpha, and Sage Creek tributary near Orpha, and average curve for soils having a relative permeability of 0.11.

Limitations

All of the basins included in this study are located in the plains and intermontane areas of Wyoming where runoff is in response to intense thunderstorms; the equations described herein should not be applied to other physiographic areas of Wyoming. The drainage areas of the basins in the study ranged from 0.81 to 3.77 mi^2; the incipient-runoff method should not be applied to larger basins. The values of the infiltration and retention-storage parameters from this study may be applicable to larger basins, but the assumptions concerning antecedent-moisture conditions and uniform rainfall have not been tested for larger basins. The incipient-runoff curves were defined for soil groups 0.06, 0.11, and 0.35. Parameter values for soil group 1.10, which defines infiltration rates just slightly greater than those of soil group 0.35, constitute the upper limit of the study.

RAINFALL-SIMULATOR INFILTROMETER TESTS

Selection and Location of Sites

Rainfall-simulator infiltrometer tests were run for two of the study basins—one single-soil basin, and a multiple-soil basin—to compare infiltration rates of different soils in the same basin. Dugout Creek tributary (basin 5, fig. 1) was selected as the single-soil basin because of the small size of its drainage area and the uniformity of its silty-clay loam soil. Infiltrometer tests were run on the three soil types in the North Prong East Fork Nowater Creek tributary (basin 2, fig. 1), the multiple-soil basin.

The infiltrometer-test sites in Dugout Creek tributary were selected by laying a grid pattern over a topographic map of the drainage basin. Thirteen sample sites were selected (fig. 19). Final field selection of the sample points

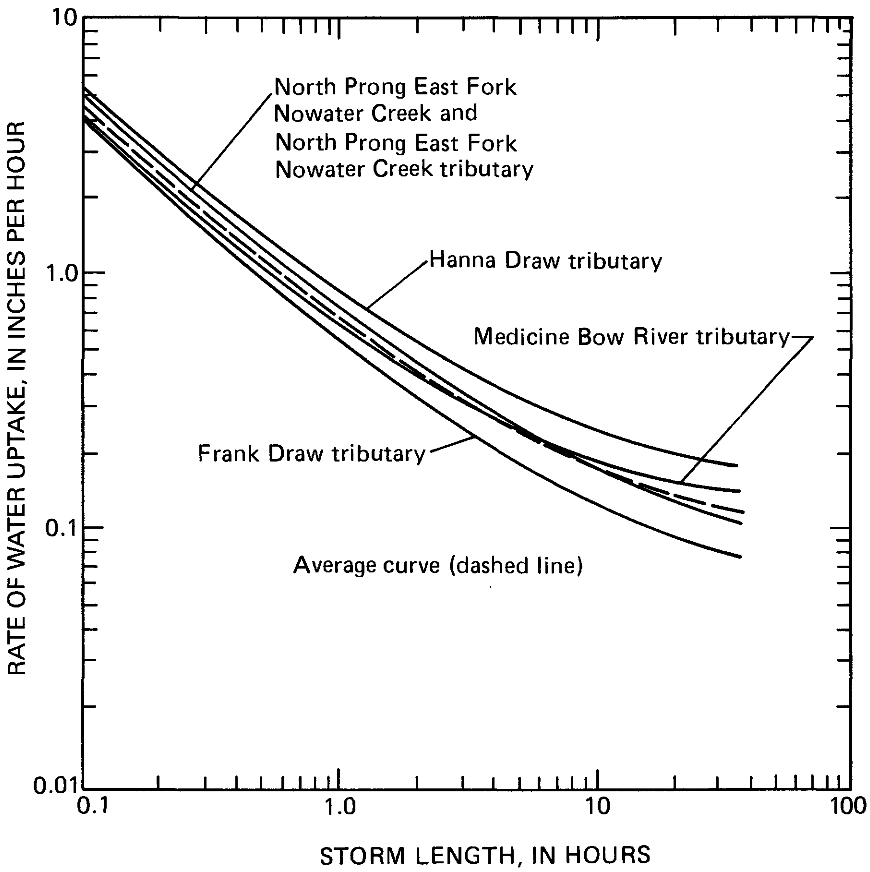


Figure 17. Incipient-runoff curves for North Prong East Fork Nowater Creek near Worland, North Prong East Fork Nowater Creek tributary near Worland, Medicine Bow River tributary near Hanna, Hanna Draw tributary near Hanna, and Frank Draw tributary near Orpha, and average curve for soils having a relative permeability of 0.35.

was made randomly. The test sites for soils in North Prong East Fork Nowater Creek tributary were selected from a Soil Conservation Service soil map. For each soil type, four tests were conducted at 100-foot (ft) intervals along a transect.

Description of Equipment

A hand-portable rainfall-simulator infiltrometer designed by McQueen (1963) was used for the tests. The equipment is lightweight and easy to set up, and it simulates a rainfall rate and drop impact similar to those of a natural storm (about 1.9 in/h). The test area covered by the simulator is 26.0 square inches (in^2), with a 5.75-in diameter. The base of the infiltrometer is attached to the soil surface without disturbing the soil by using a bentonite-water seal. The only change in the equipment from the McQueen design was to add a battery-operated, peristaltic pump to collect and remove runoff from the sample plot. The pump was run continuously to prevent head buildup on the soil surface.

Infiltrometer Tests and Corrections

The rainfall-simulator infiltrometer tests were run for 1 hour at each sample site in the two basins. Amounts of simulated rainfall and runoff were determined and recorded at 5-minute (min) intervals for each test. Rainwater was simulated by using distilled water for all infiltrometer tests. For Dugout Creek tributary, the distilled water was chilled to 5 to 12 °C, approximating temperatures typical of rainfall in Wyoming (J.D. Alyea, oral commun., 1980). For North

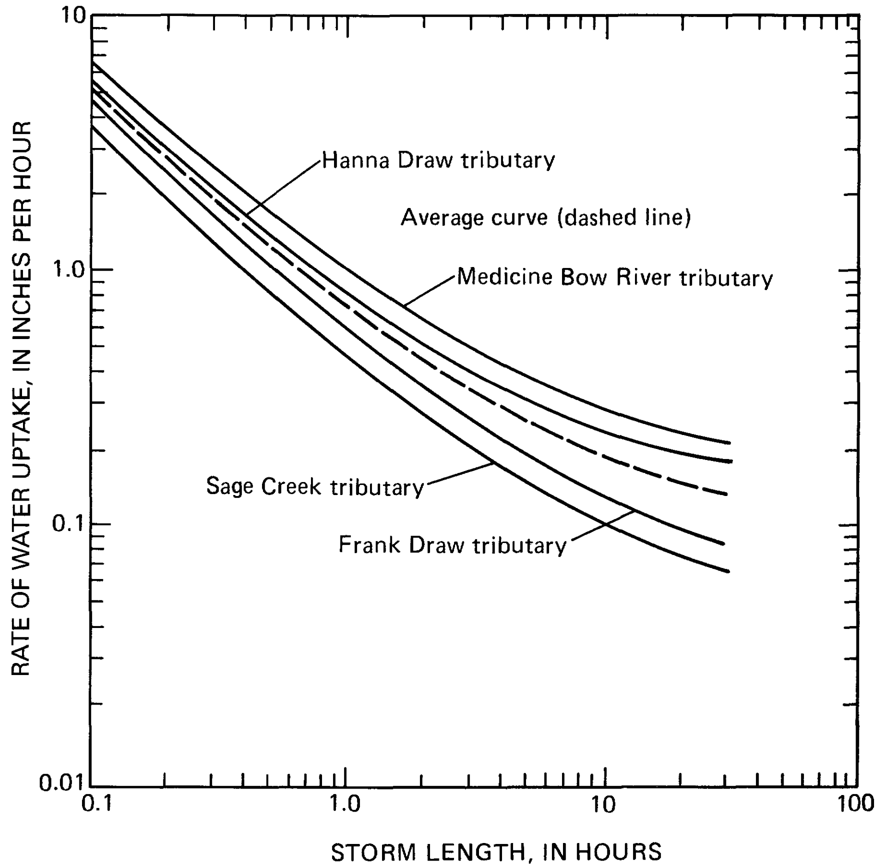


Figure 18. Incipient-runoff curves for Medicine Bow River tributary near Hanna, Hanna Draw tributary near Hanna, Frank Draw tributary near Orpha, and Sage Creek tributary near Orpha, and average curve for soils having a relative permeability of 1.10.

Prong East Fork Nowater Creek tributary, the distilled water was not chilled; therefore, the water temperature approximated air temperature. The time required to make the initial instrument readings precluded observation of the time to ponding.

Immediately after each test, the equipment was removed from the test plot and the soil column of the test area was sliced vertically to determine the depth and lateral movement of the wetting front. Two approaches were used to estimate the wetted volume. In Dugout Creek tributary, the wetted volume of the soil was best estimated by a cylinder (fig. 20*A*). The average depth to the wetted front was 1.2 in. In North Prong East Fork Nowater Creek tributary, the best estimate of the wetted volume of soils was a cone (fig. 20*B*). For both basins, the measured water uptake was adjusted by a ratio of the wetted volume of soil under the infiltrometer to the total wetted volume of soil (Hely and Peck, 1964, p. B13).

Adjusted values of water uptake for the infiltrometer tests in Dugout Creek tributary are presented in table 12. The mean and standard deviation of water uptake were computed for each 5-min interval of the data set. Values of water uptake for sample 9 are considerably larger than for the other samples. After the first 5 min of the test, the water uptake by the soil was abnormally large. The wetting front, when the soil column was sliced, was found to have followed an old root channel or a crack. This type of phenomenon is typical for this soil; therefore, sample 9 was left in the data set.

Soil-moisture samples were collected at 9 of the 13 sample sites to determine the antecedent-moisture condition. The moisture content was determined using methods described by Yong and Warkentin (1975, p. 101). The average moisture content by weight was 2.6 percent.

Comparison of Measured and Computed Infiltration Data

Water uptake was computed for Dugout Creek tributary using infiltration and retention values obtained from the fitted incipient-runoff curve and a hypothetical rainstorm

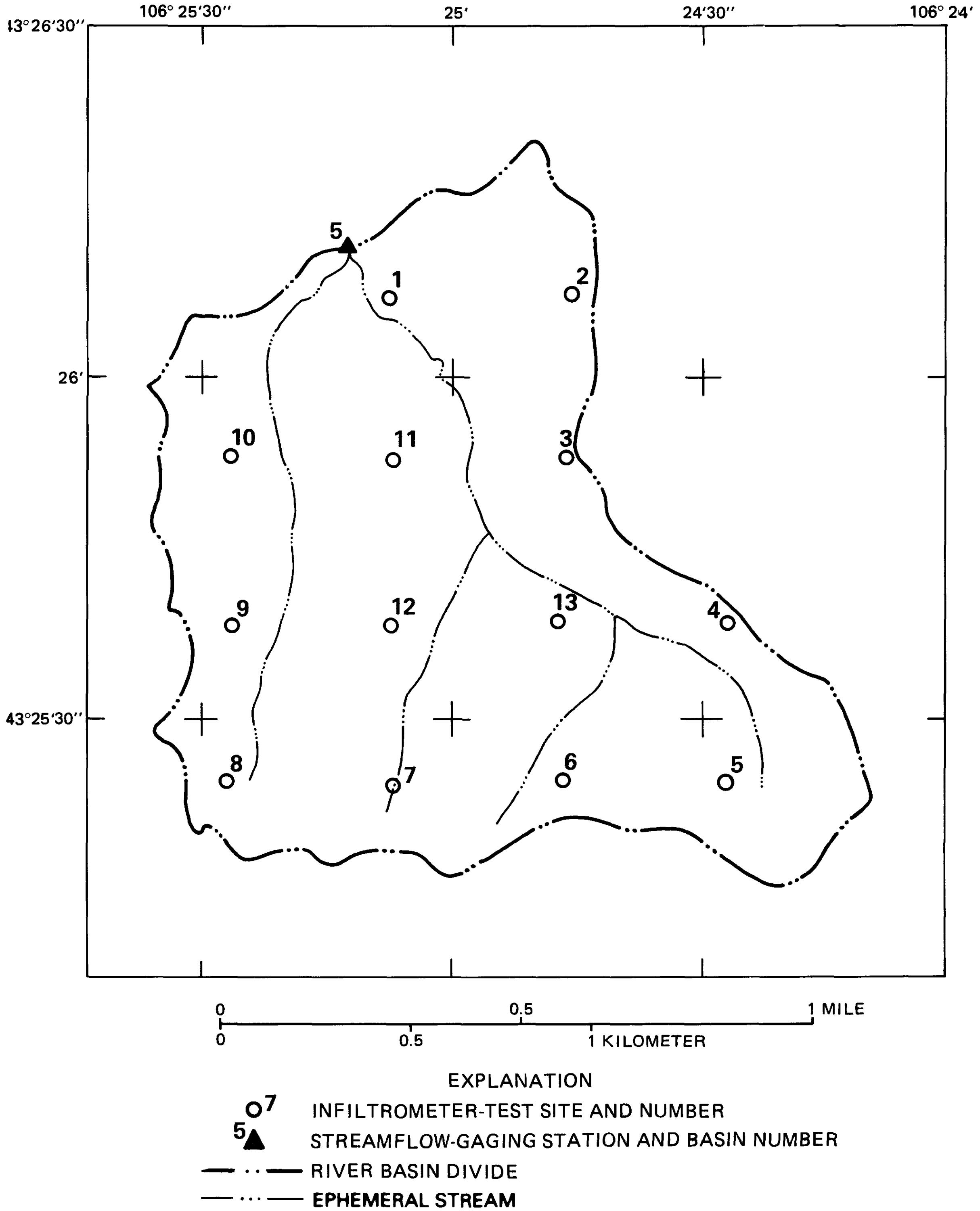


Figure 19. Location of infiltrometer-test sites in Dugout Creek tributary near Midwest (basin 5).

having a duration of 1 hour and an average intensity equal to that in the rainfall-simulator test (1.90 in/h). Water uptake was computed for each 5-min interval of the storm, and the results were compared with the mean values from the infiltrometer test (fig. 21). After 1 hour, the amount of water uptake measured by the infiltrometer tests was about three times greater than that computed from observed rainfall and runoff data.

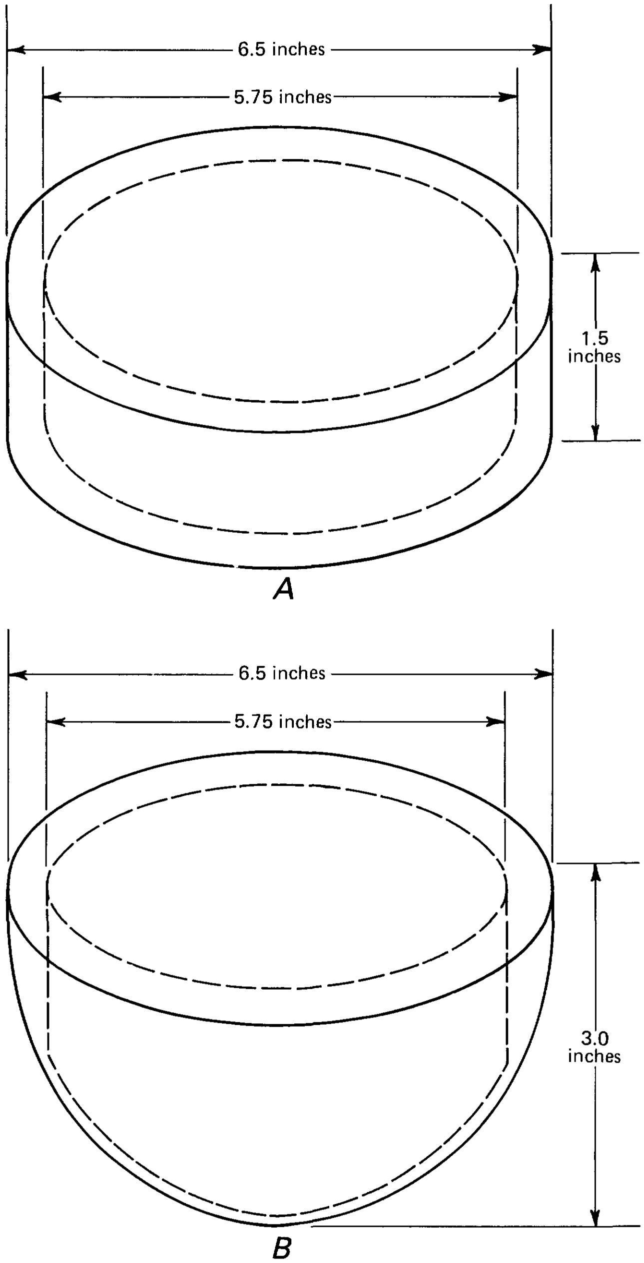


Figure 20. Total wetted volume (solid lines) and volume of infiltrometer tests (dashed lines) for cylinders (*A*) and cones (*B*).

Confidence limits (*CL*) were computed for the infiltrometer-test results using a confidence limit of 0.90 (Mendenhall, 1975, p. 400):

$$CL=\bar{y}\pm\frac{1.771s}{n}, \tag{13}$$

where

$\bar{y}$ = mean of the sample;
s = sample standard deviation; and
n = sample size.

From figure 21, it can be concluded that the infiltration rates determined from the infiltrometer tests are too large and should not be used to compute runoff from the basin.

Four infiltrometer tests were run on each of three soil complexes in North Prong East Fork Nowater Creek tributary. Two of the 12 tests failed owing to leakage between the soil and the test ring. Each of the 10 remaining tests was adjusted for the lateral movement of the wetted front as described in the preceding section on "Infiltrometer Tests and Corrections." The soil complexes tested, number of samples, average water uptake, and adjusted water uptake for the 1-hour tests are as follows:

Soil complex	Number of samples	Average water uptake (inches)	Adjusted water uptake (inches)
Fruita-Neiber	4	1.14	0.62
Muff-Neiber	3	1.00	.82
Persayo-Rock outcrop	3	.69	.65

Rainfall intensity data for North Prong East Fork Nowater Creek tributary, listed in table 7, show only two storms having an intensity slightly greater than water uptake measured in a 1-hour period. If the infiltration measured by the infiltrometer test were to represent natural infiltration rates, the basin would have had only two small runoff events during the 9-year period of record, when in fact 53 were recorded. As was the case for the single-soil basin, it is concluded that infiltrometer data should not be used to compute runoff.

SUMMARY

A point-infiltration model was developed and tested to estimate the volume of storm runoff from small ephemeral-stream drainage basins in Wyoming. For a design storm (having a user-specified average rainfall intensity and duration), data that are required to compute runoff for a given basin are (1) the distribution of soils by type and description, and (2) infiltration parameters and a retention-storage parameter.

To compute infiltration and runoff using the point-infiltration model, two assumptions are necessary: (1) antecedent-moisture condition (initially dry) for a storm is some long-term average, and (2) rainfall for a storm is uniform in both time and space.

In this study, two infiltration parameters, K_h and $P(m-m_o)$, and a retention-storage parameter, d, were determined for the soil of each basin covered by only one type of soil. Each rainstorm was identified as a runoff or nonrunoff rainstorm. An incipient-runoff curve, which was fitted between the two types of rainfall data, was used to define the infiltration and retention-storage parameters.

For basins covered by more than one soil type, only the incipient-runoff curve for the soil type having the lowest infiltration rate can be defined by the curve. Incipient-

Table 12. Infiltrometer data (values of water uptake, in inches) for soil in Dugout Creek tributary near Midwest (basin 5)

Sample number	Time, in minutes												
	0	5	10	15	20	25	30	35	40	45	50	55	60
1	0.00	0.15	0.21	0.27	0.32	0.35	0.37	0.40	0.44	0.48	0.52	0.54	0.58
2	.00	.09	.16	.20	.24	.27	.28	.30	.33	.35	.36	.37	.39
3	.00	.12	.19	.21	.23	.26	.27	.30	.33	.36	.39	.45	.51
4	.00	.12	.20	.28	.33	.39	.43	.47	.51	.54	.57	.60	.63
5	.00	.14	.18	.21	.23	.27	.30	.33	.36	.37	.38	.40	.43
6	.00	.26	.28	.32	.35	.37	.38	.40	.42	.43	.45	.46	.47
7	.00	.15	.18	.22	.26	.31	.33	.35	.36	.36	.36	.36	.36
8	.00	.21	.26	.31	.34	.38	.42	.45	.48	.51	.55	.58	.61
9	.00	.23	.38	.54	.70	.84	1.00	1.17	1.31	1.45	1.60	1.75	1.89
10	.00	.16	.30	.34	.37	.40	.43	.46	.51	.55	.59	.67	.74
11	.00	.14	.18	.23	.28	.31	.34	.38	.41	.44	.47	.50	.52
12	.00	.14	.20	.25	.28	.30	.32	.34	.36	.37	.38	.39	.40
13	.00	.09	.16	.22	.26	.28	.29	.31	.33	.35	.36	.38	.39
Mean of samples	.00	.16	.22	.28	.32	.36	.40	.43	.47	.50	.54	.57	.61
Standard deviation	.00	.05	.07	.09	.12	.15	.19	.23	.26	.29	.33	.37	.40

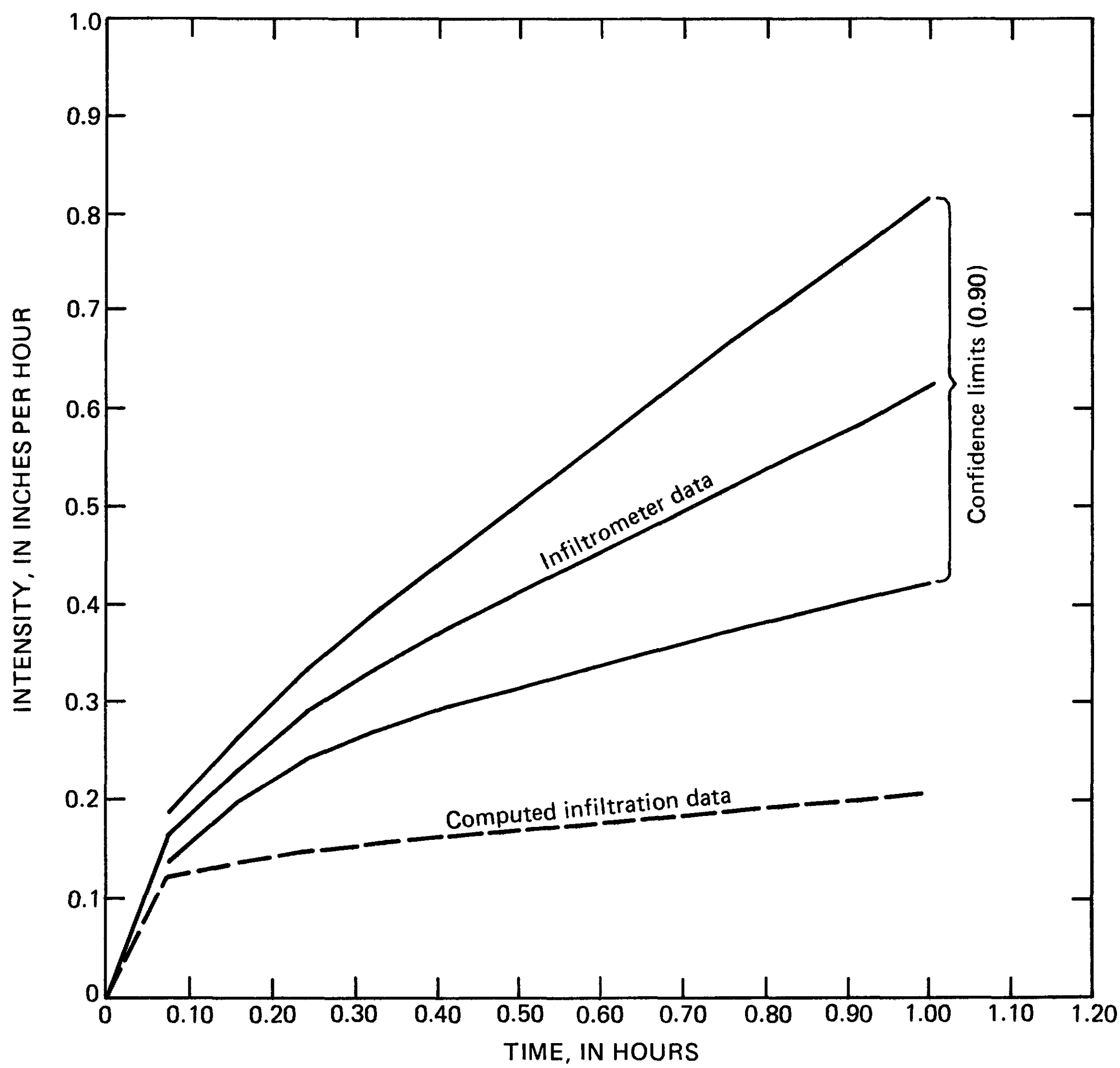


Figure 21. Comparison of infiltrometer data and computed infiltration data for Dugout Creek tributary near Midwest (basin 5).

runoff curves for the soils having infiltration rates greater than the lowest curve were defined by ranking the soils according to their relative permeabilities and optimizing the position of the curve using measured runoff as a control for the fit.

The study shows that the effective contributing area of runoff is less than the total drainage area of the basin. For multiple-soil basins, the effective areas ranged from 41.6 to 71.1 percent of the drainage area. Information on effective contributing drainage area is useful in evaluating drainage area as an independent variable in statistical analysis of hydrology, such as annual peak frequency distributions and sediment yields.

A comparison was made of the sums of the simulated runoff and the sums of the measured runoff for all runoff events in the 10 basins studied for which data were available. Summation of the simulated runoff events ranged from 12.0 percent less than to 23.4 percent more than the summation of the measured runoff events. The standard error of estimate, computed for each data set, ranged from 20 to 70 percent of the mean value of the measured data set.

Using the point-infiltration model, runoff for small ungaged ephemeral streams can be estimated for a user-designated storm, soil data, and infiltration and retention-storage parameters, which are defined in this report. The use of the point-infiltration model is limited to small basins (drainage areas less than 3.77 mi^2) in the plains and intermontane areas of Wyoming.

Rainfall-simulator infiltrometer tests were made in two of the small basins used in this study. In Dugout Creek tributary, the amount of water uptake measured by the tests was three times greater than the water uptake computed from rainfall and runoff data. From this study it was concluded that runoff cannot be estimated from infiltration rates computed from infiltrometer data.

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Multiply inch-pound units	By	To obtain metric units
acre-foot (acre-ft)	1,233	cubic meter
foot (ft)	0.3048	meter
inch (in)	25.4	millimeter
inch per hour (in/h)	25.4	millimeter per hour
square inch (in^2)	6.452	square centimeter
square mile (mi^2)	2.590	square kilometer

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 9/5\ (°C) + 32$$

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